DESIGN OF 3-PHASE STATIC MODULAR DOUBLE-CONVERSION LITHIUM-ION-BASED UPS SYSTEM

By

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DECLARATION

I, **Prosper Kabasele Ngongo**, declare that the contents of this thesis represent my own unaided work and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

August 2022

Signed **Date**

ABSTRACT

A challenge for industries nowadays is to optimize the functionality of their critical processes. Whether they be manufacturing, production, healthcare, banking, data, research, or shopping centres, they are becoming large and complex with several critical loads and processes whose availability is crucial to their overall effectiveness and market competitiveness. Based on their design specifications and accuracies expected, these processes often tend to have a low tolerance and are susceptible to power failures, spikes, brown-out, dip, or surges. They require a high integrity power supply to guarantee their correct functioning, increase their robustness against the damaging effect of power disturbances and operational availability. Eskom's network instability, lower energy availability, and poor power quality, unfortunately, cannot guarantee the integrity of supply to these critical loads. An increase in load shedding in the past few years highlights this low energy availability factor. Based on these reasons, the facility opted to install 4 x 1100kVA online lead-acid-based rotary uninterruptible power supplies (UPSs) to sustain a sturdy power supply through periods of power disturbances. The sustainability of power will also allow orderly processes shutdown in case of prolonged power interruption and avoid any outage-related financial setbacks. Commissioned back in 1995, they have attained their end-of-life and suffer regular costly maintenances, higher losses, and higher spares cost due to unavailability. Although these are considered legitimate running costs, they occur on a capital scale after few years. Given the system's age, running cost, and inefficiency, the facility would be efficiently and cost-effectively served by newer high-performance UPS systems. The process of choosing the right UPS system and energy storage solution for critical infrastructure has now become more challenging than ever. Today's UPS technologies and their corresponding backup storage solution must maintain or even increase the availability and manageability of power on their respective facilities. In the effort to reduce the total cost of ownership, it is imperative to extend lifetime, decrease footprint, streamline maintenance, and lower cooling costs and other operating expenses, in addition to reducing the upfront capital investment. Lithium-ion-based static UPS systems are poised to enhance energy storage for secure power applications. They provide benefits in reducing the installation and maintenance costs and have low waste energy resources making them have high operational efficiency and weigh less than the rotary UPS system. The energy storage system used in these systems has since transformed from medium-lifetime, sprawling, and heavy lead-acid batteries to a long-life, compact, lightweight solution with predictable performance, simplified maintenance, and robust life cycle management. It is not just the UPS system that develops through the adoption of lithium-ion technology; critical power is also going through a period of rapid changes calling for UPS systems to increase their availability and manageability of power. Facilities are, therefore, required to revisit their complete concept of critical power and develop new supply methodologies. There is now a strong need to bring up innovative ways that dispatch the battery stored energy differently. Facilities must continually evaluate their time of energy use in relation to their tariff structures for better energy management and costs control. Time-of-use tariffs are structured to reward consumer who lowers their consumption during peak periods. The intervention strategy will present a comprehensive assessment that offers a site-specific solution. It will also provide a financial and performance analysis of the current rotary UPS system versus the new static UPS system with the desire to improve the facility's power protection, secure its long-term availability, strengthen its energy efficiency capacity, and reduce maintenance costs and carbon footprint. It will evaluate the financial impact that tariff structures and various modelled energy dispatch have on the facility energy budget.

Keywords: Battery energy storage system; consumer price index; floor loading capacity; lithium-ion battery; power density; return on investment; total cost of ownership; uninterruptible power supply; usable energy density.

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GLOSSARY

Terms/Acronyms/ Abbreviations	**Definition/Explanation**
	Advanced battery management
ABM	Ampere-hour rating
Ah rating	Automatic voltage regulator
AVR	Battery energy storage system
BESS	Battery management system
BMS	Bank battery management system
BBMS	Beginning of life
BOL	Battery protection unit
BPU	British thermal unit
BTU	Controller area network
CAN	Certificate of competence
CAPEX	Measurement of what current or rate at which a battery cell is
C-Rating	being charged or discharged (C-Rating = Charge-Discharge Amps / Battery designed Capacity)
	Charge or discharge rate in Amperes (A) of $(\lambda/100)^{th}$ the rated or
λ% C-Rating	designed battery ampere-hours capacity
	Consumer price index
CPI	Distribution board
DB	A-Weighted decibels
dBA	Depth of discharge
DOD	Digital signal processor
DSP	Energy availability factor
EAF	Earth fault
E/F	Easy capacity test
ECT	Emergency distribution board
EDB	Electromagnetic compatibility
EMC	Electrical machinery regulation
EMR	End of life
EOL	Electrostatic discharge
ESD	Energy saver system
ESS	Energy quality factor
EQF	Explosion protection
Ex	Field-effect transistor
FET	Field-installed - uninterruptible power module

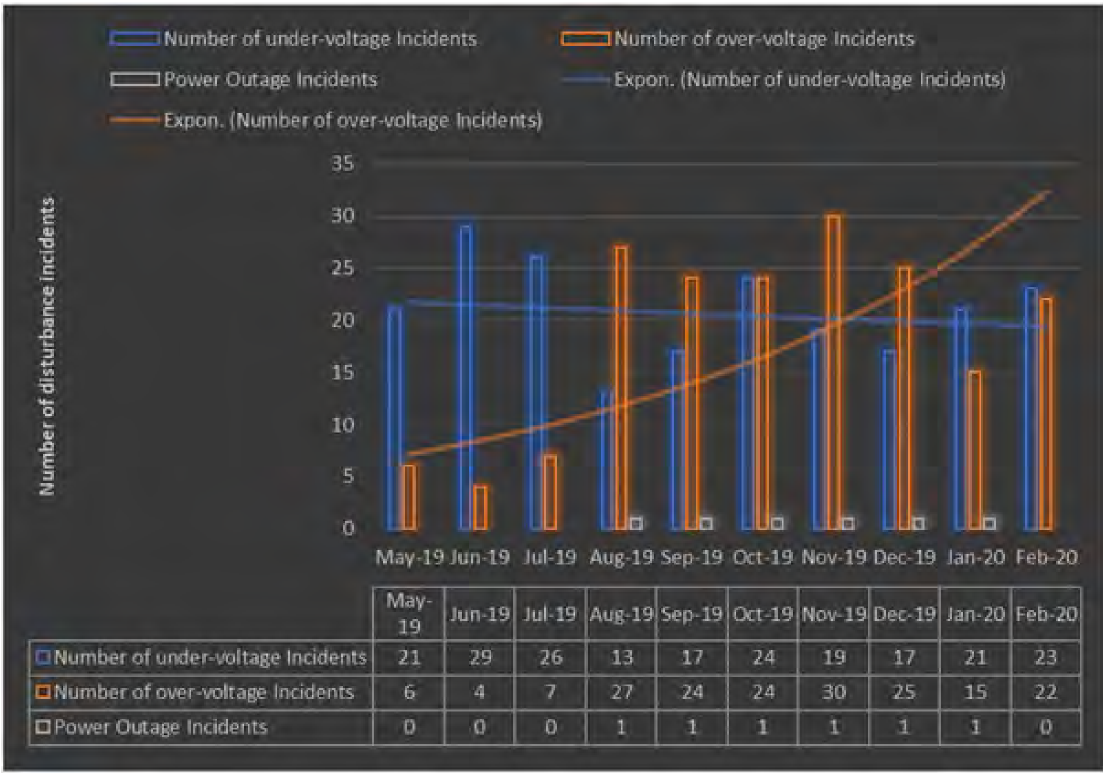
FI-UPM	High demand season
HDS	Human-machine interface
HMI	Heating, ventilation, and air-conditioning
HVAC	Inverse definite minimum time relay
IDMT	Insulated gate bipolar transistor
IGBT	Ingress protection rating
IP Rating	Lead-acid battery
LAB	Lead-acid battery energy storage system
LA-BESS	Lead-acid-based rotary UPS
LAB-RUPS	Liquid crystal display
LCD	Lithium cobalt oxide
LCO	Low demand season
LDS	Concentration limit below which, flammable mixture is leaner
LEL (low explosive limit)	Lithium-ion phosphate
LFP	Lithium-ion battery
LIB	Lithium-ion battery energy storage system
LI-BESS	Lithium-ion-based static UPS
LIB-SUPS	Lithium manganese oxide
LMO	Lithium titanite
LTO	Module battery management system
MBMS	Maintenance bypass switch
MBS	Main distribution board
MDB	Main emergency distribution board
MEDB	Motor – Generator set
M-G Set	Module output breaker
MOB	Material safety data sheet
MSDS	Mean-time between failures
MTBF	Mean-time to repair
MTTR	Lithium nickel cobalt aluminium
NCA	Lithium nickel manganese cobalt oxide
NMC	Network management system
NMS	Over-current
O/C	Output circuit breaker
OCB	Occupational health and safety act
OHSAct	Oil natural - air natural transformer cooling
ONAM	Power factor (Power factor correction)
PF or Cosφ (PFC)	Paper insulation - Lead sheathing - Copper cable
PILC	Personal protective equipment

PPE	Positive temperature coefficient
PTC	Pulse width modulation
PWM	Rack battery management system
RBMS	Remote-control panel
RCP	Radiofrequency interference
RFI	Root mean square
RMS	Return on investment
ROI	Rotary UPS
RUPS	Red – White – Blue sequence
RWB sequence	Switchgear
S/G	System battery management system
SBMS	System bypass module
SBM	Silicon controlled rectifier
SCR	Sub distribution board
SDB	Solid electrolyte interface
SEI	Single line diagram
SLD	Switched-mode power supply
SMPS	State of charge
SOC	State of health
SOH	Structured query language
SQL	Static UPS
SUPS	Total cost of ownership
TCO	Total harmonic distortion
THD	Transformer
TX	Concentration limit above which, flammable mixture is richer
UEL (upper explosive limit)	Uninterruptible power module
UPM	Uninterruptible power supply
UPS	UPS Main distribution board
UPSMDB	Voltage dependant
VD	Voltage and frequency-dependent
VFD	Voltage and frequency-independent
VFI	Voltage independent
VI	Vented lead-acid battery
VLA	Variable module management system
VMMS	Voltage per cell
VPC	Valve-regulated lead-acid
VRLA	Cross-linked polyethylene/Polymerizing vinyl chloride
XLPE PVC	

CHAPTER ONE
INTRODUCTION

1.1 Background and problem statement

For the facility providing a research platform, the sustainability of its operation is reliant on conditioned power devices that improve the quality of power supplied to its critical equipment. Critical loads are those that should be maintained at 100% uptime, and their availability is vital to the overall facility effectiveness. For that, they require a reliable and undisturbed energy supply to guarantee their correct functioning. Uninterruptible power supplies (UPSs) are devices that offer the best solution. Their capacity is chosen to ensure that operational requirements are met at times of power disruptions or disturbances emanating from the Eskom supply network. Their backup stored energy is enough to allow orderly system shutdown in case of power interruptions. Figure 1.2 below represents energy disturbance incidents report from facility installed monitoring device from May 2019 to February 2020. Although the number of under-voltage incidents remains nearly constant, there is an exponential increase in over-voltage incidents emanating from the instability of our electrical network and poor power quality (Majani & Kahn, 2009:1-5; Fritz & Kahn, 2009:1-5). These disturbances will negatively impact critical loads if the facility solely depends on the power utility.



	May-19	Jun-19	Jul-19	Aug-19	Sep-19	Oct-19	Nov-19	Dec-19	Jan-20	Feb-20
Number of under-voltage Incidents	21	29	26	13	17	24	19	17	21	23
Number of over-voltage Incidents	6	4	7	27	24	24	30	25	15	22
Power Outage Incidents	0	0	0	1	1	1	1	1	1	0

Figure 1.2: Energy disturbance trend

For this, the facility's distribution reticulation has four online lead-acid-based rotary UPSs (RUPS) comprising 4 x 1100 kVA, 600/600 V Piller Uniblock UB1100-S UPSs and 4 x 264 vented or flooded BAE Secura 25-OGi-2000 lead-acid battery (LAB) cells. This system was commissioned back in 1995 with an autonomy of 15 minutes. The UPS system is currently 26 years old and already exceeded its design lifespan of around 20 years. Piller has decommissioned facilities where these units were manufactured, the manufacturing jigs are no longer available, and there are no known used units available in the market today. The system now poses major operational threats. The potential failure of these UPS units will remove power protection and increase the susceptibility to equipment damage which, will severely disrupt production. The recovery times from power interruptions will significantly increase since various systems will be placed in cold start conditions which, might take up to a day to complete their setup (John & Patrick, 2015:1-11; Richard, 2012:1-21).

The current situation necessitates an investigation of the alternative backup source to lower protection threats posed, total operational energy losses and costs, and carbon footprint. This thesis work will address these threats and consequences, determine a viable option to mitigate this situation, and secure the long-term availability of conditioned power by replacing the existing system with a modern one of equivalent capacity. The address will provide a financial and practical analysis of the current LAB-RUPS system versus the modern one. This address is with the desire to cost-effectively improve power protection, backup time, power quality, and efficiency. The planning intervention strategy that integrates or retrofits components of the new system into the existing building space is required. A representation of a comprehensive approach to saving energy through system technology change that promotes and implements energy management and optimization that strengthens the facility's capacity in energy efficiency and carbon footprint reduction is as well required (Eaton, 2020a:1-15).

1.2 Literature review and research objective

Several papers have elaborated on the beneficial effects in evaluating the UPS efficiency, losses effects, power density, spatial footprint requirement, and floor loading of various power systems between static UPS (SUPS) and rotary UPS (RUPS) systems. They have also elaborated on the comparison between lithium-ion-based and lead-acid-based UPS on various applications, including the analysis on the optimal chemistries and technologies to be selected, while others provided a framework to guide the user to the selection of the best UPS and decision on what type of UPS to be deployed based on their specific circumstances and requirements (Amory, 2011:1-8; Carl, 2011:1-15; Greg et al., 2012:1-14; John & Patrick, 2015:1-11; Richard, 2012:1-21; Victor et al., 2018:1-12). Unfortunately, this evaluation, selection, or decision elaboration process cannot be made to fit aspects of all facilities as these aspects are situational and subjected to requirements imposed by the concerned facility. Furthermore, with the battery energy storage system (BESS) for specific application sized according to the required facility's power capacity, to the autonomy duration envisaged by the facility (power storage capacity), battery depth of discharge, battery efficiency, UPS efficiency, UPS power factor, and design efficiency. These comparisons are correspondingly situational and subject to requirements imposed by the system used and the facility's power protection requirement. This process likewise cannot be made to fit all power system's aspects of all facilities. The evaluation of usable energy density and storage capacity amongst BESS, conducted across different facility power reticulations, are in the same manner, made to differ.

The energy analysis of any UPS system is always associated with costs. The examination and assessment of only its operational electrical energy wasted can approximately determine these costs. Being linked to a volatile tariff price adjustment administered by Eskom in the past ten years, these costs will increase as the energy tariff increases. It is important to note that the 2020/2021 tariff price adjustment previously predicted is no longer valid following the affirmation of an average tariff increase of 15.06% in the 2021/22 financial year (Eskom, 2021a). However, where an optional UPS system is available, it is always necessary to compare its performance with the existing system. Establishment of how optimal and cost-effective the current UPS system is vis-à-vis the new system is done by firstly determining their wasted energy costs separately and secondly comparatively assessing them. These data are crucial in fully informed decision-making, capital expenditure (CAPEX) budget motivation, determination of their economic competitiveness, and how quickly they re-pay the capital investment injected into them.

From a design perspective, the capacity of a UPS system links to its physical size. For various UPS products, these dimension specifications are often available in the catalogues and manufacture' manuals. Although that is the case, there is no single source where these data are summarised comparatively for every product due to information limitations or lack of motive to conduct such comparison. Inside the wide range of UPS technologies presently available in the market, over and above the enhancement in power rating, modularity, redundancy, and efficiency, the compactness of their components has since drastically improved through the use of high-frequency and high-power IGBT semiconductors. This featuring characteristic drove their footprint and weight down compared to traditional lead-acid-based RUPS systems (LAB-RUPSs). Although the spatial area, weight, and consequently the power density of a new generation UPS system is most likely to be lower than that of the legacy UPS system, the evaluation to confirming and proving this hypothesis is, anyway, needed. This assessment will also determine the impact the system will have on its initial installation cost, land need, civil and structural works, and infrastructure loading requirements. It is also worth mentioning that the correlation between the UPS system's capacity and space they occupy and the physical load exerted on structures where they are mounted forms a significant aspect of their market sustainability and appraisal. It is only for these reasons that power density (kW/m^2)

assessment becomes an important metric in fully informed decision-making, selection, and budget motivation.

This project will use a specific facility-based approach to evaluate various benefits and characteristics between the old LAB-RUPS and the new LIB-SUPS system. This evaluation will conclude in three stages. The first stage will be to represent a comprehensive approach to saving energy, promote and implement an energy management system and energy system optimization that strengthens facility capacity in energy efficiency and carbon dioxide emissions reduction aligned with SANS/ISO 50001. Secondly, it will provide a statistical summary from the evaluation of power density and floor loading capacity associated with the deployment of a new lithium-ion-based SUPS following the replacement of an old lead-acid-based RUPS. The overall UPS + BESS spatial footprint in relation to its maximum power that it can physically handle or process and floor loading capacity of both UPS systems are analysed on a common basis to establish if the system selected is optimum and economical. And lastly, it will provide a statistic summary from the evaluation of usable energy density and storage capacity of both types of BESSs associated with both types of UPS systems and establish a common basis to identify their optimal and economical features.

While the development of new battery cell chemistries gains paces every day in the aim to increase and optimize their performances in relation to traditional technologies, analysis to the understanding of the battery currently in the application is key to the design improvement of the present facility's power protection systems. Even though the operational performances and consequently the usable energy density and capacity of a new generation battery cell chemistry system is most likely to be higher than a legacy battery system; so, is the spatial footprint occupied by the BESSs, those aspects should, too, be evaluated and confirmed. Furthermore, the relationship between BESS stored energy capacity and the power output they can deliver when called upon at their designed duration forms a significant aspect of their market sustainability and appraisal. The assessment of this aspect is substantial in determining the amount of power is in each BESS bank. The energy to be drawn upon if needed under adverse power conditions and clarifying the impact the BESS will have on the facility's power protection or the security during low power qualify factor periods. It is for these reasons that energy density assessment becomes a very useful metric. It plays a vital role in fully informed decision-making, selection, budget motivation, and determination of performance competitiveness.

When associating lithium-ion batteries with a UPS system, more potential applications open up. These applications run from using the lithium-ion based static UPS (LIB-SUPS) to generate revenue through the facility critical loads supply models to running it as a partial power plant. In the later models, the LIB-SUPS system converts into energy storage systems. Its lithium-ion battery energy storage system (LI-BESS) charging during periods at the lowest cost electricity tariff and stored energy used during periods at the highest cost electricity tariff to reduce overall costs. The execution of this model is possible since LI-BESS has a higher power density and are more suited to more frequent and rapid charge/discharge cycles. The battery management systems on the LI-BESS is more complex to ensure balanced charging across the lithium battery set and provide additional safety cut-outs in the event of thermal runaway (Nicolette, 2020:38-39; Vertiv, 2016: 1-8).

1.3 Significant stages of the work

The feasibility study will be concluded through four main stages, the inception of the current UPS system, the conceptualization of the new UPS system, the comparative analysis, and the improvement in the storage system.

1.4 Thesis description

This thesis has eight chapters in general. Chapter one includes the introduction part which, describes the background of the research, problem statement, significant stages of the work, and thesis description. Chapter two and chapter three outline the supply and functionality of the existing RUPS topology and its BESS. Chapter four covers the principles and configurations of SUPS. It also covers the process for selecting the best-suited UPS system for our application and its design procedures. Chapters five and six ensure that correct UPS systems and their BESS are selected. In chapter seven, an analysis of the lithium-ion-based SUPS (LIB-SUPS) versus lead-acid-based RUPS (LAB-RUPS) system is conducted. Chapter eight uses a specific facility-based approach to evaluate the impact utility tariffs and various storage capacity models have on the total cost of ownership (TCO). It also discusses how the smart use of the LIB-SUPS system can economically impact the facility's energy costs. In the end, the conclusion and future researches are presented.

CHAPTER TWO
PARALLEL ROTARY UPS SYSTEM

2.1 Introduction

This chapter will outline the functionality of the existing RUPS topology and its energy storage system. The distribution topology currently in place uses an isolated-parallel RUPS system with an option to operate either in redundant or rating mode. The system is also equipped with a centralized bypass system to continue supplying loads during the scheduled shutdown maintenance, breakdown maintenance, or forced outage.

2.2 System configuration

The current system comprises 4 x UB1100-S, 1100kVA - 600/600V, Piller RUPSs. All four units are supplying a common output bus inside the paralleling cubicle. Even though the system has high availability and can achieve high uptime, a failure on the common output bus has the potentiality to disturb the power supply to the entire critical loading system (Frank, 2012:1-15; Piller, 2001b:5-2 – 5-27).

Figure 2.2-1: General view of Uniblock Piller UB1100 RUPS (Piller, 2001b:5-2)

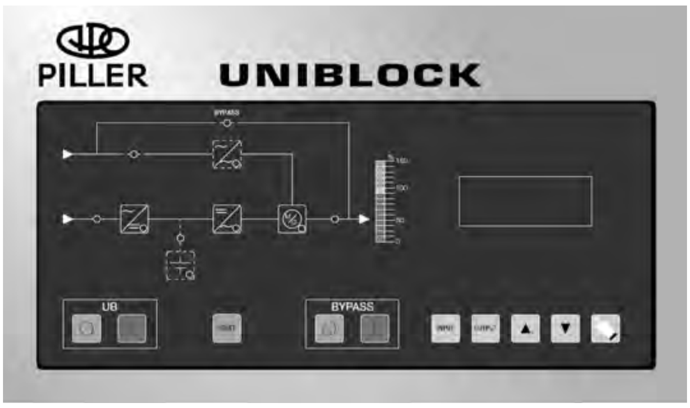


Figure 2.2-2: Uniblock Piller UB1100 control panel (Piller, 2001b:5-37)

2.3 Mechanical construction

Components of the UB1100 Uniblock RUPS house inside a rugged sheet steel cabinet and the system comprises three cabinets: AC input cabinet (Figure 2.2-1/1), converter cabinet (Figure 2.2-1/2), and load cabinet (Figure 2.2-1/3). Components required for external connections, operation, and control are located inside the AC input and load cabinet. Infeed cables are led in from above the unit, and outfeed cables led in from below. The vertically-mounted synchronous motor-generator (M-G) set which, combines synchronous motor and synchronous generator into one unit, is housed in the converter cabinet. This M-G set, essentially, comprises a stator in which alternate slots accommodate motor and generator windings, respectively, and a DC excited rotor. The upper and lower bearings of the synchronous machine get lubricated after every 4000 running or operating hours. All internal components of the UPS are accessible when the cabinet doors are open. Power circuits are isolated from the low voltage control circuits by sheet metal partitions to ensure the necessary protection against electric shock when carrying out servicing operations with the system powered up (Piller, 2001b: 5-1 – 5-4).

The set is fitted with a ventilation system for cooling the synchronous machine, the semiconductors in the various converters, and the magnetic components. Air-inlets into the machine, fitted with filters, are located on the left-hand and right-hand front door of the AC input and load cabinet, respectively, to provide cooling air. The cooling air is sucked into the RUPS unit by the synchronous machine fan and exhausted via the air outlet or exhaust duct in the top cover of the converter cabinet to the roof, as shown in Figure 2.3-1 and Figure 2.3-2 below. A damper control system placed on the exhaust air ducting exhausts 100% of hot air to the outside or, depending on the damper position, circulates a percentage of hot air back into the room. In that way, the system controls the temperature and humidity in the room, mainly during the winter season. Air is drawn into the UPS room naturally through 45-panel filters. The air exchange between UPS and the battery room, or vice versa, is not allowed. The system noise, essentially due to the fan operation, is in the order of 77dB(A) with silencers installed.

Figure 2.3-1: Uniblock Piller UB1100 ventilation (Piller, 2001b:5-4)

Figure 2.3-2: Air circulation system

2.3.1 UPS building ventilation specifications

Air intake to the UPS building	:	45 panel-filters (595 x 595 x 48mm)
Airflow to each RUPS	:	10800m³/h
UPS room footprint area	:	14.4m x 11.6m
Ceiling height	:	4.5m
Humidity	:	0 - 95%
RUPS unit temperature rating	:	0 - 40°C peak (daily average = 35°C)
Maximum room temperature	:	35°C

2.4 Electrical configuration

The Uniblock UPS is available in S, R, and RB versions. The version installed in our case is the 'S' version; its nameplate and block diagram are shown in Figure 2.4-1 and Figure 2.4-2 below. For the entire overview of UB1100 electrical connections, refer to drawings in Appendix A.

Figure 2.4-1: Uniblock Piller UB1100-S nameplate

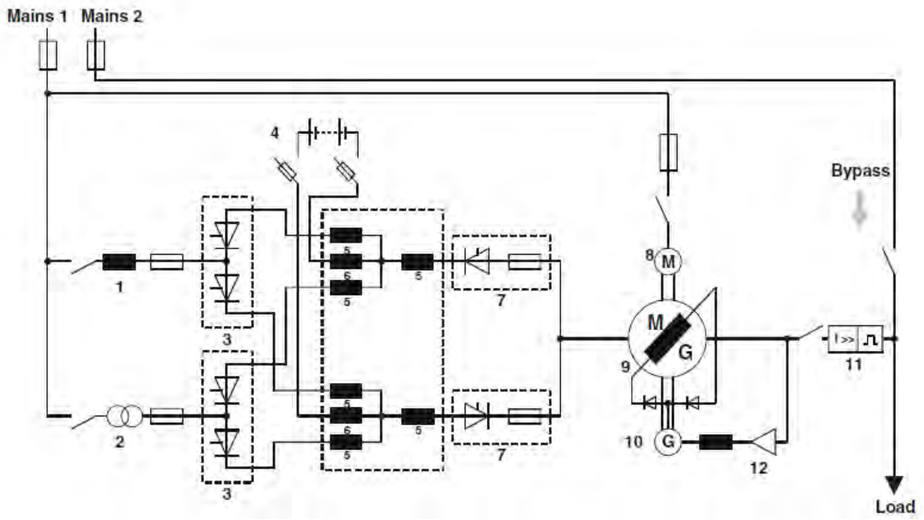


Figure 2.4-2: Block diagram of Uniblock Piller UB1100-S (Piller, 2001b:5-6)

Where '1' is the commutation choke, '2' is the phase-shift transformer, '3' are the 12-pulse three-phase bridge rectifiers, '4' are the BAE 25-OGi-2000 lead-acid batteries (LAB), '5' are the DC link circuit chokes, '6' are the battery chokes, '7' are the thyristor inverters, '8' is the pony motor, '9' is the synchronous machine, '10' is the exciter, '11' is the overload and short-circuit protection, and '12' is the voltage regulator. In normal operation, the applied AC input voltage (Mains #1) is converted into a DC voltage through a DC link circuit. This DC link circuit comprises the rectifiers and BAE LAB energy storage system (LA-BESS) '4'. For this application, only the 'Main #1' supply is connected, and if this supply fails or goes outside the permissible tolerance range, the system will go into battery operation. In that event, the batteries' voltage is immediately fed to the downstream inverter via batteries chokes '6'. The length of time this battery-operating mode sustain depends on batteries capacity and the electricity requirements at that moment. The rectifier voltage is fed to the inverter '7' via the DC link circuit chokes '5'. The rectifier is also used for charging or maintaining the charge of batteries. The inverter is a thyristor converter '7' that converts the DC voltage into a 3-phase AC voltage and operates as a machine-commutated inverter with its phase control or commutating power being provided by the terminal voltage of the synchronous motor '9' that operates at constant AC voltage. By controlling the turn-on phase of the thyristors in relation to the AC voltage, the active current uptake of the system can then be controlled in relation to the loading. The synchronous motor's operating power is taken from the DC link circuit passing through the inverter. In this 3-phase bridge thyristor inverter, the voltage of the DC link circuit is converted back into a 3-phase AC voltage. The inverter operates as a machine-controlled converter that draws the active power from the DC circuit required for running the M-G set. Since the synchronous motor cannot supply the reactive commutation power for static converter when off-load, a pony motor '8' which, is constructed as an asynchronous motor, is provided for starting the synchronous machine. The rotors of the pony motor and synchronous motor-generator are mounted on the same shaft as shown in Figure 2.4-3. During starting, the triggering of the thyristors in the converter remains disabled until the machine has approached its rated speed. At rated speed, the rated voltage appears at the motor, and, therefore, at the inverter. When triggering is enabled, the inverter supplies power to the synchronous machine, and the pony motor is disconnected.

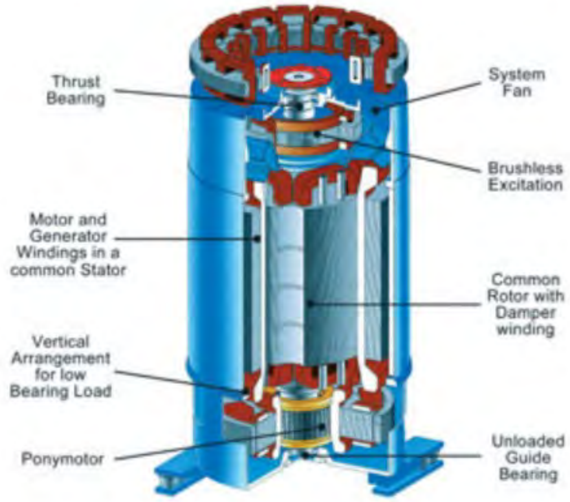


Figure 2.4-3: Uniblock motor-generator (Piller, 2001a:3)

The generator winding supplies the load currents to critical processes with characteristics like that of a normal power supply utility. The percentage impedance of the generator makes the RUPS sustain a prospective short-circuit current of up to 13.6 times its nominal rated current (see Figure 2.4-4) without system static bypass activation back to the main This remains the case even when operating on battery backup. The brushless excitation of the M-G set is provided by an exciter mounted on the same shaft. The system has an automatic voltage regulator making the sinusoidal waveform of voltage generated by the generator to be electronically regulated, undistorted, and with no harmonics, and, also, requires no unreliable harmonics pass filter circuits (Piller, 2001b:5-5 & 2001c:3).

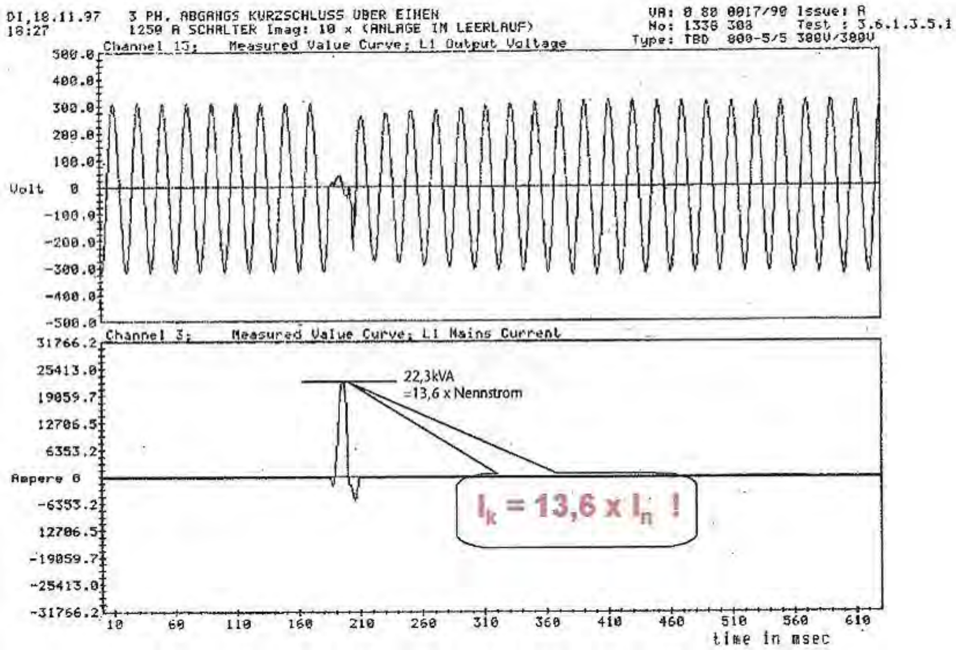


Figure 2.4-4: Three-phase prospective short-circuit test at the load side (Piller Group GmbH)

2.5 Rectifier system

The rectifier system consists of two 12-pulse rectifiers (A030 & A031), two AC power contactors (K013 & K003) in the input for potential isolation from the battery energy storage system (BESS) and Mains #1, one three-phase commutating reactor for rectifier 'A030', one three-phase transformer in Dy5 connection for supplying rectifier 'A031' as shown in Appendix A. These rectifiers are with a line commutated thyristor controller and each consists of two 6-power-thyristors withdrawable modules, one free-wheel diode, and three semiconductor fuses. All rectifier control functions are digital; the trigger pulses are controlled via the rectifier auxiliary controllers. The main controllers are the DC link circuit voltage controller and the series-connected battery current regulator. This cascade of two proportional integrator controllers receives setpoints and offsets from auxiliary controllers which, are the differential current controller, battery current characteristic, current limit controller, and other modules. A differential current regulator is installed to obtain uniform current distribution between the two 12-pulse rectifiers. This regulator is a proportional integrator (PI) controller that receives the difference between the two rectifier currents as a system deviation (Piller, 2001b:5-5 & 2001c:2 – 3).

2.6 Inverter system

The inverter system consists of two withdrawable modules of six power thyristors, six semiconductor fuses, an inverter control board, and a trigger board. This static converter operates as a machine-commutated inverter which, draws the active power required to run the rotary converter (M-G set) from the DC circuit. The synchronous motor supplies the reactive power for converter control and commutation. Speed control is done via the generator controller board, and trigger pulse control is done via the inverter control board. Since the converter triggering results directly from the motor terminal voltage, the reactive power up-take of the system can be regulated in relation to the load by controlling the thyristor turn-on phase. For improved dynamic frequency and speed control, the active component of the generator current is fed to the current control circuit as a disturbance variable. Apart from an excellent dynamic response, the secondary current control circuit also offers fast current limiting to protect the entire system. Phase control which, maintains the output voltage in synchronism with the input voltage, is superimposed on the speed control. The phase control switches off in the event of excessive frequency deviation (0.3Hz) in the mains supply. The set then runs freely at the nominal frequency (Piller, 2001b:5-5 & 2001c:2-4).

2.7 Uniblock converter

The Uniblock converter is a synchronous machine in which the motor and generator windings are supported on a single stator common to both windings. The DC excitation circuit supplies the rotor exciter winding. This rotor has damper cages, as shown in Figure 2.7 below, where damper winding lodges like the cage of an asynchronous machine.

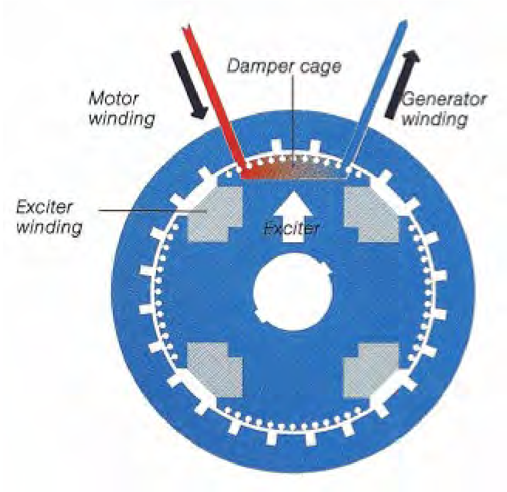


Figure 2.7: Uniblock motor-generator windings (Piller Group GmbH)

Since the motor and generator forms a set combined in a single machine, this led to the expression 'Uniblock converter' being coined. In this machine, the energy transfer from the synchronous motor to the synchronous generator is, fundamentally, made through the rotating magnetic field produced by the motor winding, to which both motor and generator windings are exposed. This rotating magnetic field, turning at synchronous speed, will take the rotor with it in synchronism. From the rotor point of view, the rotating magnetic field appears as a unidirectional flux which can be influenced by additional DC excitation of the rotor. This phenomenon allows an independent amplitude control of this rotating magnetic field vis-à-vis the input voltage and, by suitable regulation, maintains the voltage at the generator winding constant. The energy transfer to the exciter winding on the rotor takes place in the usual way without brushes (Piller, 2001b:5-5 & 2001c:4). Since two windings of rated power, namely motor and generator windings, are accommodated in the stator, the kVA rating of a Uniblock machine is equal to twice that of a normal synchronous generator of the same rated output. This construction arrangement results in windings reactance which, is only half those of a machine of conventional construction.

According to Fourier's analysis, any non-sinusoidal waveform can be considered a summation of multiple harmonics at different frequencies. For the general case of an unbalanced load, these must further be resolved according to the symmetrical component method. Each harmonic then forms three symmetrical sub-systems, namely a positive and a negative high-frequency rotary field system rotating with respect to the fundamental, rotating wave field, as well as a zero phase-sequence system. The latter generates in-phase currents in the 3-phase winding. With these characteristics, the Uniblock machine can also be represented as a 3-phase transformer with magnetic field regulation capability which, conveys only voltage waveform at fundamental frequency to critical loads, and at the same time represents both an energy storage device and a reactive current source. Harmonics in the input voltage produce rotating fields in the machine which, circulate along with the frequency of the fundamental wave but are at a higher frequency. For the following reason, the damper windings rotate asynchronously to represents a barrier to harmonics and, therefore, effectively suppressed their transmission to the generator. The damper windings are also employed as a barrier to harmonic currents emanating from the load side. Following this, the reactance of the windings, which is due to their size, is halved. This reduction in the reactance reduces the effect of harmonic currents on the output voltage considerably.

2.8 Link circuit voltage regulator

In the compensated and charged state of the battery, the link circuit voltage regulator supplies the DC link circuit with a constant voltage of 2 volts per cell (VPC) multiplied by the number of cells. In addition to supplying the converter, the rectifier charges the BESS which, is permanently installed in the link circuit. The BESS continues to supply the inverter in the event of the main-line failure (Piller, 2001b:5-5 & 2001c:2).

2.9 LA-BESS current regulator

The battery charger regulator operates with charging characteristics harmonized with the German's standard DIN 41772 voltage/constant current or UI characteristic considered to be best suited for charging LAB. The charging process is executed in three main charging stages known as charging phases or charging steps, as illustrated in Figure 2.9 (Piller, 2001b:5-12 – 5-14 & 2001c:2 – 3). The three charging stages executed by LA-BESS are described as follows. Stage #1 is a constant electric current-phase or bulk charging mode (I-Phase). Assuming the battery is starting in a full discharged state, the charger will commence operating in a constant-current mode where the charger current is maintained at a constant value as the battery voltage rises and the battery is being recharged. Approximately 80% of battery capacity is returned in this region. Stage #2 is a constant over-voltage or booster charging phase (Uo-phase). In this region, the battery voltage reaches approximately 2.4VPC and where the last 20% of battery capacity is returned. The charger voltage is held constant at this region while the battery current decreases. This voltage level is maintained until the battery current decreases to about 2% to 1% of its ampere-hour rating capacity. Stage #3 is a constant voltage or floating charging-phase or float mode (U-phase). In this region, the battery current is decreased to about 1% of its ampere-hour rating capacity. The battery charger enters float mode, and the voltage on the battery is maintained at around 2.23VPC. This voltage is aimed to maintain the battery's full charge without reaching its electrolyte boiling point or overcharging it. In general, the purpose of a UI-charging characteristic is basically to reduce the battery charging process period required to reach its full capacity without reducing its life span and to, indeterminately, maintain this charge after completion of the charging process.

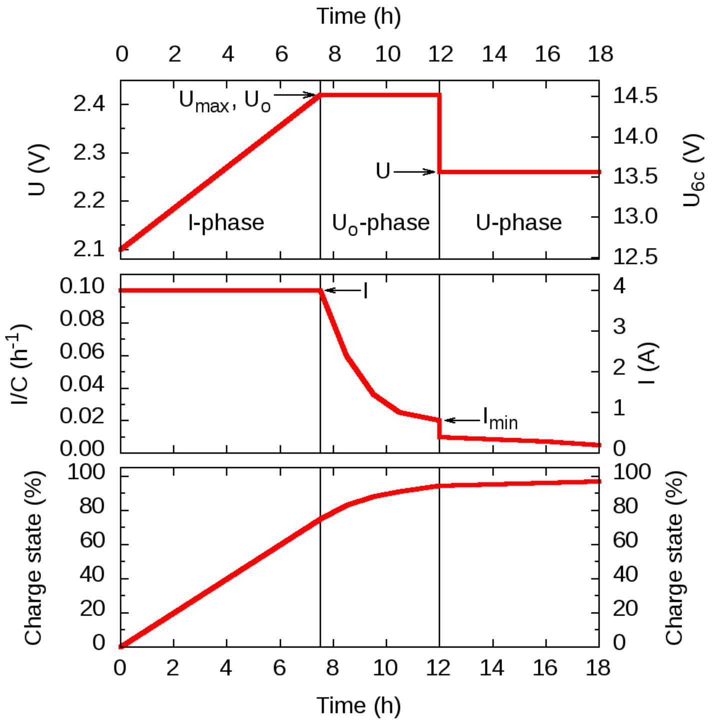


Figure 2.9: Three stages battery charging process (Piller Group GmbH)

2.9.1 LA-BESS running test

The UPS carries out a running BESS test every 1.8 hours. During this test, the rectifiers' output voltage is reduced, and a current is requested from the battery. Failure to supply this requested current, a fault message, and a general fault alarm will concurrently be generated and displayed. Every fault rectification followed by a reset button activation will alert the system to trigger and enable a new battery test request to complete its internal diagnostic coverage.

2.9.2 Protection against exhaustive discharge

A battery turn-off characteristic has been built into the Uniblock to prevent exhaustive discharges at very low battery currents (current-dependent final discharge voltage). Two limits for the battery current and two limits for the battery voltage are entered. The voltage limits are the turn-off points for low battery currents and heavy discharges. These points are set at 1.8VPC and 1.65VPC, respectively. The current limits depend on battery capacity. They are set at the factory to 10% current for the low value and 50% current for the high value. Figure 2.9.2 shows the function of the curve. At currents less or equal to 10% In, where 'In' is the battery rated current, turn-off occurs at 1.8VPC, and at currents higher or equal to 50% In, it occurs at 1.65VPC. The curve gives a turn-off point for currents anywhere between these two values. This disconnection point is also indicated on the Uniblock's control display panel (Piller, 2001b:5-13).

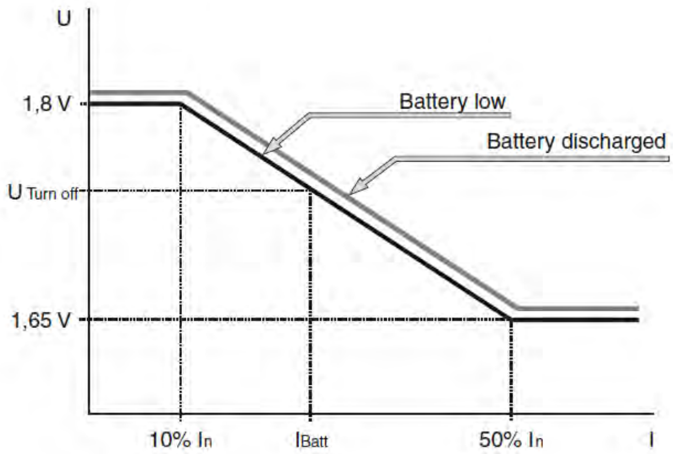


Figure 2.9.2: Turn-off voltage versus direct current (Piller, 2001b:5-13)

2.9.3 Temperature-dependent float and discharge voltage

It is necessary to reduce the final discharge voltage of the battery if the ambient temperature in the battery compartment exceeds 25°C to ensure optimum battery life. For this reason, the ambient temperature of the battery room is measured and monitored via an interface card and relayed to a local network. The final discharge voltage can then be reduced per the temperature employing a curve stored in the panel. The same applies to the final float voltage, as illustrated in Figure 2.9.3 below (Piller, 2001b:5-14).

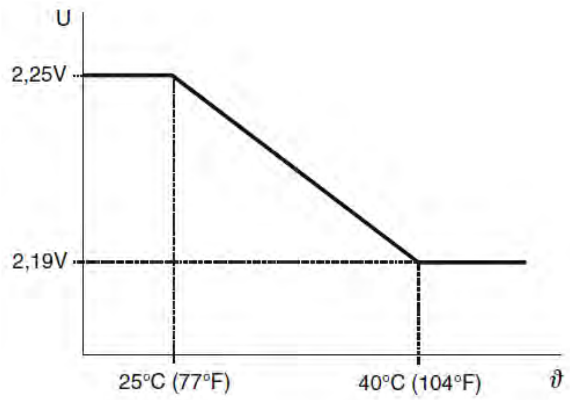


Figure 2.9.3: Final float or discharge voltage versus ambient temperature (Piller, 2001b:5-14)

2.9.4 LA-BESS monitor

The battery monitor calculates the remaining battery life as the battery is being charged and discharged. The battery performance is simulated utilising and calling up the charge and discharge characteristics of all battery cells. The remaining battery life is called up at the control panel of the RUPS. An event message and a general alarm are triggered if the remaining battery runtime falls below a set value. The system also indicates the remaining battery runtime set in minutes on a digital display, as shown in Figure 2.9.4 below. The battery runtime indicator is connected to all four RUPS sets, and the lowest battery runtime value is displayed. Due to varying environmental and load factor conditions, it is impossible to accurately predict the exact time remaining to supply a given load from the LA-BESS. The time monitor will, therefore, provide an approximate time to be used for guidance only.

Figure 2.9.4: Remaining battery life indication on the control panel

2.10 Parallel system operation

All four RUPSs outputs combine in a parallel cubicle busbar. The data exchange between RUPS sets is digital, each set receiving the output current and the operating status of every other RUPS set. The control of the load is carried out separately via the inverter current regulator or the generator voltage regulator according to the active and reactive currents. Control signals are processed independently in each set. While in power rating mode and because of non-redundancy, if an un-correctable power imbalance occurs in one RUPS set, or if one of the RUPSs fails, all four RUPS sets will automatically shut down. The system will then automatically switch to external bypass mode. And if this scene occurs while in redundant operation, the affected RUPS would automatically be removed from the parallel-group, and remaining RUPSs would continue to preserve supply to critical processes while ironing and muting any power imperfections emanating from the local power utility. This conditioned and sturdy supply of power is maintained for as long as the load does not exceed the design rating capacity of the remaining paralleled RUPSs. In this condition, the system self-perform condition-based monitoring of its output bus voltage to detect any voltage deviation condition. If such voltage deviation is out of an acceptable condition, an automatic transfer of critical loads to the external bypass line is executed. The bypass can also be switched on and off manually during scheduled maintenance shutdown operations. Because Main #2 feed is connected in our application, no internal bypass is used (Piller, 2001b:5-10 & 2001c:5). Appendix B shows the connections to the paralleling cubicle and external bypass.

2.10.1 RUPS output control

The RUPS output consists of one circuit-breaker with a motor-charged stored-energy mechanism, one generator controller board, one measuring card, and one voltage regulator. The generator controller board controls the outgoing feeder switch while handling the inverter speed and phase control and the differential active and reactive power regulation for parallel operation. The voltage regulator obtains its reference value from the generator. If this voltage differs from the set-point, it will vary the field current of the exciter machine to compensate. For parallel operation, the voltage regulator receives an offset from the controller board to correct the reactive power differential. If the generator controller board fails, the thyristor switch controller board will then assume control and switch off the output. Any of the 4 Uniblock sets installed can be run both in the power rating-parallel and in the redundant-parallel mode. They combine in a busbar coupler panel where control lines connect to the RS485 interface. Data exchange is digital, each set receiving the output current and the operating status of every other set. Load sharing control is carried out separately in the known manner according to active and reactive power with offsets to the inverter current regulator or the generator voltage regulator. The transmission of these signals is processed independently and digitally in each set.

2.10.2 Control panel

Operating statuses are displayed via a display panel with a mimic diagram and a four-line liquid crystal display (LCD), as shown in Figure 2.10.2 below. In the mimic diagram, the respective state is indicated by light-emitting diodes that change colour or flash during changes or faults. The LED bar chart displays the RUPS system loading. Voltages, currents, power levels, and frequencies are displayed on the LCD. The display provides simple operator prompts and can be switched to the input or the output of the system as required. When changes or faults occur in the system, the status display automatically changes to a plain language message with details of the date and time. In battery operation, the display shows the remaining BESS life in respect to the charged state of the batteries and the loading. All accumulating messages are recorded in an event memory in correct chronological order with date and time and can be called up as required into the display or via the serial interface. In the event of a malfunction, these event recordings make fault-finding extremely simple. There are ten potential-free contacts (changeover contacts) for remote control, operational status, or fault messages.

Figure 2.10.2: Four-line LCD - Mains OUT and BUS synchronization

2.11 Technical data Uniblock-S

2.11.1 Input data

Rated voltage	V	600
Voltage range (Mains #1)	%	+/- 5
Voltage deviation	%	+/- 10 continuous (- 20 short-time)
Rated frequency (Mains #1)	Hz	50

Frequency range	%	+/-
Rated mains current	A	1108
Input power factor (M-G set)	cosφ	0.8 inductive
Main rectifier		12-pulse
Distortion factor	%	11
Generator current	A	1056
Motor current	A	1107
Pony motor	kW	21
M-G set speed	rpm	1500
M-G set insulation class		F
M-G set IP rating		20

2.11.2 Output data

Output power	kVA	1100
Output voltage	V	600 adjustable +/- 5%
Output current	A	1056
Efficiency	%	92
Maximum heat dissipation	kW	87
Voltage accuracy	%	+/- 1 static, with symmetrical load
		+/- 5 dynamic at 50% load charge
Output frequency	Hz	50 +/- 1
Output distortion	%	1.5/2.5 Ph-Ph/Ph-N
Overload capacity	%	10 for 1 hour; 25 for 10 minutes; 50 for 2 minutes
Sudden short-circuit		13.6 times its rated current
Permissible crest factor		Without limit (crest factor = I_{peak}/I_{rms})
Phase angle (deviation)		120° (+/- 1°) for balanced or symmetrical load
Load unbalanced capacity	%	100
MTBF value	h	≥ 90 000
MTTR value	h	≤ 24

2.11.3 DC link circuit

Battery charging voltage	V	520 (minimum) and 585 (maximum)
Battery rated output current	A	1819
Battery output power	kW	946
Charging current	A	390 (maximum)
Final discharge voltage	V	422 (absolute lower limit at 1.6VPC)
Battery cells per RUPS		264 (Piller recommended)

2.12 Floor conditions and space requirements

Even though the Uniblock is designed for mounting against a wall, all four RUPSs are positioned to allow easy access from front and back. The levelling of the installation area for the RUPS sets is critical to permit accurate alignment of the individual system components. The UPS room top view layout and the actual RUPS installation layout are shown in Figure 2.12-1 and Figure 2.12-2, respectively.

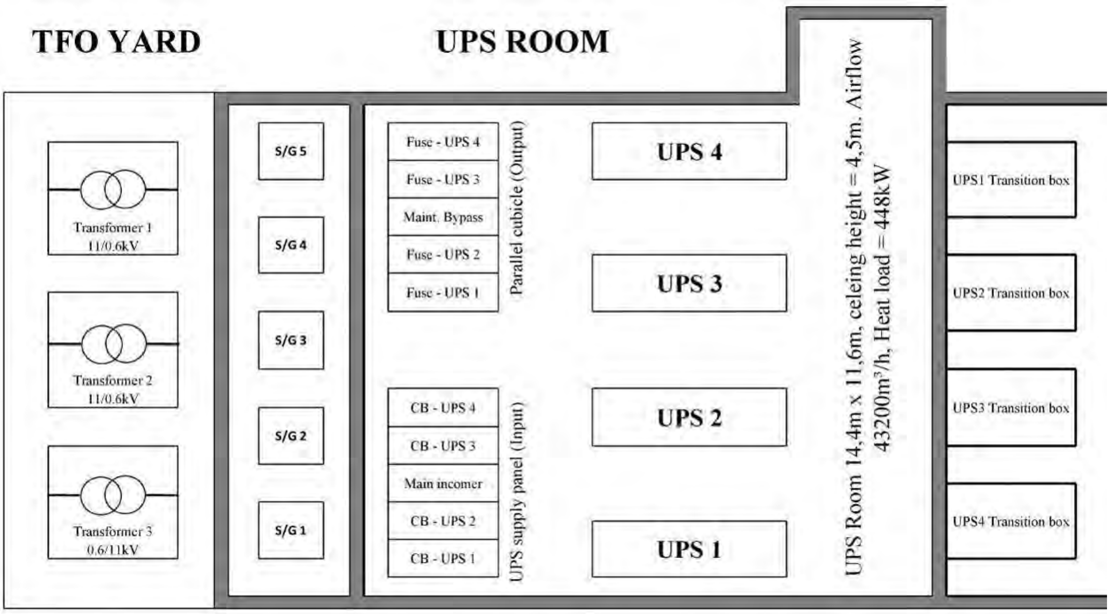


Figure 2.12-1: UPS room equipment layout (NTS)

Figure 2.12-2: Physical UPS installation layout

2.12.1 Floor loading capacity

The space footprint that takes up the weight of the AC input and load cabinets, and especially the M-G set cabinet, is quite small. Therefore, civil and structural work allowance needs to be carefully observed to ensure that the M-G set cabinet installation will not exceed the floor loading capacity of the building:

Weight of the left-hand cabinet = 2475kg

Weight of the right-hand cabinet = 1320kg

Weight of the M-G set = 7600kg

Weight of all accessories = 240kg

Weight of the silencer = 255kg

Weight of the complete system = 11890kg

The total weight of all four UPSs = 11890 x 4 = 47560kg

2.12.2 Space occupied by RUPS

Width of the RUPS = 5.16m

Depth of the RUPS = 1.32m

Height of the RUPS = 2.265m

Surface area occupied by a single RUPS = 5.16 x 1.32 = 6.811m^2

The total area occupied by all four RUPSs = 6.811 x 4 = 27.245m^2

2.13 Piller Uniblock RUPS preventive maintenance

The Piller RUPS system, given its age, requires an acute annual preventive maintenance and a planned component replacement. During the preventive maintenance, job requisitions below need to be raised, work orders created and assigned to service technicians:

1) Visual inspection and condition-based monitoring of the entire RUPS system. Visual inspection of RUPS electrical wirings. Check for any signs of component overheating, insulation damage, and loose wires, or incorrect termination
2) Check and inspect the BESS charger for the correct functioning and battery charging process for correspondence to the designed charging stages
3) Inspect and verify cabinet ventilation for potential failure. Inspect, clean, or replace RUPS cabinet and room intake air filters when necessary
4) Verify for any susceptible current leakage by measuring and comparing input and output currents. Verify for any voltage drop by measuring and comparing input and output voltages. If the system output voltage is out of phase, perform necessary adjustments to synchronize generator output voltage with the out-bus voltage at the point-of-common-connection.

5) When in paralleled operation, substantiate for appropriate distribution of load amongst RUPS modules. The critical loads are shared equally amongst all parallel units under normal operating conditions.
6) Lubricate generator bearings or replace them if their scheduled discard period recommended by the equipment manufacturer is reached (Piller recommends a change frequency of 5 years).
7) Monitor the room temperature and humidity, check the functioning of their control system. Check the correct functioning of all indicating lamps. Check the integrity of intrinsic power supplies for any evident failure, and ensure a daily record of all events logs are scrutinised. Check all the power connections for proper torque, and test insulation resistance or integrity of the main components.

CHAPTER THREE

POWER RETICULATION AND LEAD-ACID BATTERY STORAGE SYSTEM

3.1 Power reticulation system

3.1.1 Electricity supply

The site is premium supplied by the local authority from a 66/11kV substation via two 185mm² feeders with current notified maximum demand in its supply agreement seating at 5MVA. The RUPS supplies are connected to the facility's 11kV intake switchgear as indicated on the single line diagram

(SLD) in Appendix B. The relevant electrical network specifications at the point of common connection of the facility are as follow:

Supply voltage	:	11kV (nominal)
Fault level	:	9.8kA to 10.8kA (3-phase)
Frequency	:	50Hz
Phase rotation	:	RWB anti-clockwise
Cable (utility-to-transformer)	:	1 x 185mm², 3-Core PILC SWA
Cable (transformer-to-RUPS)	:	Single-core, 2/phase, 1 Neutral 740mm² XLPE PVC
Cable (RUPS-to-BESS)	:	Single-core, 3 per pole, 740mm² XLPE PVC

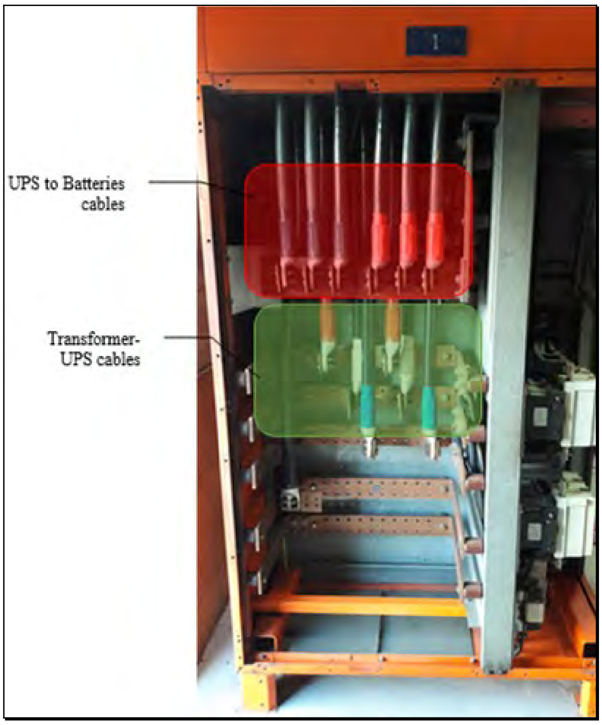


Figure 3.1.1: Cables – Transformer to UPS and UPS to BESS

Feeder #1, through the overload circuit breaker (OCB) 1, supplies all non-essential loads connected at switchgear 'A' at the medium voltage (MV) substation. Feeder #2, through OCB2, supplies RUPS units via two 3500kVA, 11/0.6kV oil-immersed, step-down transformers (TX1 and TX2) connected in parallel. All essential or critical loads connected at switchgear 'B' and 'C' are supplied by a RUPS system via a 4500kVA, 0.6/11kV oil-immersed, step-up transformer (TX3). There is a further transformation of power dropping voltages from 11kV to usable 400V. Four incoming isolators interconnect in such a way that maintains supply to the facility via both feeders or any one of the two feeders available. Similarly, bus-couplers (Bus-section 1 & 2) installed at the MV switch-room are also arranged in such a way to supply the whole facility either via the RUPS system or directly from the mains. If an un-correctable power imbalance occurs in one set, or if one RUPS fails, because of zero redundancy, the system will switch automatically to external bypass mode by opening the 600V bypass breaker Q5. For maintenance operations purposes on RUPS units, breaker Q5 can also be switched on or off manually. For maintenance on either transformers or RUPS unit's, OCB5 can be switched on or off manually.

3.1.2 Two-winding transformers

The transformer plays a vital role in any electrical distribution network. Its core function is either to turn down the high voltage applied to its primary windings to a low and usable voltage at the secondary windings (step-down transformer) or to turn up the low voltage applied to its primary windings to a high and transportable voltage at the secondary windings (step-up transformer). Its selection is mainly driven by the size (rated KVA), the number of phases, vector group (in case it is to be connected in parallel), intended primary/secondary line voltages, primary/secondary full load current, cooling type, and most importantly its percentage impedance (Martin, 1999).

3.1.2.1 Transformer Buchholz protection

The Buchholz system applies to oil-immersed transformers. It bases its operation on the fact that the violent generation of gas always precedes transformer breakdowns. Two sets of contacts are used: the first is the gas collection contact that operates for the slow accumulation of gas caused by a fault inside the transformer. Second is the surge detection contact set for a surge of oil caused by a major internal fault and displaced towards the conservator which, takes expansion and contraction to prevent undue stressing of the transformer due to temperature changes. Silica-gel breathers prevent moisture from entering the transformer during such expansions and contractions. Operation is done in two stages: alarm and trip.

3.1.2.2 Transformer pressure and temperature protection

Protection against over-pressurisation due to serious faults by relieving and limiting the pressure rise to avoid explosive rupture of the tank is used. The detection of an overload is controlled by an oil temperature gauge which, measures the thermal image of temperature at the top of the tank while the winding temperature gauge models' thermal image of windings temperature. Operation is done in three stages: Fan, Alarm, and Trip.

3.1.2.3 Transformer inverse definite minimum time relay

These are used as a backup to main protections and detect faults inside transformers. Two-stage overcurrent (O/C) protection will trip the transformer for un-cleared low voltage system faults. The operation of this relay will trip the secondary breaker and start the time lag relay set to 0.3sec to avoid early operation. When a fault persists, the time-lag relay will be reached, letting the primary breaker trip. An instantaneous O/C contact, with high-speed resetting time, is connected in series with the inverse definite minimum time relay (IDMT) to de-energize the time-lag relay as soon as the fault is cleared.

3.1.2.4 Transformer surge arrester

Lightning or surge-arrester consists of a gap in series with other elements serving to bleed a high-voltage surge to the ground before reaching the protected transformer. They present a lower impedance path to the ground than that of the transformer. The surge voltage momentarily breaks down the insulation of the arrester to allow the surge to go to the ground and dissipate itself. The insulation of the arrester then recovers its properties to prevent nominal current from flowing to the ground and return the arrester to a state ready for another operation. The surge arrestor is mounted outside the transformer tank but connected to its primary terminals. It is mounted close to the protected transformer to minimise the resistance of the connection to the ground. The arrester insulation is coordinated with that of the line or equipment. It is rated not only on the nominal voltage class of the line to which they are connected but also on the crest voltage (the basic impulse insulation level) it withstands.

3.1.2.5 Transformer cooling

Both step-up and step-down transformers used have their coils submerged in insulting oil. The heat produced by the iron and copper losses is carried by convection to the tank and dissipated into the atmosphere (ONAN cooling). Excessive temperature and the formation of hot spots are prevented, avoiding damage to the insulation and conductors. The conservator takes up the expansion and contraction of the oil with changes of temperature during service without allowing the oil to combine with the air from which it is liable to take up moisture. The displacement of air due to the change of oil volume takes place through a breather. This breather contains silica gel which extracts moisture from the air. Silica gel is a blue colour crystal when dry, turning pink as it absorbs moisture. The market offers other colours.

3.1.2.6 Transformer size

The size of a transformer must coincide with the demand for the loads connected to the secondary. To allow future growth and not prejudice its life expectancy, the size chosen should usually be slightly larger than the actual demand. The most economical load on a transformer is that for which the annual cost of its copper loss is equal to the annual carrying charges plus the annual cost of the core losses. The core losses are constant regardless of the load carried by the transformer. Values of core loss and transformer resistance, both expressed as a percentage at full load, vary with the manufacture, size, and other characteristics; and are found in the transformer specification or nameplate. Core losses are usually a fraction of 1%, while resistance is less than 2%, reflecting the high efficiency of the transformer.

Step-down transformers

Rated kVA	:	3500kVA, 3-phase
Vector group	:	Dyn11
Line voltages	:	11/0.6kV (primary/secondary)
Line currents	:	184/3368A (primary/secondary)
Cooling type	:	Oil natural and air natural (ONAN)
Percentage impedance	:	6.72%
Connection on site	:	TN-C-S

Step-up transformer

Rated kVA	:	4500kVA, 3-phase
Vector group	:	Dyn11
Line voltages	:	0.6/11kV (primary/secondary)
Line currents	:	4330/236A (primary/secondary)
Cooling type	:	ONAN
Percentage impedance	:	6.14%

3.1.3 Energy monitoring and management meter

The inclusion of system infrastructure to monitor and manage electrical energy consumed by a facility is of utmost importance nowadays. The annual facility’s financial forecast or exposure bases mainly on costs attributed to electrical energy consumed. Following a drastic increase in electricity tariff in recent days (average increase of 15.06%), effective monitoring and management of electrical energy consumed by the facility is now of great importance and cannot be overlooked if the facility was to manage its costs. The need for information about the facility’s energy consumption is of a high priority now than ever before. By installing energy monitoring and management meters on the premise, the facility can obtain detailed data about its electrical energy consumption, energy profile, and tariff analysis data to be used to strategize its annual budget forecast. Asset management can be regarded as the management of the facility’s physical assets with the aim to optimize their overall effectiveness and process availability through their performance indicators and measurements. Energy consumption monitoring and control of these physical assets form part of their performance indicators and measurements. The energy metering system will thus help the facility in making well-versed judgments about its electricity consumption. It will also guide the facility in pinpointing hot spots in its assets, e.g. electrical fault, loose connection, bearing failure on process equipment, dirty filters on a chiller unit, etc. Due to the extensive growth of cellular networks all over South Africa, the use of wireless communication mode has since simplified asset management feasibility and rendered its deployment cost-effective.

The facility has Enermax E+MA–153000 energy monitoring and management meters installed at different major loading points to control and monitor energy utilization. One of its meters is shown in Figure 3.1.3. The purpose of this metering infrastructure is for the facility to develop an energy management system capable of extracting data, half-hourly, from the power system network and passing this data to the metering entity for processing. The metering entity provides the facility with a utility meter reading data management and billing structure. The metering entity will continuously perform energy supervision, gathering, and broadcast processed metering and billing data on behalf of the facility. Broadcasted data are then made available on their web portal which, serves to graphically portray these data in a user-friendly manner and allows information regarding facility energy consumption to be well-monitored, managed, and reported. The Enermax E+MA–153000 energy meters type installed in the facility uses wireless technology in the asset management infrastructure, and they are produced in South Africa by Strike Technologies. They can perform measurements such as off-peak active energy, peak active energy, standard active energy, active and reactive energy, active and reactive power, network power factor, network demand. They can generate various energy profile statistics and determine network capacity charge.

Figure 3.1.3: Enermax energy meter

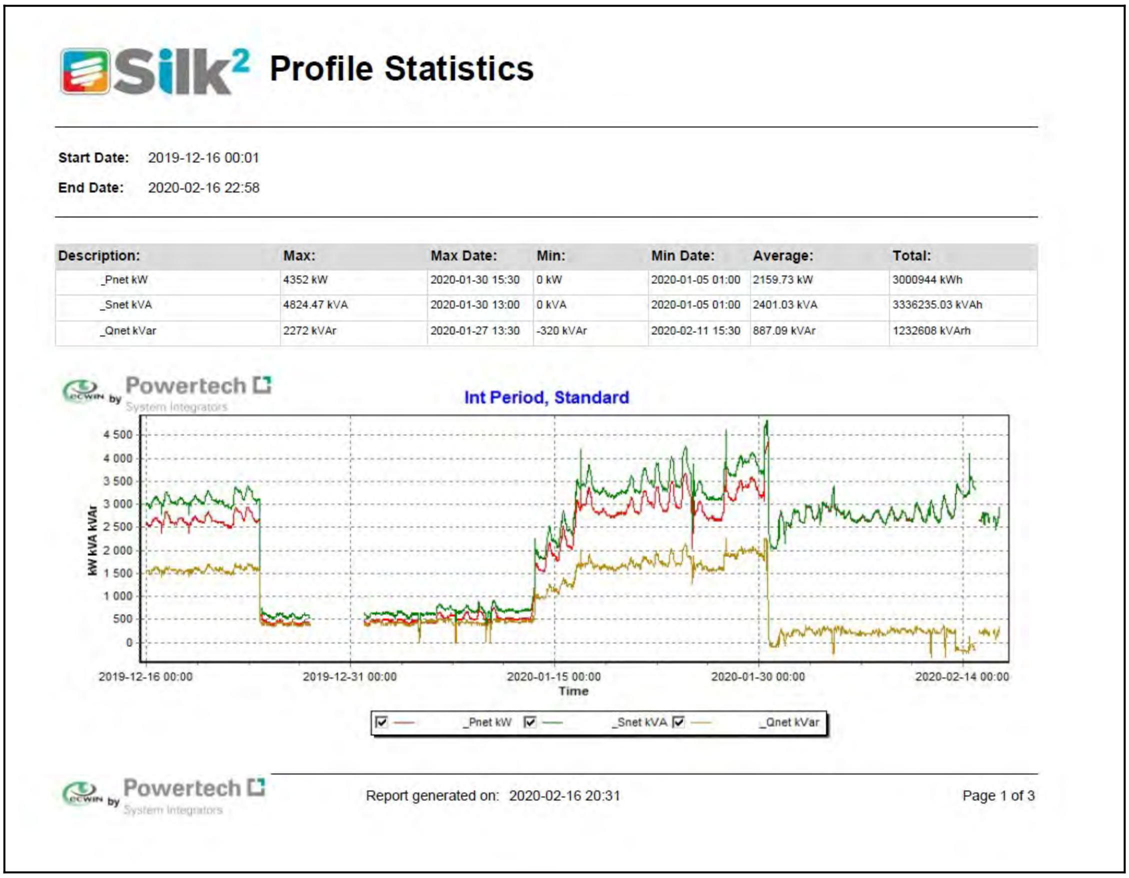
3.1.3.1 Service level agreement

The metering entity appointed must retrieve, process, monitor, and generate billing data on behalf of the client on their website. As in Figure 3.1.4, any report generated must be able to be printed on an A4 page. The meters must be read at least once per day, and the metering entity is responsible for updating all applicable tariffs on their website as and when required. The metering entity will ensure that access to data will be controlled using a secure server with password protection to ensure confidentiality. Each user, being persons within the client and nominated by the client in writing, will have his or her own username and password. The metering entity will ensure that the information to be provided on their website for each metering point includes, but not limited to, the following: A graphical load profile displaying the recorded consumption as appropriate to the tariff structure. This load profile may be viewed for any arbitrary period with a resolution of at least 30 minutes. A statistical analysis associated with the load profile is to be generated. This analysis will contain financial information regarding the application of the tariff structure to the period selected with engineering statistical data such as minima, maxima, mean values, etc. A complete and accurate monthly energy bill with applicable tariff and ancillaries' charges applied and power factor at the time of maximum demand, kWh energy consumption, and maximum demand levels are broken down into defined time-of-use periods. Information enabling the client to download raw or unprocessed data in an Excel spreadsheet and trend information. A graphical representation of the historical monthly billing data showing both the monthly trends and a breakdown of each component of tariff to the monthly bill.

The metering entity will ensure that the collected data consist of the active and reactive energy consumption data consumed within the demand interval applicable to the tariff structure implemented. He must also ensure that, through automated software procedures, all interval data is accounted for. Missing data must be detected and collected within a prescribed number of hours. Raw data must not be changed, and data that cannot be read off from the meter(s) due to communication failure must somehow be retrieved. The metering information must be stored in an industry-standard SQL compliant database. The metering entity must ensure that the metering database has provision for summating a group of metering points for obtaining an aggregate consumption. The monthly meter data will be concluded on the last hour of the last day of every month. The metering entity will take full responsibility for the safekeeping and integrity of all metering data obtained during the duration of the agreement. They will ensure that daily backups of the metering data are maintained. These backups must contain the full database along with all commissioning and other records pertinent to the agreement. They need to confirm that all the metering data acquired and stored by them are the exclusive and confidential properties of the client and will not be divulged to any third party without written instruction from the client.

3.1.4 Power factor correction

Power factor is a ratio of active power to the apparent power consumed by any load. A maximum demand excursion beyond the notified maximum demand as stipulated in the supply agreement or system power factor below the tariff penalty threshold ($\cos\varphi \leq 0.96$ below which the facility pays reactive energy charges) will result in a penalty.


Silk² Profile Statistics

Start Date: 2019-12-16 00:01
End Date: 2020-02-16 22:58

Description:	Max:	Max Date:	Min:	Min Date:	Average:	Total:
_Pnet kW	4352 kW	2020-01-30 15:30	0 kW	2020-01-05 01:00	2159.73 kW	3000944 kWh
_Snet kVA	4824.47 kVA	2020-01-30 13:00	0 kVA	2020-01-05 01:00	2401.03 kVA	3336235.03 kVAh
_Qnet kVar	2272 kVAr	2020-01-27 13:30	-320 kVAr	2020-02-11 15:30	887.09 kVAr	1232608 kVArh

Figure 3.1.4: Energy profile with and without PFC

The facility achieves its power factor correction (PFC) with two capacitor banks, 600kVArs and 1200kVArs, whose capacities have been deduced from the load profile, as illustrated in Figure 3.1.4 above. The facility reactive power mainly changes from 600kVars to 1200kVars which are values used to design the PFC system. Each capacitor bank consists of three capacitors constructed in a star configuration, as shown in Appendix C. The power factor of the non-essential loads (feeder #1) and essential loads (feeder #2) averages, respectively, 0.885 and 0.892 lagging. The facility uses the PFC system connected to isolator #7 on the non-essential loads' side only, as shown in Appendix B. The facility has opted for this option with an agreement with the local authority. It overcompensates feeder #1 while effectively wheels the reactive power through the utility 11kV bus bar to compensate feeder #2. That way, the overall summated correction in the facility side will still provide an acceptable lagging or close to unity power factor as seen by the supply utility. The advantages of this solution are simplicity and cost, as all other solutions will entail the installation of two or more power factor correction (PFC) systems.

3.1.4.1 Capacitor bank protection relay

The PFC system uses RLC04 protection relay manufactured by local manufacturing entity Strike Technologies, as shown in Figure 3.1.4.1 below. RLC acronym derives from the type of fundamental electrical elements that it can assume protection to either at medium or high voltage network. From the acronym, R is the resistive elements (including resistive elements of shunt capacitor banks and harmonic filter circuits), L is the inductive elements, and C is the capacitive elements. The RLC04 offers protection against overcurrent and overvoltage emanating from fundamental and harmonic signals. It also detects over-temperature situations and earth leakage currents. Its precise fault detection and rapid reaction time make it suitable for any electrical system protection while enhancing personnel safety and preventing equipment deterioration. It also provides high fault discrimination to avoid nuisance tripping while avoiding superfluous financial impact owing to the lower power factor penalty. With the power factor bank consisting of three identical capacitors connected in a balanced star configuration, line currents drawn by each leg of the star configuration are virtually equal, and their vectorial resultant is zero. A failure of any capacitor on any branch of the star configuration will unbalance the PFC system. The unbalance will cause the vectorial resultant of the line currents to be different from zero and be picked by the RLC04 relay. The permissive condition of the relay will then generate a signal to trip a corresponding protection unit.

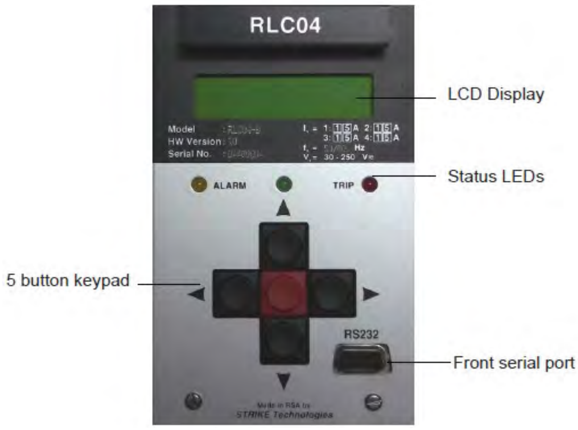


Figure 3.1.4.1: PFC protection relay RLC04

3.1.5 System switchgears and harmonics

All existing MV switchgear are oil-filled metal-clad indoor gear (Yorkshire and Reyrolle parsons). MV isolators are designed to be opened or closed when no-load current flows through them. They are installed to enable feeders or distribution equipment to be isolated. They provide a visual and positive break in the circuit as a safety measure for the workers. MV circuit breakers, on the other side, are built to interrupt both load and fault current. They are operated automatically by an over-current or fault-sensing relay or can manually be opened or closed when desired using the remote control and battery tripping unit. For the low voltage (LV) switchgear feeding RUPSs, all four existing 600V infeed switchgear are ‘Schneider Masterpact NW12H2’ circuit breaker, 1250A 3-pole, and draw-out type. The infeed and outfeed breakers from the RUPS system are Unelec 5000A, 3-pole, and draw-out type. Each RUPS feeds a paralleling cubicle through its output breaker ‘Siemens 3WN5231-1GB56-1GA1, 1250A’ and a set of 1250A fuses in the parallel cubicle. Voltage harmonic distortion measurements taken at the point of common connection on the MV feeders (5th, 7th, 11th, 13th….) were all below 1% total harmonic distortion (THD) as prescribed in NRS 048-4 and are included in Appendix D.

3.2 Lead-acid battery energy storage system

The current LA-BESS uses BAE 25-OGi-2000 single-cell, vented, or flooded LAB (see Appendix E). The BAE battery cell contains two low-antimony-alloy-based electrodes made of different chemical materials, as seen in Figures 3.2-1 & 2. These electrodes of round-grid and flat-plate design are, in turn, implanted inside a tank containing sulphuric acid solution with a density of 1.24kg/l. The positive electrode is a round-grid flat plate with spherical bars in a corrosion-resistant PbSbSnSe-low antimony alloy. The negative electrode is a rounded-grid flat plate in PbSbSnSe-low antimony alloy with the capability to prolong material life expectancy. The composition of the electrolyte solution is characteristically such that there is 65% of clean water and 35% of sulphuric acid (H_2SO_4). On the other end, unadulterated lead (Pb) would not support itself due to its extreme softness. A minute amount of other chemical elements or additives is, therefore, been added to boost its mechanical strength and advance its electrical features, such as an improvement in power density and current capability. Additives on BAE batteries are antimony (Sb), tin (Sn), and selenium (Se) as described above on the composition of their electrodes (Ana et al., 2016:46-47; Chargetek, 2015:1-17; ETH, 2010:45; IPAE, 2012a:5 – 17; IPAE, 2012b:1-55).

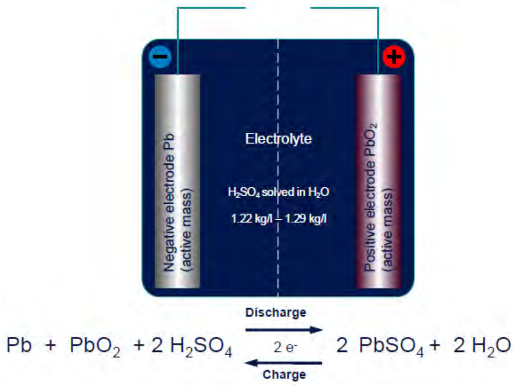


Figure 3.2-1: Stoichiometric equation of chemical reaction (BAE Batterien GmbH)

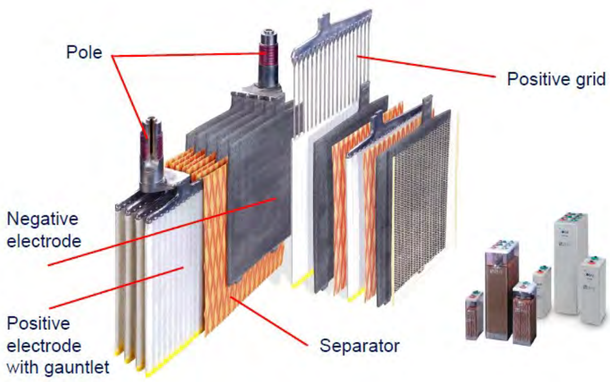


Figure 3.2-2: BAE battery composition (BAE Batterien GmbH)

During the discharging process, the interaction between electrolyte's sulphite-ions with the negative and positive electrodes forms lead sulphate on both electrodes. The lessening of sulphite-ions in the electrolyte solution will, in turn, reduces its specific gravity proportionally to the amount of charge transported. During the recharging process, the electric current alters the electrodes back to their charged condition while converting the sulphate back to its natural sulphuric acid state. This augmentation of sulphite-ions in the electrolyte solution will now increase again its specific gravity proportionally as a result. With the stoichiometric equation of battery chemical reaction shown in Figure 3.2-1, we can, therefore, deduce that when the sulphuric acid encounters lead plates, a chemical reaction occurs followed by energy production. This energy then sets a potential difference between the two consecutive plates to a nominal universal voltage of 2V. The chemical reaction process of the BAE vented LAB is rescindable, and battery cells can support several discharging and recharging processes with no consequence whatsoever. The battery ampere-hour capacity is subject to the amounts of active lead dioxide PbO_2 material on its positive electrode, active spongy lead material on its negative electrode, and percentage sulphuric acid present in its electrolyte solution. The ratio of active lead dioxide PbO_2 material, active spongy lead material, and percentage sulphuric acid present in its electrolyte solution is required to be specific to optimally maintain battery ampere-hours capacity. The BEA vented LAB cells are openly constructed to allow the seepage of gas and prevent any internal positive pressure build-up. This seepage of gas has the added benefit of facilitating the cooling of the battery cells. They have a higher temperature-withstanding capability making them highly forbearing at high-temperature operation and during over-charging conditions. Electrolyte solution topping can be done anytime during their scheduled maintenance.

3.2.1 Features of lead-acid battery

The main features to be considered when using LAB are the amp-hour capacity, temperature, overcharging, over-discharging, depth of discharge, and excessive cycling. The ampere-hour capacity in a battery depends on its discharge rate. The higher the current, the less is the capacity and vice versa. The reason for this is that the chemical reaction during discharge limits the rate at which power can be drawn from the battery. The lifespan of a battery greatly depends on the temperature at which it operates. The degree to which the chemical reactions, such as corrosion, occur in the interior of the battery cell can be stated using the expressive Equation 3.2.1 below (ETH, 2010:47):

$$K = C^{\frac{E_A}{R \times T}} \tag{3.2.1}$$

Where C is a constant, E_A is the instigation energy, and R is the universal gas constant (R = 8.314Joule/mole. Kelvin). Application of this equation to the LAB will lead to show that, the natural life of the battery will halve for every 10°C rise in electrolyte solution temperature and, above 55°C, the separators and plates will be irreparably damaged. This will then increase the fragility of its structural casing and make electrolyte solution lose its sponginess to lead to a precipitated battery cell failure. These conditions can be avoided by, prominently, keeping the operating temperature inside the battery room at the manufacturer's recommended level whenever conceivable.

The efficiency of charge and rate of charge acceptance drops as the battery approaches the top of its charge. Near the top of its charge, the charger voltage rises to a level where the battery starts gassing. Extended charging beyond this stage will increase battery temperature, cause excessive gassing, and reduce battery life considerably. On the other end, every time a battery is cycled (discharged and recharged), a chemical conversion and volume change takes place on the positive plate. This ultimately leads to the shedding of active material, resulting in a loss of capacity and reduced battery life. For this, excessive cycling of cells must always be avoided. Water containing salts, chlorides, metals, and other impurities will react with the plates and can render them useless within days. Using only approved water for topping up is, therefore, essential. Typical specifications for topping water must be such that it must be pure, uncoloured, and unscented, it must have a potential of hydrogen (pH) sandwiched between 5 and 7, it must, whenever conceivable, be stockpiled in a plastic or glass container, its impurities concentration or total dissolved solids must not exceed 3 mg/l, and its conductivity must not exceed 5 μS/cm. Concerning the cycle life and rate of discharge considerations of LABs, regular draining of these battery cells charges past 80% of their designed ampere-hours capacity without systematic equalization of their charges may irreversibly damage some of the electrode plates and consequently reduce their lifespan. If we want to use these LABs for many cycles they should not run past 80% of their charge. This not only extends the number of cycles we get from these batteries but degrades them drastically to the point where they start delivering less run time than their design calls for. For this, the end or final discharge voltage of cells in our BESS will be taken to be 1.8VPC (20% of 2.23VPC). Some battery chemistries give much fewer ampere-hours if you discharge them fast. This situation is called the Peukart effect. This effect has a significant effect on alkaline, carbon-zinc, zinc-air, and LAB. For example, if you draw at 1C - Amps on a LAB, you will only get half of the capacity that you would have if you had drawn at 0.05C – Amps.

3.2.2 Battery cell heat dissipation

During normal operation of battery cells, a considerable amount of heat is transformed over and above the alteration of mass and exchange or transfer of electrical energy emanating from the chemical reactions (BAE, 2004:1-14; BAE, 2020: 10-13; Schiemann, 2000:1 – 12; Wieland et al., 2006:1-9;). Categories of heat-dissipation transformed in power loss in a battery cell, expressed in watts, are the heat-dissipation power during the float, discharge, and charge operation mode. All the calculations below are carried out only for one cell. For the whole battery set, the power dissipated should be multiplied by 264 cells per UPS.

a) Float operation

The heat dissipation power during the float operation mode for one cell can be formulated by Equation 3.2.2-1 and calculated in Equation 3.2.2-2:

$$P_{float} = \left(U_{float} - U_{gas}\right) \times I_{float} + R_i \times I_{ac}^2 \qquad (3.2.2\text{-}1)$$

Where, U_{float} is the float voltage given to be equal to 2.23VPC, U_{gas} is the constant describing the water decomposing voltage given to be equal to 1.48V for all flooded batteries assuming that all the current is used for water decomposition, I_{float} is the float current (at normal conditions of 20°C operating temperature and 2.23VPC float voltage, the float current is nearly 25mA/100 Ah of nominal capacity for flooded or vented batteries and during battery lifetime this float current increases by a factor of 1.5 to 2 caused by antimony poisoning of the batteries), Ri is the internal resistance of the cell equal to 0.09mΩ (the internal resistance depends on the plate design of the cells and the capacity as read from BAE 25-OGi-2000 technical specification), and I_{ac} is the effective ripple current of the charging unit (according to EN 50272-2, the maximum allowed permanent ripple current is 5A per 100Ah).

$$P_{Float} = \left(2.23 - 1.48\right) \times \left(2000Ah \times \frac{25mA}{100Ah}\right) + 0.09 \times 10^{-3}\Omega \times \left(\left(\frac{5A}{100Ah}\right) \times 2000Ah\right)^2 = 1.275W \qquad (3.2.2\text{-}2)$$

b) Discharge operation

Heat dissipation during discharge operation depends on the discharge current and the difference between open-circuit voltage (U_0 = 0.84 + electrolyte gravity) and the actual discharge voltage of the battery cell. Equation 3.2.2-3 below is used to formulate the heat dissipation per cell which, is calculated in Equation 3.2.2-4:

$$P_{discharge} = \left(U_0 - U_{discharge}\right) \times I_{discharge} \qquad (3.2.2\text{-}3)$$

For all calculations, a discharge during 1 hour is assumed with a final voltage of 1.8VPC. As for the discharge current, the corresponding 1-hour current (I_{1h}) from the BAE project planning data is selected.

$$P_{discharge} = \left(\left(0.84 + 1.24\right) - 1.8\right) \times 1069 = 299.32W \qquad (3.2.2\text{-}4)$$

c) Recharge operation

The calculation is nearly the same as at discharge operation using Equation 3.2.3-5 and Equation 3.2.3-6. The heat dissipation is now a product of the mean value of the recharge current and the difference between the open-circuit and the recharge voltage. The heat dissipation due to the ripple current is neglected because it is less than 5% of the recharge current effect. The calculation is carried out for an initial recharge current of 1.5 x I_{10} (nominal current) and a boost charge voltage of 2.4V. The recharge time for the calculation is limited to a charging factor of 1. The average current during the boost charge operation can be assumed as 90% of the initial current.

$$P_{recharge} = (U_{recharge} - U_0) \times I_{recharge} \tag{3.2.2-5}$$

Recharge during 360 minutes (6 hours) of BAE 25-OGi-2000 cell, initial charging current 200A, the average charging current will then be = 1.5 x I_{10} x 0.9 = 1.5 x 200 x 0.9 = 270A.

$$P_{recharge} = ((2.23 \pm 1\%) - (0.84 + 1.24)) \times 270 = 46.52W \tag{3.2.2-6}$$

3.2.3 Sizing of the LA-BESS

An important consideration related to the sizing and selection of an appropriate BESS suitable for a given UPS application is its rated power and self-sufficiency period at various load rates following the analysis of the facility's energy usage of critical equipment. The amount of electrical power to be considered is the power delivered by that BESS when called upon ($P_{bat\text{-}UPS}$). For that reason, its rating should be calculated starting with the UPS apparent power required to support critical loads (*S*) while also considering the overall UPS system efficiency (η_{UPS}) and power factor (*cosφ*) as per Equation 3.2.3-1 below:

$$P_{bat\text{-}UPS} = \frac{S \times \cos\varphi}{\eta_{UPS}} \tag{3.2.3-1}$$

The most salient approach in determining the size of the BESS is to bring up its project planning datasheet. This project planning datasheet details the battery performance data (constant discharge power and current) based on its autonomy time under various load rates and at a predetermined operating temperature and end-of-discharge. It is imperative to ensure uniformity of battery type throughout the battery storage system.

The current system uses BAE Secura 25-OGi-2000 single-cell, vented, or flooded LAB. Each 1100kVA RUPS unit is connected to 264 battery cells installed on metallic racks. These battery cells are connected in series to provide voltage corresponding to the nominal UPS input battery voltage of 520V (585V max) required for system operation. The nominal potential difference between battery cell terminals is at a universal voltage of 2VPC, and the float is at the voltage of 2.23VPC. The total LA-BESS voltage is, therefore, equal to 528V (2VPC x 264 cells). The LA-BESS voltage at float is equal to 588.72V (2.23VPC x 264 cells). These batteries can provide 1100kVA of clean and conditioned power during power disturbances or forced power outages. The current RUPS system provides 15 minutes backup time at full UPS loading with battery cells' end/final voltage (U_f) set to reach 1.8VPC. With that said, from Equation 3.2.3-1 and based on the maximum installed capacity of 1100kVA per RUPS, the BESS power is determined in Equation 3.2.3-2 below (BAE, 2004a & b:1-14; BAE, 2020: 10-13; Wieland et al., 2006:1-9;):

$$P_{bat\text{-}RUPS} = \frac{S \times cos\varphi}{\eta_{RUPS}} = \frac{1100 \times 0.8}{0.92} = 956.52kW \text{ or } P_{bat\text{-}RUPS} = 520 \times 1819 = 946kW \qquad (3.2.3\text{-}2)$$

The battery discharge direct current is read directly from the RUPS' nameplate and found to be equal to 1819A. This current can also be calculated as the ratio between the full rated RUPS power to the system voltage and is 1100/600 = 1833A. Referring to BAE project planning data shown in Table 3.2.3-1, for a constant discharge current of 1886A as indicated, which is higher than the system discharge-current read from the nameplate or calculated, the LA-BESS UPS is able to sustain the full load power for a run-time of up to 15 minutes. Correspondingly, referring to BAE project planning data shown in Table 3.2.3-2, the constant discharge power per cell as indicated is found to be equal to 3456W. These determinations lead to having the designed storage or amp-hours capacity for the LA-BESS be equal to 2000Ah, and the designed power be equal to 912.4kW (3.456kW/cell x 264 cells), and the cut-off voltage be equal to 475.2V (1.8VPC x 264 cells).

Table 3.2.3-1: Constant discharge current - Project planning data (BAE, 2004a:9)

BAE Secura OGi PROJECT PLANNING DATA Page 9 from 14

Uf = 1,8 V/Cell	Discharge current in A																							
Battery	1'	3'	5'	6'	7'	8'	9'	10'	15'	20'	25'	30'	40'	45'	50'	55'	1h	2h	3h	4h	5h	6h	7h	8h	9h	10h
5 OGi 400	445	445	445	445	445	445	444	435	393	360	334	312	276	261	247	234	223	141	104	83	71	61	54	49	45	42
6 OGi 480	524	524	524	524	524	524	523	513	463	424	393	367	325	308	291	276	262	166	122	98	83	72	64	58	53	49
7 OGi 560	600	600	600	600	600	600	599	587	530	486	450	420	372	352	333	316	300	190	140	112	95	83	73	66	61	56
8 OGi 640	673	673	673	673	673	673	671	658	594	545	505	471	418	395	373	354	337	213	157	126	107	93	82	74	68	63
9 OGi 720	742	742	742	742	742	742	741	725	655	601	556	519	461	436	412	390	371	235	173	139	118	102	91	82	75	69
10 OGi 800	891	891	891	891	891	891	889	870	786	721	668	623	553	523	494	469	446	282	208	167	141	122	109	99	90	83
11 OGi 880	971	971	971	971	971	971	969	949	857	786	728	679	602	570	539	511	486	307	226	182	154	133	119	107	98	91
12 OGi 960	1049	1049	1049	1049	1049	1049	1047	1025	926	849	786	734	651	616	582	552	525	332	245	196	166	144	128	116	106	98
13 OGi 1040	1126	1126	1126	1126	1126	1126	1123	1100	994	911	844	788	698	661	625	592	563	356	262	211	178	155	138	125	114	105
14 OGi 1120	1201	1201	1201	1201	1201	1201	1198	1174	1060	972	900	840	745	705	666	632	601	380	280	225	190	165	147	133	122	112
15 OGi 1200	1274	1274	1274	1274	1274	1274	1271	1245	1125	1031	955	892	791	748	707	670	638	403	297	239	202	175	156	141	129	119
16 OGi 1280	1346	1346	1346	1346	1346	1346	1343	1315	1188	1089	1009	942	835	790	747	708	674	426	314	252	213	185	165	149	136	126
17 OGi 1360	1416	1416	1416	1416	1416	1416	1413	1384	1250	1146	1062	991	879	831	786	745	709	448	330	265	225	195	173	157	143	132
18 OGi 1440	1484	1484	1484	1484	1484	1484	1481	1451	1310	1201	1113	1039	921	871	824	781	743	469	346	278	235	204	182	164	150	139
19 OGi 1520	1692	1692	1692	1692	1692	1692	1689	1654	1494	1370	1269	1184	1050	993	939	890	847	535	394	317	268	233	207	187	171	158
20 OGi 1600	1769	1769	1769	1769	1769	1769	1765	1729	1562	1432	1326	1238	1098	1039	982	931	885	559	412	331	281	243	217	196	179	165
21 OGi 1680	1845	1845	1845	1845	1845	1845	1841	1803	1629	1493	1383	1291	1145	1083	1024	971	923	583	430	346	293	254	226	204	187	173
22 OGi 1760	1920	1920	1920	1920	1920	1920	1916	1876	1695	1554	1439	1344	1191	1127	1065	1010	961	607	447	359	304	264	235	213	195	180
23 OGi 1840	1993	1993	1993	1993	1993	1993	1989	1948	1760	1613	1494	1395	1237	1170	1106	1049	998	630	465	373	316	274	244	221	202	186
24 OGi 1920	2065	2065	2065	2065	2065	2065	2061	2019	1823	1672	1549	1446	1282	1212	1146	1087	1034	653	481	387	327	284	253	229	209	193
25 OGi 2000	2137	2137	2137	2137	2137	2137	2132	2088	1886	1729	1602	1495	1326	1254	1185	1124	1069	676	498	400	339	294	261	237	217	200
26 OGi 2080	2206	2206	2206	2206	2206	2206	2202	2156	1948	1786	1654	1544	1369	1295	1224	1161	1104	698	514	413	350	303	270	244	224	206
27 OGi 2160	2275	2275	2275	2275	2275	2275	2270	2224	2008	1841	1706	1592	1412	1336	1262	1197	1139	719	530	426	361	313	278	252	231	213
28 OGi 2240	2343	2343	2343	2343	2343	2343	2338	2290	2068	1896	1756	1640	1454	1375	1300	1232	1172	741	546	439	371	322	287	259	237	219
29 OGi 2320	2409	2409	2409	2409	2409	2409	2404	2354	2126	1950	1806	1686	1495	1414	1337	1267	1205	762	562	451	382	331	295	267	244	225
30 OGi 2400	2474	2474	2474	2474	2474	2474	2469	2418	2184	2002	1855	1731	1535	1452	1373	1301	1238	782	577	463	392	340	303	274	251	231

Temperature: 25°C 12.02.2004

OGi cell_Amps 25 degC_00

ENERGY FROM BATTERIES

Table 3.2.3-2: Constant discharge power - Project planning data (BAE, 2004b:9)

BAE *Secura OGi* PROJECT PLANNING DATA

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BA11

Uf = 1,8 V/Cell — Discharge power in W

Battery	1'	3'	5'	6'	7'	8'	9'	10'	15'	20'	25'	30'	40'	45'	50'	55'	1h	2h	3h	4h	5h	6h	7h	8h	9h	10h
5 OGi 400	806	806	806	806	806	806	806	790	[illegible]	664	618	579	516	489	463	440	419	267	198	159	135	118	105	96	88	82
6 OGi 480	950	950	950	950	950	950	949	931	[illegible]	782	728	682	608	575	546	519	494	315	233	187	159	139	124	113	104	96
7 OGi 560	1087	1087	1087	1087	1087	1087	1087	1066	[illegible]	895	833	781	696	659	624	594	565	360	266	214	182	159	142	129	119	110
8 OGi 640	1219	1219	1219	1219	1219	1219	1218	1194	[illegible]	1004	934	875	780	738	700	665	634	404	298	240	204	178	159	145	133	124
9 OGi 720	1344	1344	1344	1344	1344	1344	1343	1317	[illegible]	1107	1030	965	860	814	772	734	699	445	329	265	226	196	176	160	147	136
10 OGi 800	1613	1613	1613	1613	1613	1613	1612	1581	[illegible]	1328	1236	1158	1032	977	926	881	839	534	395	318	271	235	211	192	176	164
11 OGi 880	1758	1758	1758	1758	1758	1758	1757	1723	[illegible]	1448	1347	1262	1125	1065	1010	960	914	582	430	347	295	257	230	209	192	178
12 OGi 960	1900	1900	1900	1900	1900	1900	1899	1862	[illegible]	1565	1456	1364	1216	1151	1091	1037	988	629	465	375	319	277	248	226	208	193
13 OGi 1040	2038	2038	2038	2038	2038	2038	2038	1998	[illegible]	1679	1562	1464	1304	1235	1171	1113	1060	675	499	402	342	297	266	242	223	207
14 OGi 1120	2174	2174	2174	2174	2174	2174	2173	2131	[illegible]	1791	1666	1561	1391	1317	1249	1187	1131	720	533	429	365	317	284	258	238	220
15 OGi 1200	2307	2307	2307	2307	2307	2307	2306	2261	[illegible]	1900	1768	1657	1476	1398	1325	1260	1200	764	565	455	387	337	301	274	252	234
16 OGi 1280	2437	2437	2437	2437	2437	2437	2436	2389	[illegible]	2007	1868	1750	1560	1477	1400	1331	1267	807	597	481	409	356	318	289	266	247
17 OGi 1360	2564	2564	2564	2564	2564	2564	2563	2513	[illegible]	2112	1965	1841	1641	1554	1473	1400	1333	849	628	506	430	374	335	304	280	260
18 OGi 1440	2688	2688	2688	2688	2688	2688	2687	2635	[illegible]	2214	2060	1930	1720	1629	1544	1468	1398	890	658	530	451	392	351	319	294	273
19 OGi 1520	3064	3064	3064	3064	3064	3064	3063	3003	[illegible]	2524	2348	2201	1961	1857	1760	1673	1594	1015	751	604	514	447	400	364	335	311
20 OGi 1600	3204	3204	3204	3204	3204	3204	3203	3140	[illegible]	2639	2455	2301	2050	1941	1840	1749	1666	1061	785	632	538	468	418	380	350	325
21 OGi 1680	3341	3341	3341	3341	3341	3341	3340	3275	[illegible]	2752	2561	2400	2138	2024	1919	1824	1738	1107	818	659	561	488	436	397	365	339
22 OGi 1760	3476	3476	3476	3476	3476	3476	3475	3407	[illegible]	2864	2664	2497	2225	2106	1997	1898	1808	1152	851	686	583	507	454	413	380	353
23 OGi 1840	3609	3609	3609	3609	3609	3609	3608	3538	[illegible]	2973	2766	2592	2310	2187	2073	1971	1877	1196	884	712	606	527	471	429	395	366
24 OGi 1920	3740	3740	3740	3740	3740	3740	3739	3666	[illegible]	3081	2866	2686	2393	2266	2149	2042	1945	1239	916	738	628	546	489	444	409	379
25 OGi 2000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3187	2965	2779	2476	2344	2223	2112	2012	1282	948	763	649	565	505	459	423	392
26 OGi 2080	3996	3996	3996	3996	3996	3996	3994	3916	3569	3291	3062	2869	2557	2421	2295	2181	2078	1324	979	788	670	583	522	474	437	405
27 OGi 2160	4120	4120	4120	4120	4120	4120	4118	4038	3680	3394	3157	2959	2636	2496	2367	2249	2143	1365	1009	813	691	601	538	489	450	418
28 OGi 2240	4242	4242	4242	4242	4242	4242	4240	4158	3789	3494	3251	3046	2715	2570	2437	2316	2206	1405	1039	837	712	619	554	504	464	430
29 OGi 2320	4362	4362	4362	4362	4362	4362	4360	4275	3896	3593	3343	3133	2791	2643	2506	2382	2268	1445	1068	860	732	637	570	518	477	442
30 OGi 2400	4480	4480	4480	4480	4480	4480	4478	4391	4001	3690	3433	3217	2867	2714	2573	2446	2330	1484	1097	884	752	654	585	532	490	454

Temperature: 25°C
12.02.2004

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ENERGY FROM BATTERIES

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3.2.4 LA-BESS maintenance schedule

The facility has a service level agreement with a local BAE representative who conducts maintenance biannually on their behalf. Battery cells voltage, general appearance, cleanliness, electrolyte level, visible damage, float voltage, electrolyte temperature, specific gravity, BESS voltage, charger output voltage, room temperature, ventilation equipment condition, monitoring equipment operation, connection resistance readings, rack condition, and integrity are activities that form part of this service level agreement and are required to be performed, measured, and recorded in accordance with IEEE 450 and 1188. They serve as a means of checking and confirming the reliability of the LA-BESS. Any deviation detected is immediately rectified, recorded data are analysed further for intrinsic compliance, and service reports generated and issued to the facility, as seen in Tables 3.2.4-1, 2 & 3 below (IPAE, 2012b:56-59).

The total BESS terminal voltage during battery float condition as determined in Section 3.2.3 is equal to 588.72V. This system voltage needs to be checked during BESS inspection. If a ±1% is voltage deviation is detected, the charger will need to be checked and adjusted accordingly. All the individual cell voltages are checked and recorded during maintenance. All the individual cell voltages are checked and recorded during maintenance. The single-cell voltage tolerance is +0.1 or -0.05V compared to the nominal float voltage of 2.23VPC; this gives us a range of 2.18VPC to 2.33VPC. If the individual cell voltages are not within these allowable tolerances, specific gravity readings of those cells will be measured, and corresponding rectification will be made. The nominal electrolyte or specific density at the maximum electrolyte level in a fully charged condition for the BAE OGi is 1.24 ± 0.01kg/l at 25°C yielding a tolerance range of 1.23 - 1.25kg/l. It worth noting that, for the correct evaluation of the measured electrolyte density, specific gravity is greatly affected by service conditions such as temperature, electrolyte level, and insufficient mixing. Extreme high temperatures reduce electrolyte's relative density, while low temperatures will increase its relative density. The change in density is 0.006kg/l for every 10°C. Electrolyte density varies proportionally as a function of the electrolyte solution composition. The topping of cells with water will result in lower specific gravity readings above the plates. For complete mixing to occur and bring the density to the correct range, a longer charging time might be required if the battery cell was in a fully discharged state.

Furthermore, it is vital that the procedure for taking connection resistance readings be consistent for each periodic inspection to spot resistive variations instigated by wobbly connections or corrosive surfaces on connection terminals. Drastic change, evidently an increase, of this resistive value through detective maintenance causes concern that requires a cause of failure to be identified and corresponding corrective action to be taken. Terminal resistances measured are then compared with the established terminal resistances baseline values, specific to each connection, measured immediately post BESS installation. A 20% connection resistance upsurge from the baseline values serves as the criteria for initiating corrective action. Establish new baseline data values every time after a major design change or repair using IEEE 450 and 1188 for guidance.

Table 3.2.4-1: LA-BESS maintenance and inspection report (summary page)

Site Information							
Battery		Battery System	Thresholds			UPS System	
		Open C Voltage					
Manufacturer:	BAE	Nominal Float:	Volt Low	2.100	Vdc	Manufacturer:	PILLER UNIBLOCK
Model:	25OGi2000LA	Float Voltage	Volt High	2.250	Vdc	Model:	
Date code	Jan-18	Ripple	SG Low	1.220		Capacity:	1100KVA
No. of Blocks/String	264		SG High	1.260			880KW
No. of Cells/Block:	1	Pos. to Gnd.	Temp Low	20	°C	Input Voltage:	600Vac
No. of Cells/String:	264	Neg. to Gnd.	Temp High	25	°C	Output Voltage:	600Vac
Date of Installation:	Oct-15	Charge Current					
		Water level					

Test Equipment:	DMA 35N Density Meter Model 2900-32 ; Serial No: DMA35NCRT-09-327
	Fluke 179DMM True RMS MULTIMETER SER NUMBER: 90690018
	ALBER CELL RECORDER PLUS SERIAL NO: 2016011
Tests Performed by:	
Inspected By	

PM Summary
Performed Quarterly PM in accordance with IEEE 450-2010. Checked all cell voltages, pilot cell specific gravities (10%) and electrolyte temperatures (10%). Checked and open circuit voltage the charger was off. Top up with Deionised Water is in order.Electrolyte Levels are good. The battery is in good condition and is ready for service
Observations and Recommendations
All readings are within manufacturer's recommended tolerances. Temperatures and differences are all OK.

-52	5	9								
String Name:			Bank 1		Avg	Max	Cell No	Min	Cell No	
			Pilot	Battery Electrolyte Temp:	26.30	26.433	190	26.167	60	°C
				Cell Voltage:	2.150	2.157	63	2.118	70	Vdc
			Pilot	Specific Gravity	1.2544	1.262	200	1.248	210	Sg
				Room Temperature	23	25		21		°C

Table 3.2.4-2: LA-BESS maintenance and inspection report (Page 1 of bank 1)

Bank1		2020 January 07-10			
Block Number	Cell Number	Voltage (V)	Electrolyte Temp °F	Electrolyte Temp °C	Specific Gravity
1	1	2.153	76.8	26.311	1.254
2	2	2.152			
3	3	2.153			
4	4	2.153			
5	5	2.152			
6	6	2.153			
7	7	2.150			
8	8	2.151			
9	9	2.150			
10	10	2.152	76.1	26.233	1.254
11	11	2.150			
12	12	2.152			
13	13	2.150			
14	14	2.150			
15	15	2.151			
16	16	2.150			
17	17	2.152			
18	18	2.149			
19	19	2.151			
20	20	2.149	75.9	26.211	1.254
21	21	2.149			
22	22	2.152			
23	23	2.150			
24	24	2.151			
25	25	2.153			
26	26	2.154			
27	27	2.151			
28	28	2.152			
29	29	2.152			
30	30	2.152	75.7	26.189	1.255
31	31	2.150			
32	32	2.153			
33	33	2.154			
34	34	2.152			
35	35	2.153			
36	36	2.154			
37	37	2.152			
38	38	2.154			
39	39	2.151			
40	40	2.152	75.6	26.178	1.257
41	41	2.152			
42	42	2.153			
43	43	2.151			
44	44	2.154			
45	45	2.153			
46	46	2.153			
47	47	2.152			
48	48	2.154			
49	49	2.153			
50	50	2.152	75.6	26.178	1.255
51	51	2.151			
52	52	2.154			
53	53	2.154			
54	54	2.153			
55	55	2.151			
56	56	2.152			
57	57	2.150			
58	58	2.150			
59	59	2.154			
60	60	2.151	75.5	26.167	1.251
61	61	2.155			
62	62	2.154			
63	63	2.157			
64	64	2.155			
65	65	2.154			
66	66	2.155			

Table 3.2.4-3: LA-BESS maintenance and inspection report (last page of bank 1)

Bank1		2020 January 07-10			Bank 1
Block Number	Cell Number	Voltage (V)	Electrolyte Temp °F	Electrolyte Temp °C	Specific Gravity
199	199	2.153			
200	200	2.156	76.4	26.267	1.262
201	201	2.152			
202	202	2.151			
203	203	2.153			
204	204	2.148			
205	205	2.146			
206	206	2.145			
207	207	2.146			
208	208	2.149			
209	209	2.145			
210	210	2.145	75.8	26.200	1.248
211	211	2.145			
212	212	2.145			
213	213	2.145			
214	214	2.145			
215	215	2.143			
216	216	2.146			
217	217	2.148			
218	218	2.148			
219	219	2.149			
220	220	2.148	75.7	26.189	1.250
221	221	2.150			
222	222	2.152			
223	223	2.151			
224	224	2.149			
225	225	2.148			
226	226	2.144			
227	227	2.146			
228	228	2.151			
229	229	2.146			
230	230	2.145	75.7	26.189	1.249
231	231	2.146			
232	232	2.146			
233	233	2.148			
234	234	2.145			
235	235	2.151			
236	236	2.150			
237	237	2.149			
238	238	2.151			
239	239	2.149			
240	240	2.149	75.8	26.200	1.255
241	241	2.149			
242	242	2.152			
243	243	2.152			
244	244	2.150			
245	245	2.151			
246	246	2.153			
247	247	2.150			
248	248	2.151			
249	249	2.151			
250	250	2.148	76.0	26.222	1.253
251	251	2.151			
252	252	2.152			
253	253	2.151			
254	254	2.150			
255	255	2.150			
256	256	2.149			
257	257	2.148			
258	258	2.148			
259	259	2.150			
260	260	2.148	76.4	26.267	1.253
261	261	2.152			
262	262	2.150			
263	263	2.150			
264	264	2.149			

3.3 LA-BESS room requirements

The battery room, shown in Figure 3.3-1, contains 1056 flooded or vented LAB cells installed. Each battery bank associated with a RUPS has 264 dedicated cells and occupies a footprint, as illustrated in Section 3.3.2. Battery banks of RUPSs are 1.5m apart from a consecutive bank. As previously mentioned, to ensure optimum battery life, it is necessary to control the temperature inside the battery room so that the ambient temperature in the battery compartment does not exceed 25°C. On the other end, when LABs go through the charging process, they release hydrogen gas. The excess accumulation of this hydrogen gas inside the battery room can potentially cause an explosion. For these reasons, the battery room is force-ventilated with its temperature measured and closely monitored, as shown in Figure 3.3-2. The ventilation system installed will also help control and prevent any excess build-up of the escaped hydrogen gas inside the battery room and consequently protect the room against any danger of explosion. With the battery room is classified as Zone 1 hazardous area, a hydrogen detection system is provided to detect a high concentration of hydrogen and generates a warning message to allow responsible personnel to come up with mitigation measures. Both a hydrogen gas detector, inspected and calibrated biannually, and a heating-ventilation-and-air-conditioning (HVAC) system safeguard batteries and battery charging room against the risk of premature failures and explosion. Maintenance, inspection, and calibration of these systems cannot, at any time, deferred, and their deterioration rate needs to be closely monitored as they always need to perform optimally to prevent acute loss to the facility (Stephen, 2011: 1-9 & 2012b:1-7).

Figure 3.3-1: Batteries installation layout

Figure 3.3-2: Battery room temperature monitoring

3.3.1 Battery room and ventilation specifications

The length, width, and height of the battery room are, respectively, equal to 20m, 15m, and 4.5m, as illustrated in Figure 3.3.1-2. The battery room is rated a Zone 1 hazardous area constituting with 100mm diameter drain encased in concrete, sinks, shower, eyewash station, two emergency exit doors, and has flat concrete ceilings to prevent the pocket accumulation of hydrogen gas. The battery room consists of two HVAC systems (HVAC #1 & 2) to control temperature and prevent the unsafe accumulation of hydrogen gas. Both HVAC systems are of York make and require a 3-phase supply. The cooling and heating input power of HVAC#1 is, respectively, rated at 21kW and 14kW, and for HVAC#2, these powers are, respectively, rated at 16kW and 14kW (Stephen, 2011:1-9 & 2012b:1-7). If unknown, the battery room ventilation should be specified in compliance with SANS 62485-2 to ensure safe prevention of dangerous accumulation of hydrogen and to control hydrogen explosive limit level. Ventilation requirements are determined as per Equations 3.3.1-1 to 5 below and all applicable parameters for vented LABs are given in Table 3.3.1-1 (Bhatia, 2019:1-15; Hoppecke, 2018:24-26; Stephen, 2011:1-9 & 2012b:1-7):

$$\upsilon = \frac{100\% - 4\%}{4\%} \tag{3.3.1-1}$$

$$q = 0.42 \times 10^{-3} m^3/Ah \tag{3.3.1-2}$$

$$\upsilon \times q \times fs = 0.05 m^3/Ah \tag{3.3.1-3}$$

$$Q_{air} = 0.05 \times n \times I_{gas} \times C_n \times 10^{-3} \tag{3.3.1-4}$$

$$I_{gas} = I_{float} \times f_g \times f_s \text{ resp. } I_{gas} = I_{boost} \times f_g \times f_s \tag{3.3.1-5}$$

Where υ is the attenuation factor at maximum permissible hydrogen concentration in the air equal to 4%, q is the quantity of accumulated hydrogen per actual Ah capacity, Q_{air} is the required ventilation flow rate in m³/h, n is the number of battery cells, C_N is the nominal battery ampere-hours capacity regarded as the C_{10h} capacity, I_{gas} is the constant describing the water decomposing current, I_{float} is the charge current at float mode operation expressed in mA/Ah, I_{boost} is the charge current at boost charge operation expressed in mA/Ah, f_g is the gas emissions factor which, is the proportion of current drawn during the charging phase responsible for the release of hydrogen gas, and f_s is the factor of safety that factors the current carrying capacity of the battery cell beyond its designed specifications, e.g. damage or short-circuit.

Table 3.3.1-1: Applicable parameters for vented LABs (Hoppecke, 2018:25)

Parameter	Lead-acid batteries vented cells Sb < 3%
f_g: Gas emissions factor	1
f_s: Safety factor for gas emissions (includes 10% faulty cells and aging)	5
U_{float}: Float charge voltage, V/cell	2.23
I_{float}: Typical float charge current, mA per Ah	1
I_{gas}: Water decomposing or gas current (float charge), mA per Ah (used only for calculating the air volume flow for float charge)	5
U_{boost}: Boost charge voltage, V/cell	2.40
I_{boost}: Typical boost charge current, mA per Ah	4
I_{gas}: Water decomposing or gas current (boost charge), mA per Ah (used only for calculating the air volume flow for boost charge)	20

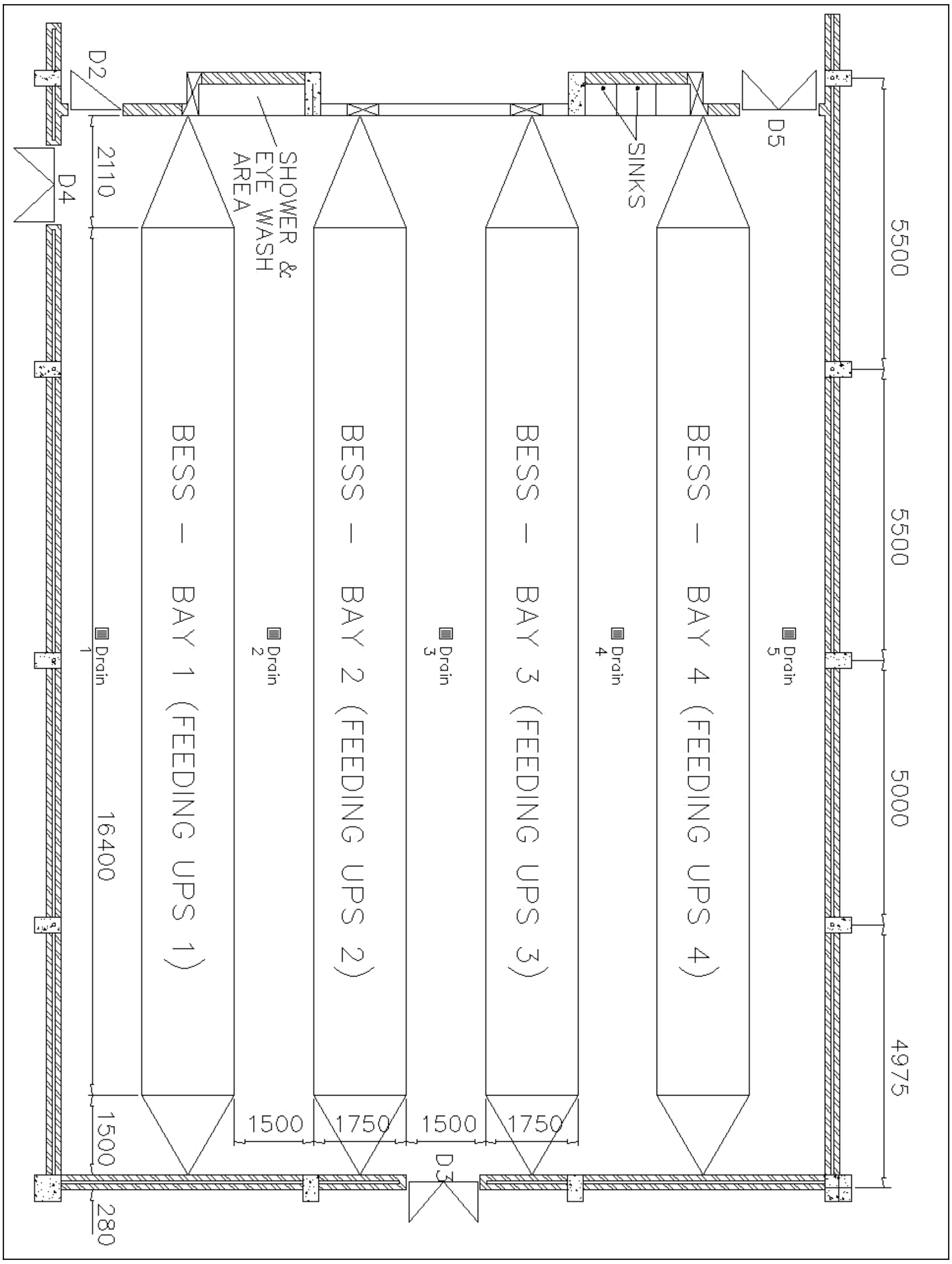


Figure 3.3.1: Battery room layout (NTS)

3.3.2 LA-BESS footprint and floor loading

The 264 batteries associated with each RUPS are double-stacked into four rows (lower and upper row), each containing 66 cells (264/4 = 66).

Length of the cell = 0.44m

Width of the cell = 0.21m

Height of the cell = 0.67m

Surface area occupied by a single cell = 0.44 x 0.21 = 0.0924m²

The total area occupied but excluding ventilation gaps = 0.0924 x 132 = 12.2m²

The total area occupied and including ventilation gaps = 16.4 x 1.75 = 28.7m²

The total area occupied by batteries of all four RUPSs = 28.7 x 4 = 114.8m²

Weight of each cell = 154.085kg

The total weight but excluding weight of metallic racks = 154.085 x 264 = 40678.52kg

The total weight for batteries of all 4 RUPSs = 154.085 x 1056 = 162713.76kg

3.3.3 Hydrogen monitoring system

LABs vent flammable mixture in the room; if this mixture reaches a high concentration, an explosion might occur. The monitoring of this vented flammable mixture prevents this risk of explosion. The facility uses a Dräger Regard-2400 controller, as shown in Figure 3.3.3-1. It is a flexible control unit used to detect toxic gases, oxygen, and combustible gases and vapours. The controller is wall-mounted in the UPS room outside the battery room and is suitable for four Dräger PEX-3000 transmitters.

Figure 3.3.3-1: Dräger Regard-2400 controller

All four PEX-3000 transmitters, as shown in Figure 3.3.3-2, are used as sensing devices for gas detection and intended to continuously monitor the mixtures of flammable gases and vapours with air under atmospheric conditions for reliable protection, availability, and maximum safety of the battery room. Dräger PEX-3000 transmitter is contained inside a shock-proof increased-safety or Ex 'e' enclosure, explosion protection rating that makes it suitable for potentially explosive gas (Zone 1 and 2) and dust atmosphere (Zone 21 and 22) classified areas. The entire system complies with the ATEX directive, and its safety performance level is approved by TÜV Süd in accordance with all harmonized ATEX-standards EN 61779-1, EN 61779-4, and EN 50271, and has an intrinsic protection measure making it suitable for hazardous and explosive environments (Dräger, 2005:5). Calibration of hydrogen monitoring system and alarm settings thereof is as in Table 3.3.3. When hydrogen is detected, all BESSs and their corresponding chargers must be isolated.

Figure 3.3.3-2: Dräger PEX-3000 transmitter (Dräger, 2005:1)

Table 3.3.3: Hydrogen monitoring system calibration and alarm settings

Details	**Settings**
Gas	H_2
Calibration gas	50% LEL H_2
Measuring range	0 – 100% LEL (full-scale range)
Contact	Actual value alarm
Alarm 1	10% LEL
Alarm 2	20% LEL
Horn	20% LEL
Error	System failure

3.3.4 Safety hazards and environmental considerations

Technical personnel should be aware of the various risks and hazards (including their origin) involved when handling LABs through their life cycle phases. Tasks such as adjustment, dismantling, removal, housekeeping, isolation, restoring electrolyte level, failure analysis, repairing, testing, measurement, disconnections, lifting, loading, and disabling conducted during scheduled maintenance, troubleshooting, fault-finding, and dismantling phase should be risk-assessed and risk-evaluated. Through the executions of these tasks, potential consequences such as electrocution or electrical shock, poisoning, corrosion, fire, explosion, ergonomic related to cells heavyweight, and contamination may arise. The facility should ensure that the technical personnel involved in maintaining these batteries obtain the necessary knowledge, skill, and training in safe work practices relating to handling these LABs. Material safety data sheets corresponding to their electrolyte substances must be made available to assist and guide them during accidental contact with such substance or during disaster control management or spillage. For safety measures, all personnel performing tasks must wear suitable personal protective equipment (safety glasses, boots, and gloves) that protect them from any danger.

3.3.4.1 Risk of exposure to chemical and waste management

The sulphuric acid substance has a potential of hydrogen of less than 2 (pH<2) to make it a very corrosive substance. Direct exposure to sulphuric acid can permanently cause health issues such as eye damage, skin burns, or even death if swallowed as it is toxic. Lead materials being the fundamental elements from which these batteries electrodes are constructed, are similarly harmful to human health and need to be disposed of controllably. Furthermore, due to chemical reaction, the recharging process of vented LABs is always accompanied by hydrogen (H_2) release. This colourless flammable gas is also toxic. Even though all materials used in BAE LABs are recyclable, wastes emanating from them must be viewed as hazardous wastes that require a controlled and safe disposal measures to be put in place. An incorrect disposal procedure deviating from the material safety data sheet (MSDS) of these BAE LABs can pollute the disposal site and the environment. Through the battery's disposal procurement process, part of the appointment pre-requisite requirement, the service provider must provide details of the approved waste disposal site used for the final disposal of these lead materials waste. They must present all legal registrations documents permitting them to act as a certified waste handling and disposal entity. After the disposal process, the service provider must deliver all related safe disposal certificates to the facility's safety department.

Disaster management of any electrolyte spillage incident needs to be addressed in consultation with the specific electrolyte MSDS in question. MSDS is a document containing information on the potential hazards, safe handling, restraint, cleaning, and discard procedure of this chemical product. Personnel involved in disaster management must make use of suitable protective gear to prevent their exposure through handling. If minor spillage occurs, it must immediately be contained using sand or super-absorbent material. Carefully discard chemically adulterated waste material once it has saturated the spilt electrolyte, safely clean the contaminated area using sulphuric acid nullifier content, and then rinse the area with fresh water.

3.3.4.2 Fire and explosion hazards

The battery room is rated Zone 1 hazardous area which, is the extent of a hazardous area in which a flammable gas, mist, or vapour is likely to be released under normal operating conditions. Three enablers must simultaneously be present in a pre-determined proportion to cause an explosion. Those enablers are fuel (explosive gas, vapour, mist, or dust), oxygen, and source of ignition (equipment surface heat, spark, or flame), as illustrated in Figure 3.3.4.2-1

(Pieter, 2015:3-10). The required fuel/oxygen ratio capable of causing explosion varies with each combustible material, as shown in Figure 3.3.4.2-2. A fundamental and inherent way to prevent any explosion is by designing a system that prohibits the simultaneous co-existence of all these three enablers or inhibits the presence of at least one of these enablers. The discharge process of vented LAB cells exhausts minute hydrogen vapour. But the charging process releases a considerable amount of vapour in the form of an explosive mixture containing hydrogen (H_2) and oxygen (O_2) which, often possess a mist of sulphuric acid. Hydrogen vapour is colourless, odourless, weighing less than air, and explosive. Oxygen, on the other end, is an oxidizer that endorses the ignition process of non-flammable materials. The exhausted hydrogen vapour will be allowed to create an explosive mist in the battery room if the ventilation system does not dilute or prevent its excess build-up. Escaped hydrogen vapour weighs less than air and is prone to accrue on pockets left on the ceiling spaces of the battery room poorly ventilated. Its, therefore, practical to have a hydrogen detector fixed and mounted at the upper interior surface of the battery room. The concentration limit of accrued hydrogen vapour below which flammable mixture becomes leaner is 4%. The concentration limit of accrued hydrogen vapour above which flammable mixture becomes richer is 75.6%, as given in Table 3.3.4.2 (Pieter, 2015:1-13; Stephen, 2012a:1-10).

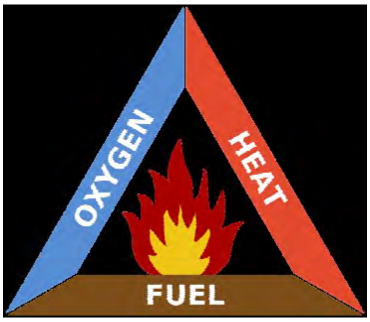


Figure 3.3.4.2-1: Fire triangle (Pieter, 2015:3)

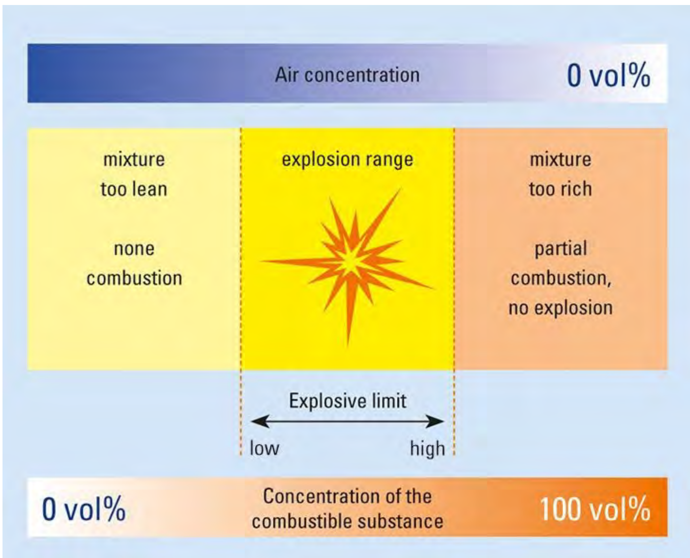


Figure 3.3.4.2-2: Concentration of combustible substance

Table 3.3.4.2: Combustible gas concentration levels (Pieter, 2015:5 – 6)

Combustible Gas LEL's and UEL's			
		LEL	UEL
Acetylene	C2H2	2.5%	100%
Benzene	C6H6	1.2%	8.0%
Methane	CH4	5.0%	15.0%
Ethane	C2H6	3.0%	15.5%
Ethyl Alcohol	CH2H5OH	3.3%	19.0%
Ethyl Ether	(C2H5)2O	1.7%	36.0%
Ethylene	C2H4	2.7%	36.0%
Hexane	C6H14	1.1%	7.5%
Hydrogen	H2	4.0%	75.6%

3.3.4.3 Electrical hazards

The core function of the BESS being the storage of energy, disconnected BESS or battery cell should always be considered to be live and capable of causing an electrical shock hazard. BAE battery cells are constructed to release their ampere-hours charge capacity at nominal constant discharge currents of around 1800A. Unintended shorting of their terminals can produce electrical arc flash carrying enough energy to cause skin burn and electrocution to personnel in that arc flash zone. For adherence to safe work practice, when troubleshooting, fault-finding, maintaining, installing, or dismantling a BESS, using or placing bare metal parts or uninsulated tools near battery terminals must be avoided. If this is unavoidable, then consider installing an insulating shroud around batteries terminals. A conspicuous sign needs to be placed in the battery room to alert technicians on the danger of wearing jewellery while performing any task on the BESS. Another sign needs to be placed in front of the battery room to prohibit unauthorised entries on any occasion. When technicians perform any task on the BESS, they need to follow the lock-out/tag-out procedure. A permit to work and all listed precautions before task execution must, respectively, be obtained and conducted.

3.3.4.4 Ergonomic hazards

BAE 25-OGi-2000 LAB cells are heavy; each cell weighs 113kg when dry and 154kg when filled with electrolyte. Cell construction contains lead material weighing 104.6kg which, is about 68% of the total weight of the battery cell when filled with electrolyte. Due to their heavyweight, facility-specific hazard identification and risk assessment regarding lifting, handling, and conveyance method need to be elaborated to determine correct injury-prevention procedures to be followed.

3.4 Summary

The four Piller RUPSs installed are over 26 years old, spare parts are no longer available, the equipment and die to produce a replacement unit are no longer available. Although they are still operational, any significant failures would most likely also make them unrepairable. With ageing, they now require regular heavy maintenance and suffer higher electromechanical energy losses inherent to pony motor, frictional, windage. When compared to new UPSs, they are running at high operation loss due to their low power factor (0.8 lagging), low efficiency (92%), high heat dissipation, and a requirement for high room ventilation. They are bulky and occupy high footprint space. Noise level is also a big factor in a RUPS installation, and appropriate noise-reducing enclosures over the rotating motor-generator set must be well-thought-out.

Like with most equipment, current specifications differ totally from or bear little resemblance to those of earlier years, experiences and technical developments have shown the previous specifications to be deficient. Examples of differing requirements between earlier and current standards relate to operating mechanisms, diagnostic coverage, and personnel protection during equipment failure. On the other end, the associated BAE 25-OGi-2000 LA-BESS now requires biannual maintenance costing the organization approximately R300 000 annually. Although this is considered a legitimate running cost of the plant, it occurs on a capital scale with repetitions of 8 to 10 years. The cost of a cell in 2021 is seating at around R35 000. All cells came with an initial 2-year warranty. The extension of this warranty by an additional three years cost the facility approximately R700 000. Even though the BAE battery cell has a prescribed life expectancy of 20 years, various aspects can undesirably influence it. During the normal operation of flooded cells, a considerable amount of heat dissipated adds to the system running cost. Due to the presence of hydrogen, the battery room requires high ventilation to monitor its concentration. The battery room is zoned (zone 1) hazardous utilizing costly explosion-protected electrical and hydrogen monitoring equipment.

CHAPTER FOUR

STATIC UPS PRINCIPLE CONFIGURATION AND SELECTION PROCESS

4.1 Scope

This section covers selection processes, background theories, configuration principles, determination of parameters for design specification and selection, operational principles, system classification, rating, sizing, and required performance characteristics for a SUPS system. The management-of-change program, though not covered in this thesis, needs to be developed. This change program assesses and controls the modification to the UPS system to prevent any negative safety and business impacts.

4.2 UPS system configurations

There are multiple UPS configurations available nowadays. The main configuration types are offline, line-interactive, and online double-conversion. Decisions on which configuration type to select are largely market, requirements, and choices related more than their technological expertise. The selection of a well-suited UPS for any facility is through a thorough type-examination of its designed features and benefits towards the facility's power protection viewpoint (Chris & Ed, 2015:1-8; Legrand, 2012:4; Neil, 2011a:1-10; Roberto et al., 2007:1-5).

4.2.1 Offline UPS configuration

In this configuration, as illustrated in Figure 4.2.1, critical loads are supplied directly from the mains supply during normal operating conditions. The utility unconditioned input power is directly transferred to the UPS output via a line selector switch while backup batteries charge through the battery charger. The utility unconditioned input power is directly transferred to the UPS output via a line selector switch while backup batteries charge through the battery charger. During a utility power outage or interruption, the system will transit to UPS mode, where backup batteries supply critical loads through the inverter.

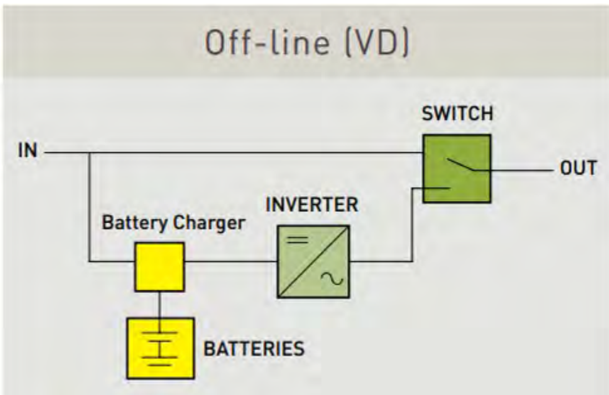


Figure 4.2.1: Offline, voltage-dependent (VD) configuration (Legrand, 2012:4)

4.2.2 Line-interactive UPS configuration

In this configuration, as illustrated in Figure 4.2.2, during normal operation conditions, the supply of critical loads from the power utility is interfaced or isolated by an automatic voltage regulator (AVR) circuit which, assumes filtering and stabilization of power signal supplied to them. Voltage-regulated utility power is transferred to the UPS output via a line selector switch while backup batteries charge through the battery charger. Even though filtering and stabilization are conducted, signal disturbances from the input to the output side are not fully proofed. During the utility power outage or interruption, the system will transit to UPS mode, where backup batteries supply critical loads through the inverter.

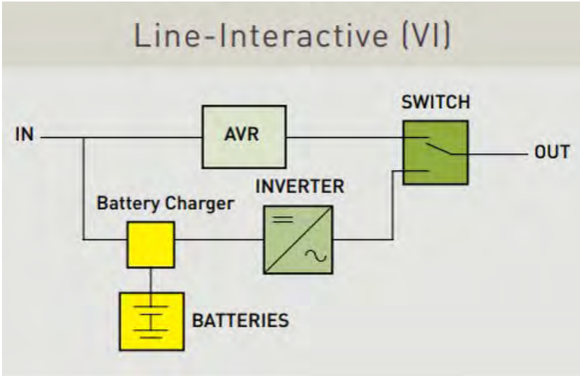


Figure 4.2.2: Line-interactive, voltage-independent (VI) configuration (Legrand, 2012:4)

4.2.3 Online double-conversion UPS configuration

In this configuration, as illustrated in Figure 4.2.3, critical loads are permanently supplied by a fully-conditioned input signal. The utility unconditioned input power undergoes double-conversion where it is initially rectified by a rectifier circuit and then converted back into a sinusoidal waveform by an inverter circuit. This double-conversion process presents the advantage of having input signal disturbances from the utility power fully proofed from the output signal. During the utility power outage or interruption, the system will maintain its supply to critical loads using its backup energy stored in batteries. This configuration has a bypass option to transfer input power automatically and directly to essential loads in case of UPS system failure to ensure maximum redundancy.

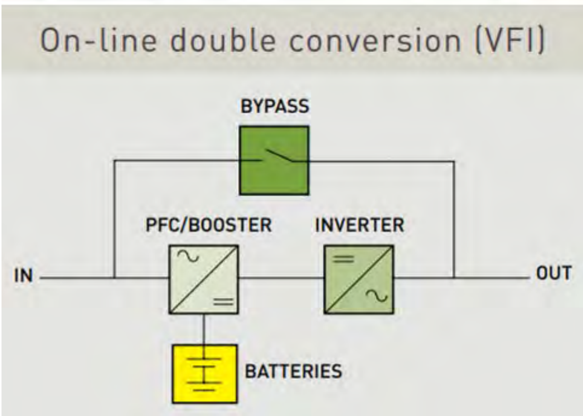


Figure 4.2.3: Online double-conversion, voltage-frequency-independent (VFI) configuration (Legrand, 2012:4)

4.2.4 SANS/EN 62040-3 classification

UPS power rating specification must not be the only factor to consider when identifying the best-suited UPS for any application. Having a well-rated UPS does not necessarily prove that it is optimally selected to achieve the quality power requirements of critical loads (Legrand, 2012:5). The SANS/EN 62040-3 standard defines performance classifications of a UPS system based on its ability to manage and condition disturbances as shown in Table 4.2.4 and Figures 4.2.4-1 & 2 below:

Table 4.2.4: UPS performance classification (Legrand, 2012:5)

XXX	YY	ZZZ
Output dependence from the Input	Output waveform	Output dynamic performance

The first column from the left of Table 4.2.4 which, is the XXX classification code, outlines its type:

- VFI (voltage and frequency-independent) type: This type offers independence and variation-based control of voltage and frequency between input and output signal to within specified limits (refer to SANS/IEC EN 61000-2-2 standard)
- VFD (voltage and frequency-dependent) type: This type offers no independence and variation-based control of voltage and frequency between input and output signal
- VI (voltage-independent) type: This type provides a level of isolation between input and output powers by an automatic voltage regulator circuit which, assumes filtering and stabilization of power signal supplied to within specified limits.

The second column from the left of Table 4.2.4 which, is the YY classification code, outlines its output signal distortions level during standard or battery-backup operation:

- SS: Sinusoidal signal with a voltage total harmonic distortion (THDu) of less than 8%,
- XX: Sinusoidal signal with linear load, non-sinusoidal with distorting load (THDu > 8%),
- YY: Non-sinusoidal signal.

The third column from the left of Table 4.2.4, the ZZZ classification code, outlines the performance integrity level of its output voltage relative to the supplied load. Below are three different disparities situations in normal or battery-based operating modes:

- 111: Disparities emanating from normal operating conditions,
- 112: Disparities emanating from the insertion of the step-based linear load, and
- 113: Disparities emanating from the insertion of the step-based non-linear load

<u>**Note**</u>: “VFI SS 111” classifies the best performing UPS system.

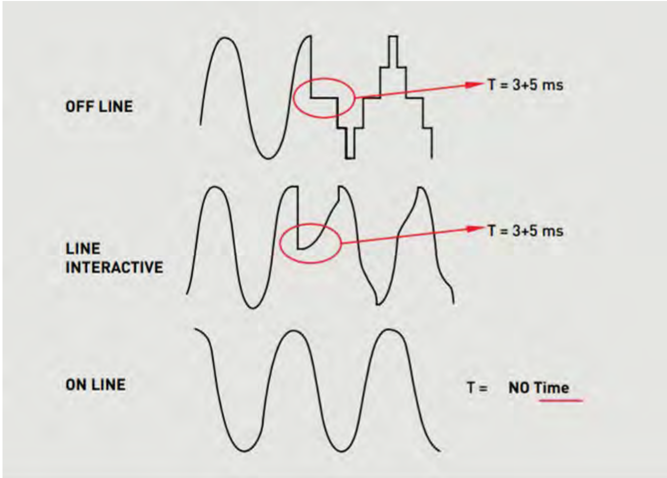


Figure 4.2.4-1: UPS output voltages (Legrand, 2012:6)

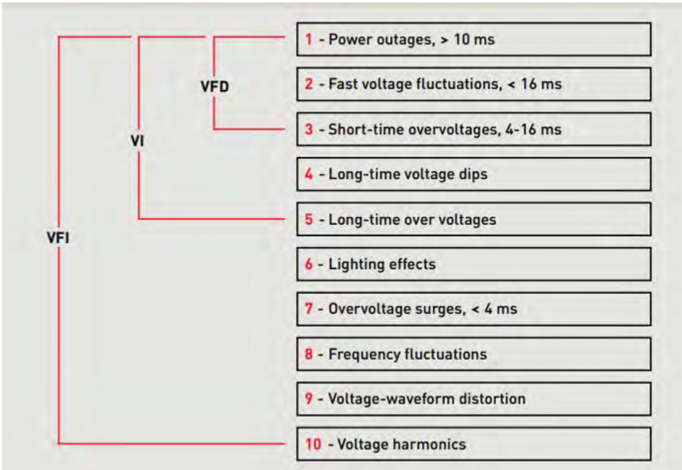


Figure 4.2.4-2: UPS features and classification (Legrand, 2012:6)

4.2.5 UPS size required

A correctly sized UPS will need to have its input parameters well-matched with the supply distribution from where it is fed and its output parameters well-matched with the critical loads to be supplied and safe-guarded. In this research work, the replacement UPS system selected needs to support the voltage range (600V) compatible with the existing RUPS system to eliminate the cost of a new power reticulation system. It is crucial to define functional and parameters-based performance structures to which the UPS design is developed to obtain a suitable and well-sized UPS system. This process determines factors that assist the UPS system achieve its optimum integrity and performance level. These factors are:

1) Maximum power demand of critical loads
2) Maximum active power of the selected UPS
3) Power factor (PF)
4) Input and output power supply characteristics (number of phases, operating voltage level, operating frequency, of the selected UPS
5) Required integrity or performance level of the system to be protected
6) Designed integrity or performance level of the selected UPS

7) Configuration type and design features of the selected UPS system
8) Compatible energy storage system and maximum backup time at full load

The total power the UPS is expected to draw from the utility is expressed by Equation 4.2.5 below:

$$P_{line} = P_{UPS} \eta_{UPS} \tag{4.2.5}$$

Where P_{line} is the total UPS input power drawn from the main, P_{UPS} is the total available output power offered by the UPS, and η_{UPS} is the overall UPS performance efficiency. It is, however, difficult to determine the correct energy absorbed by a UPS as most of them are regarded as non-linear loads, and their insertion into the network can cause transient disturbances. These disturbances are mainly triggered by harmonics produced by any incorrectly set input circuits. Therefore, this situation must be factored, particularly when recommending a UPS system having a limited maximum current total harmonic distortion (THDi) near 3%.

4.2.6 UPS system efficiency

Rectifier and inverter are regarded as the principal power conversion circuits inside the UPS and undoubtedly the key electronic components. Migration of electrical energy from input to output and conversion process on an online double-conversion UPS are permanently made via these two circuits. The high electrical energy usage and, consequently, loss or dissipation of some of this electrical energy also happens inside these two circuits. This high energy consumption comes with a constant flow of current that stresses them electrically and thermally. In the purpose to lessen and enhance this electrical energy loss, the newly designed UPS systems use high-efficiency, high-performance electronic components such as insulated gate bipolar transistors (IGBTs). These IGBTs are compact and possess superior properties to help achieve a high-quality electrical energy conversion at very little energy consumption or dissipation. The use of IGBTs has allowed UPS manufacturers to deploy high-frequency monitoring and pulse width modulation (PWM) control technologies. The birth of these components has since replaced transformers-based technologies with transformer-less technologies and made passive harmonic filter usage almost inexistent. The latest generation of transformer-less UPS systems employs active filters to continuously monitor and counteract the effects of unwanted harmonics generated by the rectification process. This scenario can result in THDi levels of less than 2% at full load and around 3.5% at 25% load. The removal of transformers and filter equipment in the manufacturing of UPSs has since brought a drastic reduction in running energy losses while improving the overall system efficiency, requiring relatively smaller ventilation systems, and reducing footprint, weight, and manufacturing cost (Legrand, 2012:23 – 24).

As elaborated above and by referring to Figure 4.2.6 below, the newly designed SUPS systems, like any other equipment produced nowadays, put more emphasis on their overall performance, integrity, effectiveness, efficiency, and ability to save energy throughout their life cycle operation. Based on their overall efficiency and performance curve, their overall efficiency and performance level are directly proportional to the percentage at which they are loaded (load rate) in relation to their maximum rated full power. For this reason, accurate sizing of the UPS system whose output power is symmetrised with load demand is of utmost importance. This symmetrisation not only offers a positive economic benefit on overall electrical power consumption but, correspondingly, brings initial capital investment cost down. Furthermore, with the diversity factor of critical loads so ever-changing and fluctuating through the day, week, and month, the load demand rate will also not be constant. In this case, UPS must be designed to have a level of homogeneous and diverse redundancy structures build into it to offer high efficiency at any load rate. Overall, the superlative solution is to select a UPS that has a high integrity and performance level.

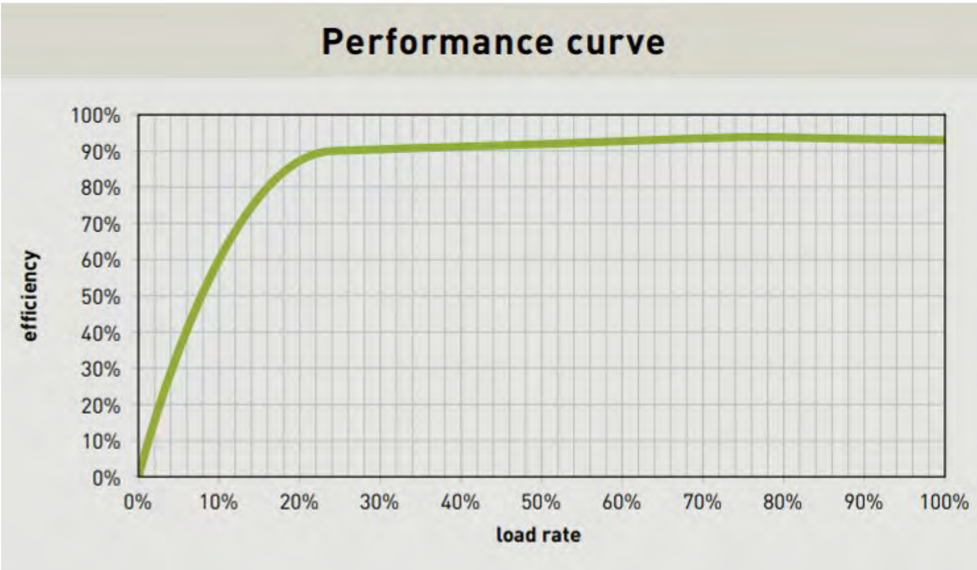


Figure 4.2.6: Typical UPS performance curve (Legrand, 2012:24)

4.2.7 Three-phase modular UPS system

The three-phase modular SUPS system, shown in Figure 4.2.7, consists of synchronised and self-governed uninterruptable power modules (UPM) interconnected together to power downstream critical loads. The total output power rating of the UPS system is, therefore, a sum of the output power rating of each constituent module. The transport, installation, and replacement of these modules are without great effort as they are compact and light in construction. They are self-detecting, hot-swappable, and requiring no configuration, programming, or change in their settings during installation or module swap. Service technicians do not require special tools or device communication protocol to place them into operation. This modular SUPS system is more reliable, presents a very high power efficiency leading to less power consumed during power energy processing, and offers added advantages related to breakdown maintenance, planned-component replacement, reliability-centred maintenance, running maintenance, controllability, availability, and overall cost management. The system can accept configuration to either adjust power or system backup time as and when required. Its modularity and scalability features enhance the initial capital investment into system implementation. They also present high flexibility and adaptability to the load demand without impeding future development. Installation of supplementary or field-installed modules makes diverse and homogeneous internal redundancy possible to ensure a continual supply of power to critical loads. Thus, an out-of-service of any specific module will not compromise conditioned supply to critical loads. The manufacturing of the UPS system that comes with factory settings is a thing of the past. Manufacturers of the UPS system nowadays have presented users with a new modularity topology. They offer users a procurement option to select the UPS configuration type, size, integrity, and performance level appropriate for its application requirements to circumvent system over-architectural design and enhance overall system efficiency.

Figure 4.2.7: Eaton type SUPS unit (Appendix F)

4.2.8 Power factor and harmonic distortion

A three-phase modular UPS system introduces almost no transient disturbances while inserted onto the supply mains. It has a power factor close to unity ($\cos\varphi \approx 1$) at their input while only 20% loaded accompanied by fully filtered harmonics (total harmonic distortion of less than 3%). The active power (*P*) and reactive energy (*Q*) are, respectively, the real and imaginary component of the entire system's apparent power (*S*) consumed ($S = P + jQ$). The imaginary portion of the apparent power is not a usable power, thus not actually used by the system. Its increase is affected by a rise in angle φ between voltage and current of the system caused by inductive or capacitive loads connected downstream. The bigger this angle gets, the far its cosinus ($\cos\varphi$) will drift away from unity and, consequently, the greater the reactive power absorbed by the installation. This reactive energy, consumed by the facility but not used, will still contribute to and increase the overall apparent power of the facility. This power increase will, in turn, lead to a higher electrical current (*I*) flowing through conductors that upsurge the thermal or copper energy loss costs (E_C) through a pre-determined period (*t*) ($E_C = R_C \times I^2 \times t$). The inherent power factor correction that modular SUPS brings adds a saving to the facility by, hypothetically, eliminating the necessity of having a power factor correction system installed upstream to bring up critical loads power factor to unity, as illustrated in Figure 4.2.8.

Non-linear loads connected to supply mains tend to produce harmonics. These harmonics currents are seen as additional circulating currents waveforms superimposed over the fundamental current waveform. The superimposition of these undesirable waveforms to the fundamental waveform will produce a resultant current of high intensity flowing through conductors, like in the case of a bad power factor, to upsurge the system's thermal or copper energy loss. Moreover, due to the high-frequency nature of harmonics waveforms, all frequency-dependent losses such as hysteresis and core or iron losses in transformers will also increase. Controllability of the current drawn by the UPMs permits an extreme lessening of current harmonic distortions on the UPS input (THDi < 3%).

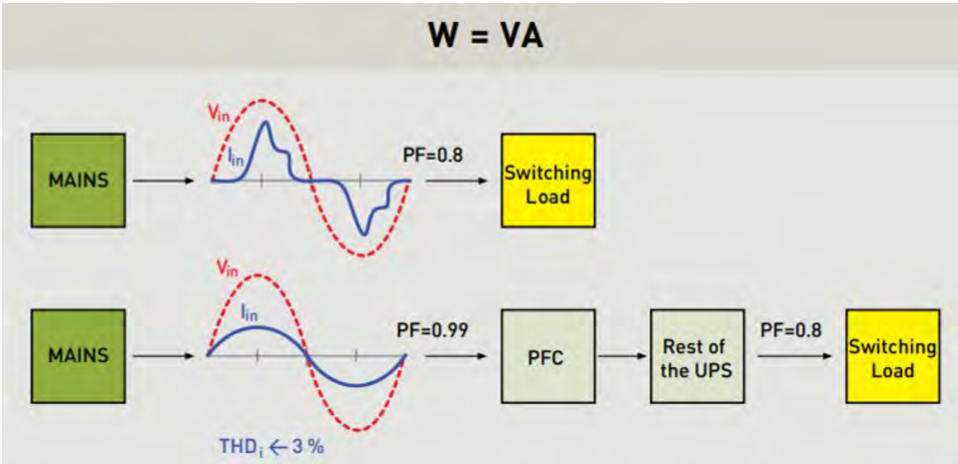


Figure 4.2.8: Power factor and harmonic distortion (Legrand, 2012:27)

4.3 Operation principles of an online, double-conversion SUPS

The online, double-conversion, battery-based SUPS consist of a battery charger or rectifier, inverter, bypass switch, and BESS as described in Section 4.2.3. In normal operating condition, the operation starts with the rectification or conversion of an alternating current from the utility power supply into a direct current at the rectifier's output. This rectified current is simultaneously fed into battery chargers to charge and maintain the capacity of the BESS and into the inverter that converts it back into alternating current to supply critical loads. Apart from the principal function of storing energy, BESS performs like capacitors and, in combination with DC chocks, filter currents generated by the rectifier circuit and diminish their ripple content. The backup power will typically be supplied by the BESS, first via the rectifier and then through the inverter to critical loads. The inverter is then positioned to feed essential loads under normal and battery backup conditions and operates as a voltage and frequency regulator. This inverter is also equipped with an internal oscillator that preserves its frequency regulated and synchronized with mains frequency by governing switching-signals timing to its power switching semiconductors devices (IGBTs). A bypass switch transfers critical loads to the main power supply when the UPS system fails or during system maintenance (TIC, 2014:7-33).

During a utility power outage, the power supply to the inverter will still be maintained by the battery backup system. In that case, the provision and delivery of electrical energy to critical loads will, therefore, remain unbroken until the utility power is reinstated. In a case where the BESS attains its discharged condition prior to the utility reinstatement, a DC under-voltage detection device automatically initiates a system shutdown signal to, controllably, shut down the UPS system. The normal system operation will resume immediately after the reinstatement of the utility power. Even though the BESS has attained its optimum discharged state, the output of the rectifier charger is adjusted to the equalizing voltage to recharge the battery cells simultaneously as the inverter supply critical loads. At the end of the battery recharging time, the rectifier will adjust its output to the floating voltage. During transient or momentary disturbance incidents on the Main AC (voltage dips or surges) that are out of tolerable boundaries, the conditioned DC power supply to the inverter will still be preserved by the BESS, making the delivery of electrical energy to critical loads remain unbroken.

4.3.1 Rectifier and inverter principle

Rectifier and inverter use solid-state power switching devices (IGBTs) that govern the flow direction of power. The high switching rate of their power semiconductor devices allows fast rectification of alternating power to direct current or inversion of this direct current back into alternating form. The IGBT power semiconductor devices amalgamate the attributes of the bipolar and the field-effect transistors (FET). The control voltage is put in their base to switch the device on and off. They possess superior lenience to temperature variabilities than the FETs, have notably high efficiency, and are facile to control than the other power semiconductors. Their birth has permitted the construction of SUPS of up to 750kVA without paralleling units. Nevertheless, like all other transistors, they possess the weakness of saturation and switching losses that need to be considered during the design phase.

The conversion of an alternating current to a direct current is named rectification. This conversion is realized by the utilization of unidirectional semiconductor devices (IGBTs). Rectifiers can be so constructed as to convert an alternating current to regulated or unregulated direct current. The unregulated rectifier DC output voltage will vary with the load owing to drops in voltage. On the contrary, a regulated rectifier has its DC output voltage controlled to a wanted level by varying IGBTs firing angle α (phase control). The voltage regulation is achieved by a closed feedback loop that detects changes in DC output voltage and signals the AVR to fine-tune the IGBTs phase control accordingly. Inversion, on the other end, is the conversion of direct current power to alternating current power. Line rectification, inversion can be achieved using IGBT electronic components. The common method of inverter output voltage control is with PWM, as illustrated in Figure 4.3.1. The PWM uses several cyclic and rapid switching of IGBTs to deliver a train of pulses of equal height but different thicknesses. The coherent combination of these pulses forms the output voltage signal, and an adjustment of the height and width of these pulses controls its amplitude and period. Careful and precise adjustment of their height and width can produce a pure and harmonic-free sinewave that renders the use of output filters inutile. Inverters utilizing this practice offer quick transient response time, possess lower impedance. They can operate in a controlled closed-loop system.

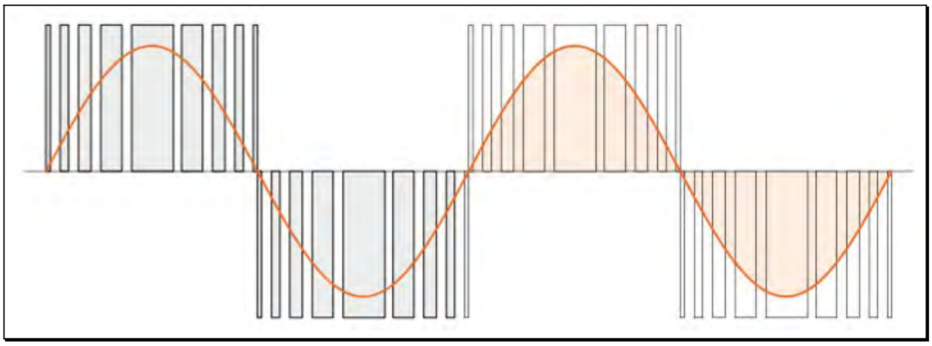


Figure 4.3.1: Pulse width modulation (PWM)

4.3.2 UPS bypass mode

4.3.2.1 Integrated bypass switch

During a defective condition or an occurrence of a major alarm in the UPS system, the necessity of an automatic migration of all critical loads directly to utility supply is required to avoid any interruptions of supply. For this reason, a bypass switch is provided. This bypass switch also provides fault clearing capability for any downstream load-faults. Without this feature, the inverter might not supply enough current to activate the circuit breaker and might continue feeding the fault current to cause a prospective hazard. The allocation of the fault current to the utility mains by the bypass switch permits full short-circuit current to transit, hence initiating the circuit breaker trip. The bypass switch is set to automatically assign critical loads back to the UPS when all is normalised (TIC, 2014:7-33). With the difference between a fault and inrush current not easily detectable by the control circuit at start-up, it is acceptable to manually initiate a momentary migration of these critical loads to the utility mains during preliminary supply. When the inverter logic detects any abnormality in the utility or load side whose value is outside the programmed value range, the bypass IGBTs will be gated on by the logic board to automatically allow the UPS bypass line to take up critical loads. Re-allocation of critical loads back to the UPS system is automatic and happens when the detective logic circuitry confirms that the problematic concern at the UPS output has been eradicated. In this circumstance, the logic system circuitry sustains the synchronisation of the inverter output in relation to the UPS bypass power.

4.3.2.2 External maintenance bypass switch

External bypass switchgear has also been considered to permit the bypass of the complete UPS system or paralleled UPS systems. The core function of this bypass line is to sustain the provision of power to critical loads during maintenance or UPS system malfunction. In compliance with the electrical safe work practice, working on an energized equipment is deemed unsafe and must be avoided at all costs. For this reason, isolate the concerning UPS system completely before executing any task on it as there are circuitries inside this UPS enclosure that are prone to retain and susceptible to deliver high and deadly voltages. It is, therefore, of utmost importance to have the UPS system designed such that all its sections, susceptible to establish a redundant path, be linked by the system control logic to inhibit their partial shutdown. Furthermore, an attempt to operate the UPS system with the aim to provide conditioner power to critical loads while the BESS is isolated for maintenance must be avoided as this can affect the system control logic. After shutdown, offline load testing on all UPS systems must be conducted (Ashok, 2011:1-7).

4.4 SUPS selection process

The process for selecting the best-suited SUPS system for the application will consist of nine main detailed specifications. These are the specification of its power, safety, affordability, availability, reliability, maintainability, scalability, design performance, and selection of configuration type requirements.

4.4.1 Power requirements

Determination of power requirements is often crucial since it establishes the required conditions for the rest of the specification stages. Skipping this stage might lead to the selection of an oversized system (exercise that will increase the initial capital investment of the project) or an undersized system (exercise that will compromise the energy availability factor). Moreover, facilities are often exposed to a substantially imminent and forthcoming evolution in their maximum load demand as they develop. This future power provision must as well be accounted for in the sizing of the SUPS system. The power supply architecture in the facility is arranged into two load groupings, critical and non-critical. Critical loads are the only loads supplied through the UPS system, while the power utility supplies non-critical loads directly. The new SUPS system replaces and upgrades the existing 4 x 1100kVA, 600V/600V RUPS system. The power requirement of the new system needs then to match the current power requirement.

4.4.2 Safety requirements

Safety considerations are a prevailing apprehension in any project or system implementation. The implemented system needs to remain compliant with the occupational health and safety act, regulations, and any harmonized standard or regulation adopted in the country throughout its life cycle stages. Hazard identification and risk assessment of each task undertaken to assist the completion of the project must be elaborated through the management-of-change process by a well-trained group of members with knowledge and experience to conduct such a vital process.

4.4.3 Affordability requirements

A decision on the capital investment injected into any project is vital. This investment is the determining factor to the configuration, architecture, and protection level the system offers to critical loads. Affordability study is often placed first because the project cannot go to tender or send to the approval process if it has not been appropriated and if the design evaluation and development of the UPS system to be implemented have not been scoped. The affordability evaluation of a UPS system must consider all costs, such as the purchasing, implementation, return on investment, operating and system support, spare parts, lifecycle maintenance, and disposal costs. The implementation cost includes structural modification, consulting, and rigging costs.

4.4.4 Availability, reliability, and maintainability of UPS system

Availability of the facility's installed equipment, machinery, or system is of supreme importance in its success. It is defined as a ratio between the total hours a piece of equipment, machinery, or system is ready to be used to the total hours that equipment, machinery, or system is required or expected to deliver. The mathematical expression of the intrinsic or design-availability of a piece of equipment is as per Equation 4.4.4-1 below (Joel & Eric, 2002:3-7 – 3-11; Neil, 2011b:1-6):

$$A = \frac{MTBF}{MTBF + MTTR} \tag{4.4.4-1}$$

Where A is the system's intrinsic or inherent availability, $MTBF$ is a measure of reliability or the system's mean-time-between-failures, $MTTR$ is a measure of maintainability or the system's mean-time-to-repair, λ is the system's failure rate (λ = 1/MTBF), and μ is the system's repair rate (μ = 1/MTTR). Based on Equation 4.4.4-1 above, we can deduce that the equipment availability depends directly on its reliability and maintainability.

The probability that a piece of equipment, machinery, or system will complete the execution of its envisioned functions for a defined time under its design specifications is called reliability. The latter can also be expressed as the mean time between failures (MTBF) which, specifies the number of failures within a specified operation period as stated in Equation 4.4.4-1. Reliability is a factor contributing immensely to keeping the equipment available to perform its intended duty. It is a function of the UPS system design, configuration, redundancy selected, spare parts used, and installation environment. Ecological impacts, for instance, extreme humidity, cold, heat, or airborne dust, may notably affect the reliability of the entire UPS system. Redundancy is the doubling of fundamental components of the installation for enhancing its overall effectiveness or reliability. This principle reduces the overall system's failure rate since the failure of any single unit is unlikely to induce failure of the entire system.

On the other end, maintainability is the probability that a piece of equipment, machinery, or system can be returned into full operation or made to achieve its full functionality. This recovery is made through repair, overhauling, scheduled maintenance, or planned component replacement in the quickest, swiftest, and cheapest way, with reduced labour intensity. The latter can also be expressed as the meantime to repair (MTTR) as stated in Equation 4.4.4-1. Regarding the facility's system configuration, the UPS system is represented by a reliability block diagram shown in Figure 4.4.4. The reliability of each SUPS rests on the reliability of its three main components, namely: rectifier, battery storage system, and inverter. The determination of the failure rate of a single SUPS is, therefore, as per Equation 4.4.4-2 below:

$$\lambda_{UPS} = \lambda_{RECTIFIER} + \lambda_{BATTERY} + \lambda_{INVERTER} \qquad (4.4.4\text{-}2)$$

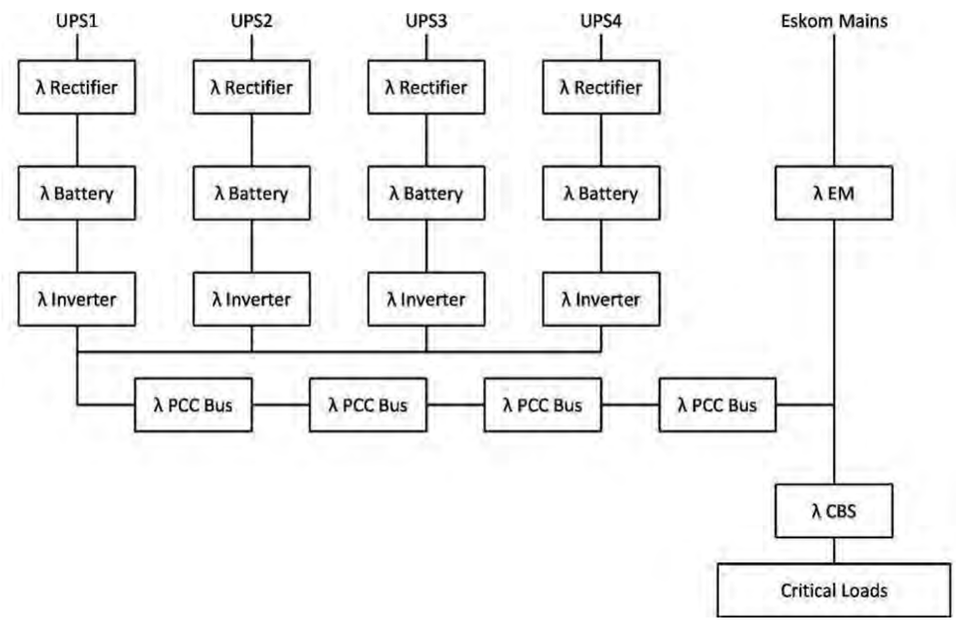


Figure 4.4.4: Reliability block diagram of facility's UPS system

Determination of MTBF for N+1 redundant parallel UPS system with common bypass switch is as per Equations 4.4.4-3, 4 & 5 below:

$$MTBF_{UPSS+PCC+CBS} = \frac{1}{\lambda_{UPSS+PCC+CBS}} \qquad (4.4.4\text{-}3)$$

$$\lambda_{UPSS} = \lambda_{UPS} // \lambda_{EM} = \frac{\lambda_{UPS} \times \lambda_{EM} \, (\mu_{UPS} + \mu_{EM})}{\mu_{UPS} \times \mu_{EM}} \qquad (4.4.4\text{-}4)$$

$$\lambda_{(N+1)UPSS+PCC+CBS} = (\lambda_{UPS1} // \lambda_{UPS2} \cdots // \lambda_{UPS(N+1)}) // \lambda_{EM} + (N+1)\lambda_{PCC} + \lambda_{CBS} \rightarrow$$

$$\lambda_{UPSS+PCC+CBS} = (\lambda_{UPS1} // \lambda_{UPS2} // \lambda_{UPS3} // \lambda_{UPS4}) // \lambda_{EM} + 4\lambda_{PCC} + \lambda_{CBS} \quad (4.4.4\text{-}5)$$

Where $MTBF_{UPSS+EM+PCC+CBS}$ is the mean-time-between-failures of the complete UPS system, $\lambda_{UPSS+EM+PCC+CBS}$ is the failure rate of the complete UPS system, the subscripts *CBS* is the acronym of "common bypass switch", *PCC* is the acronym of "point of common coupling", and *EM* is the acronym of "Eskom mains". As can be seen, an (N+1) parallel redundant system, like in this case study, has its reliability resting mainly on the reliability of the paralleling cubicle or point of common coupling viewed as the unique common section that will make the entire system fail. For example, take a yearly MTBF and MTTR for all four UPSs as 8640 and 176 hours, respectively. For a two-unit configuration in redundant-parallel connection, denoted by connecting the two UPS units in parallel, the intrinsic or inherent availability would, therefore, be given as per Equations 4.4.4-6, 7 & 8 below:

$$\lambda = \lambda_{UPS1} // \lambda_{UPS2} = \frac{\lambda_{UPS} \times \lambda_{EM} \, (\mu_{UPS} + \mu_{EM})}{\mu_{UPS} \times \mu_{EM}} = \frac{\lambda^2 \times 2\mu}{\mu^2} = \frac{2\lambda^2}{\mu} \quad (4.4.4\text{-}6)$$

$$MTBF = \frac{1}{\lambda} = \frac{\mu}{2\lambda^2} = \frac{\frac{1}{176}}{2 \times \left(\frac{1}{8640}\right)^2} = 212073.73 \text{ hours} \quad (4.4.4\text{-}7)$$

$$A = \frac{MTBF}{MTBF + MTTR} = \frac{212073.73}{212073.73 + 176} = 0.999 \quad (4.4.4\text{-}8)$$

For a two-unit configuration where both UPS units are required, denoted by connecting the two units in series, the intrinsic or inherent availability would, therefore, be given as per Equation 4.4.4-9 below:

$$A = \frac{MTBF}{MTBF + MTTR} = \frac{\left(\frac{1}{\frac{1}{8640} + \frac{1}{8640}}\right)}{\left(\frac{1}{\frac{1}{8640} + \frac{1}{8640}}\right) + 176} = \frac{4320}{4320 + 176} = 0.961 \quad (4.4.4\text{-}9)$$

From all the equations above, we can deduce that the system availability increases when increasing the reliability (MTBF) or reducing the maintainability (MTTR). The reliability could be increased by selecting a reliable UPS unit, derating the unit (operate the UPS unit below its designed capacity to reduce stresses), or implement system redundancy. But a redundant system comes at a cost. Depending on how this redundancy is designed, operational costs may increase. Risk analysis to support the decision between the incremental operational and downtime costs is, therefore, required.

The maintainability could be decreased by selecting an inherently more maintainable system or perhaps by improving diagnostics, training, or procedures (Joel & Eric, 2002:3-8; Neil, 2011b:1-6). Furthermore, a reduction in equipment, machinery, or system downtime through rapid interventions will improve availability. Availability is optimized through correct failure and repair history analysis, execution of detective maintenance, functional maintenance management structures. Consideration of aspects such as the system diagnostics, the accessibility of spare parts, the skills of maintenance-personal, the resources needed to repair the system, and the maintainability of the selected UPS are also key to that optimization. They are also included in the management of change (MOC) process to ensure due diligence is applied during the design phase. Failure analysis on a UPS system necessitates a built-in diagnostic coverage capability that comprises condition-based monitoring, performance indicators, management and measurement logics, troubleshooting guides, or remote support from service providers. Maintenance personnel access faulty components once the diagnostic coverage capability pinpoints the cause of failure. This accessibility is governed by system configuration and design. Difficulty in accessing some sections of a UPS system may render maintenance activities more strenuous when positioned in a constrained space, even if the UPS system is configured and designed to ease its maintainability. On the other end, although a UPS system possesses the utmost reliability features and diagnostic coverage capability and is designed and configured for facile access, this system will not be economically maintained if there are no competent personnel. The necessity to have competent and highly skilled personnel will, for sure, increase the cost of maintenance. Training costs will also increase if the facility was to upskill unskilled personnel. For this, the consequences or financial impact on the facility will go beyond the cost of actual repairs. Preferably, to reduce the training cost, the UPS system must be designed in such a way that maintenance personnel will only need a modest competency acquired through basic training. Their qualifications can fundamentally consist of electronic and electrical design principles, functional maintenance structure, testing, safe work practices, facility-specific operating procedures, system surveillance. Attainment of a cost-effective support structure is also hard if exclusive tools and testing devices are required to maintain the UPS system. Preferably, the only tools and testing devices needed are those available in the maintenance team workshop.

A considerable portion of the UPS system operating cost is determined by the budget allocated to maintaining it. If properly executed, maintenance will enhance the overall effectiveness or reliability of this UPS system. But improper execution of this maintenance will compromise its overall effectiveness and performance level. An optimal equipment design configuration with proper condition-based monitoring, performance indicators, system management, and self-diagnostic capability renders the UPS system inherently maintainable. Added aspects determining the maintainability of equipment are the presence of the overall equipment manufacturer (OEM), the manufacturer's local representative or third party in the country, the location of their repair centre or workshop, and the availability of spare parts. Repair of the UPS system through spare parts replacement depends on the rate these spare parts are procured, their estimated time of delivery, and obsolescence rate. The location of repair facilities is equally important because if located at a significant distance from the facility, lead time, transportation, and cost to procure parts may increase.

4.4.5 Scalability design performance

Scalability is an upgradable capability built into the UPS system to handle future capacity expansion to meet the facility's load demand. The achievement of this capacity expansion is without having to undergo major system reconfiguration or overhauling. Choice of a suitable and compatible UPS system, thus, rests on several well-thought-out aspects subjected to all requirements imposed by the facility. These aspects need to embrace equipment configuration and architecture, deliverables, system implementation and purchasing cost, safety performance and integrity level, equipment manufacturer's support structure, environmental impact, market availability, scalability, and maintainability. Concerning the design performance classification, the new UPS system needs to consider features and abilities it possesses against power disturbances, as elaborated in Section 4.2.4.

4.4.6 SUPS type selection

Numerous LIB-SUPS models can achieve compatibility with the existing RUPS system. Those models, amongst others, are Delta UPS – Ultron Family (DPS Series, DPS-1000K or DPS-1200K), Liebert® EXL S1 1000kVA or 1200kVA, Toshiba G9400 Series UPS 1050kVA, Legrand Keor XPE IOBM 1000 or IOBM 1200. All these models are compatible with lithium-ion batteries, but they all come with a common standard voltage of between 400V to 480V. In this research, the correctly sized UPS will need to have its input/output voltage well-matched with the 600V supply distribution of the existing RUPS system to eliminate the cost of a new power reticulation system. Eaton Power Xpert 9395P modular SUPS unit has an input/output voltage option of 600V/575V besides the standard voltage of 480V. For all reasons elaborated above, the study case selects Eaton Power Xpert 9395P modular SUPS brand. The system is a popular and well-known brand with a proven record of accomplishment and support structure in the country and worldwide. Its modularity feature lowers maintenance costs to unburden the facility economically. The system is easy to handle with minimum and not highly skilled personnel. With the facility running continuously throughout the year, it is imperative to have the availability of the UPS system be designed to at least be 98%, and the availability of the Eaton Power Xpert 9395P modular SUPS, according to manufacture specification, is at approximately 99%. The position of the new SUPS system would be to ensure that equipment accessibility for maintenance is easy.

CHAPTER FIVE
STATIC UPS DESIGN SPECIFICATIONS
(Model: Power Xpert 9395P, 1100kVA 600V, High-Performance)

5.1 Objective

This chapter ensures that components of the new LIB-SUPS system are correctly selected, all parameters correctly set, and project implementation adheres to all applicable safety and technical standards. Compliance with these standards assumes that the project team has implemented the management of change, risk assessment, and the design safety review process to their overall execution philosophy while maintaining adherence to all corporate standards and requirements. Decisions based on cost or flexibility requirements needed for the project's success must not compromise safety. The team must also ensure that all design variances be fully risk assessed and conformance decisions focusing on adequate risk mitigation and safety control measures be applied and maintained at all times.

5.2 The Power Xpert 9395P High-Performance SUPS

Technical specifications of the online, double-conversion, 3-phase, Power Xpert 9395P High-Performance LIB-SUPS selected for the application are detailed in Table 5.2.1, and the system reticulation is illustrated in Figure 5.2.1. This new LIB-SUPS system replaces the legacy LAB-RUPS system currently in use. It will operate in conjunction with or be retrofitted into the existing facility electrical system to provide conditioned and uninterruptable power to critical loads and processes. The system will consist of four 1100kVA SUPSs (each constituted of four UPMs rated at 275kVA per UPM), a number of cabinets or racks associated with each SUPS that house LIB battery modules, battery management systems (BMSs), maintenance bypass, and any other features specified. System implementation is expected to be safely executed with details of its management of change correctly followed. The system will undergo final checks and tests on wiring and system validation and certification before handing it over to the user. Project execution must be conducted per the project plan, schedule, and specifications, with the construction drawings package issued, the instructions of the facility's project lead, and the provisions of the facility's bill of materials stipulated. The project plan needs to indicate the estimated man-hours to ensure the shortest possible installation and smooth completion. A construction pack detailing a step-by-step guide for all tasks execution to completion will need to be prepared and provided (Eaton, 2019b:11).

Table 5.2.1: Eaton Power Xpert 9395P SUPS technical specifications (Appendix G; Eaton, 2019b:11)

General characteristics		
UPS rating (unit power factor 1.0)	1100 / 1100 kVA/kW	
Efficiency	- 99% in Energy Saver System (ESS) - Up to 96% (600V) in double-conversion	
Parallel capability	- 4 UPS units maximum for distributed bypass - 8 UPS units maximum with SBM	
Max modules per size	- Up to 2 modules, 300kW - Up to 3 modules, 600kW - Up to 4 modules, 900/1200kW	
Audible noise	75dBA @ 1 meter	
N+1 redundancy capable	Yes	
Field upgradeable	Yes	
Dimensions and weight 1100 kW/kVA	224"w x 34.4"d x 74"h	11550 lb (5239 kg)
Field upgrade module, 275kW	29"w x 34.4"d x 74"h	1037 lb (470 kg)
Input characteristics		
Voltage	600/575V	
Voltage range	+10% / -15%	
Frequency	45-65Hz	
Power factor	0.99 (minimum)	
Output characteristics		
Voltage	600/575V	
Regulation	+/- 1%	
Inverter	PWM with IGBT switching	
Voltage THD	< 2% (100% linear load); < 5% (non-linear load)	
Load power factor range	Up to .9 power factor leading without derating	
Battery		
Battery type	VRLA, AGM, wet cell, lithium-ion	
Battery voltage	480V	
Charging method	ABM technology or float, selectable	

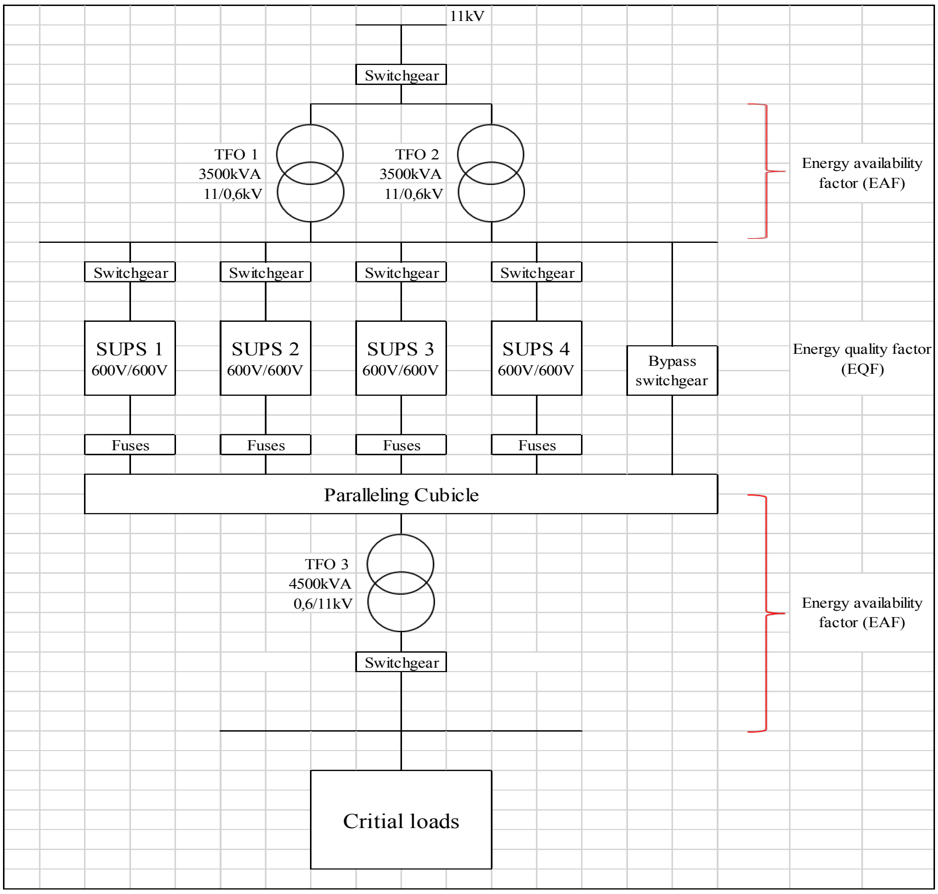


Figure 5.2.1: System with Eaton Xpert 9395P modular SUPS

The risk assessment on the N+1 configured UPS system, described in Table 5.2.2 below and referred to in Figure 5.2.1, will be based on four factors, namely, the energy availability factor (EAF), the energy quality factor (EQF), the impact of off-grid autonomy on the UPS system, and production.

Table 5.2.2: UPS system risk assessment on N+1 configuration

Factors	Risk rating	Comments
EQF	Low	Failure to one UPS unit will not affect supply capacity to critical loads and processes. The probability of more than one UPS unit failing at the same time is very low.
EAF	Low	Failure of one transformer will not affect supply capacity to critical loads. The probability of any transformer failing is very low due to their high reliability (bypass line can also be used). But the rate of load shedding and power interruptions from the local power utility might affect this risk rating.
Off-grid autonomy (UPS system)	Low	Good autonomy upon power utility interruptions sustained up to 20 minutes at rated load to allow the safe shutdown of assets.
Off-grid autonomy (production)	High	Production to stop for prolonged power utility interruptions.

5.2.1 SUPS system specification

The SUPS system must have the following main specifications:

- Approved manufacturers: Eaton.
- Model: Power Xpert 9395P High-Performance.
- Four Eaton Power Xpert 9395P SUPS, 1100kVA units configured in a parallel centralized bypass system where all four SUPS units connect through the existing parallel cubicle. The new SUPS system will use the current MBS installed in that parallel cubicle.
- Each SUPS has an input-output module, with no integrated bypass system installed, and will consist of four internal 275kVA UPMs and each UPM constituted by a rectifier, inverter, and section of the BESS.
- Each SUPS unit output disconnection and isolation must be done via the module's output breaker (MOB) equipped with auxiliary contacts for communication back to the global SUPS system.
- Strings of LIB in matching racks or cabinets are to be installed inside the existing facility's battery room.
- A push-button installed on the parallel cubicle or configured directly on the SUPS human-machine interface (HMI) initiates the transfer of critical loads from the SUPS system to a maintenance bypass line. When manually performed by an operator or support technician, this transfer of critical loads to the maintenance bypass line must first be checked by the inverter logic to authenticate the correct transfer sequence and operation. This migration request must be prohibited if the maintenance bypass line voltage and frequency are not within a specified range (+/- 10% of the rated SUPS system voltage) and (+/- 3Hz of the rated fundamental frequency), respectively. This migration request must also be prohibited if the maintenance bypass line voltage is not synchronized with SUPS output voltage or if an unmatched phase sequence between the maintenance bypass line and SUPS system's output is detected.
- The selected SUPS system uses a three-level, high-switching speed, pulse width modulated, insulated gate bipolar transistors (IGBTs) designed rectifier/charger. The modularity offered by the selected SUPS system has the advantage to allow harmless and rapid part exchange, component replacement, and ejection. It also reduces repair or downtime and increases maintainability.
- The rectifier is specified to operate at a power factor close to unity ($PF = 0.99 \approx 1$). This improved power factor has the added advantage of decreasing the total system input current to abate cables and switchgear size.
- The rectifier is designed to protect and stop insulated gate bipolar transistors (IGBTs) components from any overcurrent.
- The inverter is designed to still maintain a supply of conditioned output power within operational range to critical loads either during the normal operating condition

(conditioning power received from the utility mains) or backup condition (converting DC power received from BESS)

- The SUPS system is configured to detect and react to conditions such as the expiration of overload set time, the unspecified output voltage range condition, the system over-temperature condition, the excessive battery discharge condition, or the system defect or failure condition.
- The selected SUPS system offers the following controllability and condition-based management and monitoring features: HMI indicating operating conditions and statuses of the system; power map and statistic display; control, metering, setting, and status display; logs, major alarms, minor alarms display; and facility alarm management and display.
- The SUPS contain a BMS capable of offering the following design specifications. Firstly, it continuously indicates the remaining battery cell capacity, remaining battery cell life, and maximum run-time (exhibited in real-time) system can get out of that capacity at any load rate. This display is constantly retrievable by the operator or service technician whether the SUPS system operates at normal or battery backup operating mode. Secondly, the BMS is programmed to run a test on battery strings to guarantee capacity provision in excess of 80% of their rated capacity and detect any other abnormality (e.g. open-circuit or short-circuit condition) that might negatively affect the provision of this capacity. Normal operation of the SUPS system or its ability to supply critical loads is not interfered with when this scheduled battery testing takes effect. The BMS generates a warning alarm if any battery string is non-compliant with any system's pre-set testing parameters. Any events or incidents emanating from the BMS conducted test must be registered for failure analysis or failure mode investigation by service technician when required.

5.2.2 Key operational features

The selected SUPS system is of modular design. This modularity improves intrinsic redundancy. The system offers homogenous and diverse redundancy, produces less audible noise, dissipates less heat dissipation (reduced HVAC system and energy cost) during operation than the legacy RUPS system, and provides better controllability. In addition to the advantages specified above, the system also lowers the total cost of ownership (TCO), weighs less, has an improved output signal quality (use of IGBT technology), and provides more power in the same footprint than the existing RUPS system. Moreover, the SUPS system comprises factory-wired modules eliminating the costly exercise of having them site-wired and reducing the project planning time and execution costs. Furthermore, its 3-wire supply requirement reduces the amount of copper cable used in the installation, thus, reducing the initial project implementation costs.

Reduction in heat dissipation and, consequently, its HVAC system size reduces the overall operating costs and improves the overall system efficiency. The system also incorporates a digital signal processor (DSP), HMI control panel and uses an integrated communication server to enhance its performance. The UPS unit presents high-power flexibility to match the facility's future power demand requirements due to its field-installed UPM design capability. Furthermore, the newly selected Eaton Power Xpert 9395P High-Performance SUPS uses a double-conversion technology conducted on three levels. This topology reduces stresses and thermal losses on its major converting components (rectifier and inverter) by reducing the current flowing through them in normal operation. The three-level converter topology operates at less than 50% of the stress endured in traditional converters, thus, improving the overall SUPS system efficiency. Other electronic components have also been miniaturized and become less inefficient than in the case of traditional topology (Eaton, 2019b:3; Eaton, 2020b:1-18).

5.2.3 System operating mode

The Xpert 9395P High-Performance SUPS has the option to select between these two mutually exclusive features, the variable module management system (VMMS) and the energy saver system (ESS) mode:

5.2.3.1 VMMS operating mode

Referring to the efficiency curve, UPS runs more efficiently when they carry the load at above 50% of their fully designed capacity. Placing UPS in VMMS operating mode enables the UPS to manage its load distribution amongst its UPMs automatically. For a SUPS constituted with three identical UPMs, each loaded at only 30% and running at an inefficient region of their efficiency curve, the VMMS system will load one UPM at 90% and let other modules idling. The selected module thus runs at the best efficiency region of its efficiency curve, resulting in the enhancement of its energy efficiency and, consequently, the efficiency of the entire system (refer to Figure 5.2.3-1 and Figure 5.2.3-2). The same applies in multiple SUPS parallel operations, with the difference that the sharing of the load is now amongst SUPSs connected in parallel. For a parallel SUPS system constituted with 3 SUPSs operating as a traditional double-conversion and loaded at only 30% and running at an inefficient region of their efficiency curve, the VMMS system will instead load one SUPS at 90%. The selected SUPS thus at the best efficient zone of its efficiency curve, ending up optimizing its energy efficiency and, consequently, the efficiency of the entire parallel system. The functionality of all unused modules is not totally deferred but put in idling or standby mode. These deferred modules will be called upon a change in load requirements. The VMMS mode, therefore, squeezes up to 3% efficiency out of a SUPS system. The mode improves the overall system effectiveness and lowers the overall operational stress (Eaton, 2015:1 – 2; Neil, 2014:1-15).

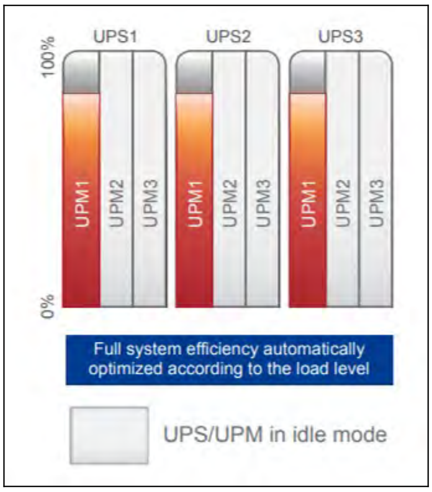


Figure 5.2.3-1: Eaton Xpert 9395P VMMS (Eaton, 2015:1 – 2)

5.2.3.2 ESS operating mode

Under-loading of SUPS system either caused by system redundancy requirements or initial over-scoping of the entire installation reduces the total-cost-of-ownership. As shown in Figure 5.2.3-2 and discussed above, the efficiency of the SUPS generally dips as load levels decrease (typically down to 20% load). However, ESS technology introduces a feature that uses an online/offline mode to operate at 99% efficiency even at low-load levels providing real energy savings, resulting in 99.999% overall availability of the SUPS when on that mode. The operation feature is such that, when a SUPS or multiple parallel SUPSs are in operation, ESS mode will let the utility power be supplied directly to critical loads through the integrated system static bypass switch. The transfer of critical loads to the SUPS system will be executed automatically only during the detection of an uncharacteristic condition in the utility power supply line (Eaton, 2019a:1-6; 2019b:4; Neil, 2014:1-15).

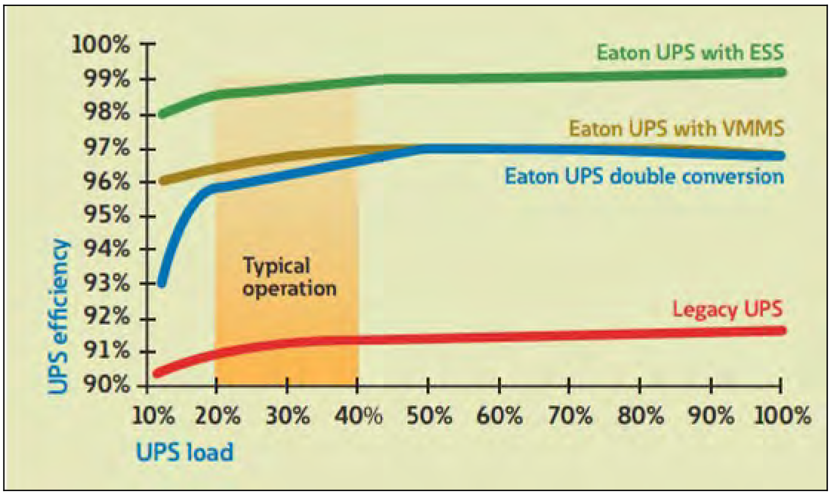


Figure 5.2.3-2: VMMS vs ESS mode - SUPS efficiency curves (Eaton, 2019b:4)

5.2.4 Easy capacity test

As illustrated in Figure 5.2.4, Eaton Power Xpert 9395P High-Performance SUPS has a built-in capability called 'easy capacity test' (ECT) that allows operators to conduct or simulate a full battery discharge and full load test without having to connect an external load. Each Eaton

SUPS unit is automated to process power in a revolving pattern, using its internal inverter and rectifier as a test load. This exclusive feature prevents wastage expenditures relating to time, cost, and power consumed during system implementation, conformity assessment, and validation processes compared with the traditional testing method (Eaton, 2019b:5).

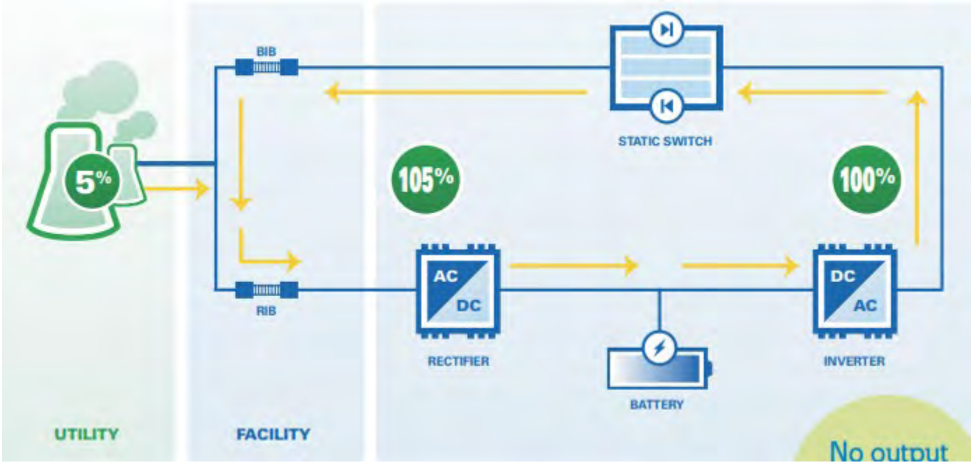


Figure 5.2.4: SUPS easy capacity test (Eaton, 2019b:5)

5.2.5 Inherent redundancy and scalability

UPSs are often under-loaded, frequently at less than 50% of their full load capacity. The VMMS operating feature offers the Eaton power Xpert 9395P High-Performance an inherent or built-in redundancy where UPMs are automatically set to an N+1 redundant mode when the load is below 50% of the total rated capacity. Inherent redundancy allows users to add redundancy into the SUPS system without actual change in the system. The modularity design of the Eaton Power Xpert 9395P High-Performance SUPS allows capacity to increase any time by simply adding a field-installed UPM (FI-UPM) to the existing SUPS. The amount of FI-UPMs can be specified so that capacity matches the facility's future growth. Redundancy is then maintained proportionally to the facility growth, and capacity is added when needed.

5.2.6 Service support and customer interface

The reliability of an effective SUPS system necessitates an impeccable support structure from the equipment manufacturer. Eaton acknowledges these needs and has since included key elements in their service level agreement to the Xpert 9395P High-Performance SUPS model. They offer 24 hours x 7 days a week full-year technical and service supports. This support includes installations, start-up, training, modifications, additions, software programming, engineering, repairs, spares. They also make use of a PredictPulse™ to offer condition-based monitoring and condition-based management capability where information is remotely gathered for analysis. Their SUPS units are factory-warrantied for twelve-month. For building alarm monitoring, the Xpert 9395P High-Performance SUPS system possesses five auxiliary I/O contacts where the facility's detector or sensing device feedbacks can be connected. These I/O will then be assigned to a specific alarm array of the SUPS system and allow it to monitor them. Another I/O contact is made available for connection to any building equipment at the facility, such as audible light, warning light, or trigger a warning siren.

5.2.7 System configuration

The new SUPS system will consist of four 1100kVA Eaton 9395P Four-UPM SUPS units configured in a centralized parallel configuration, as shown in Figure 5.2.7. The system configuration uses a common and centralized maintenance bypass switch where integrated bypass circuitry is not connected (Kevin & Victor, 2016:1-27).

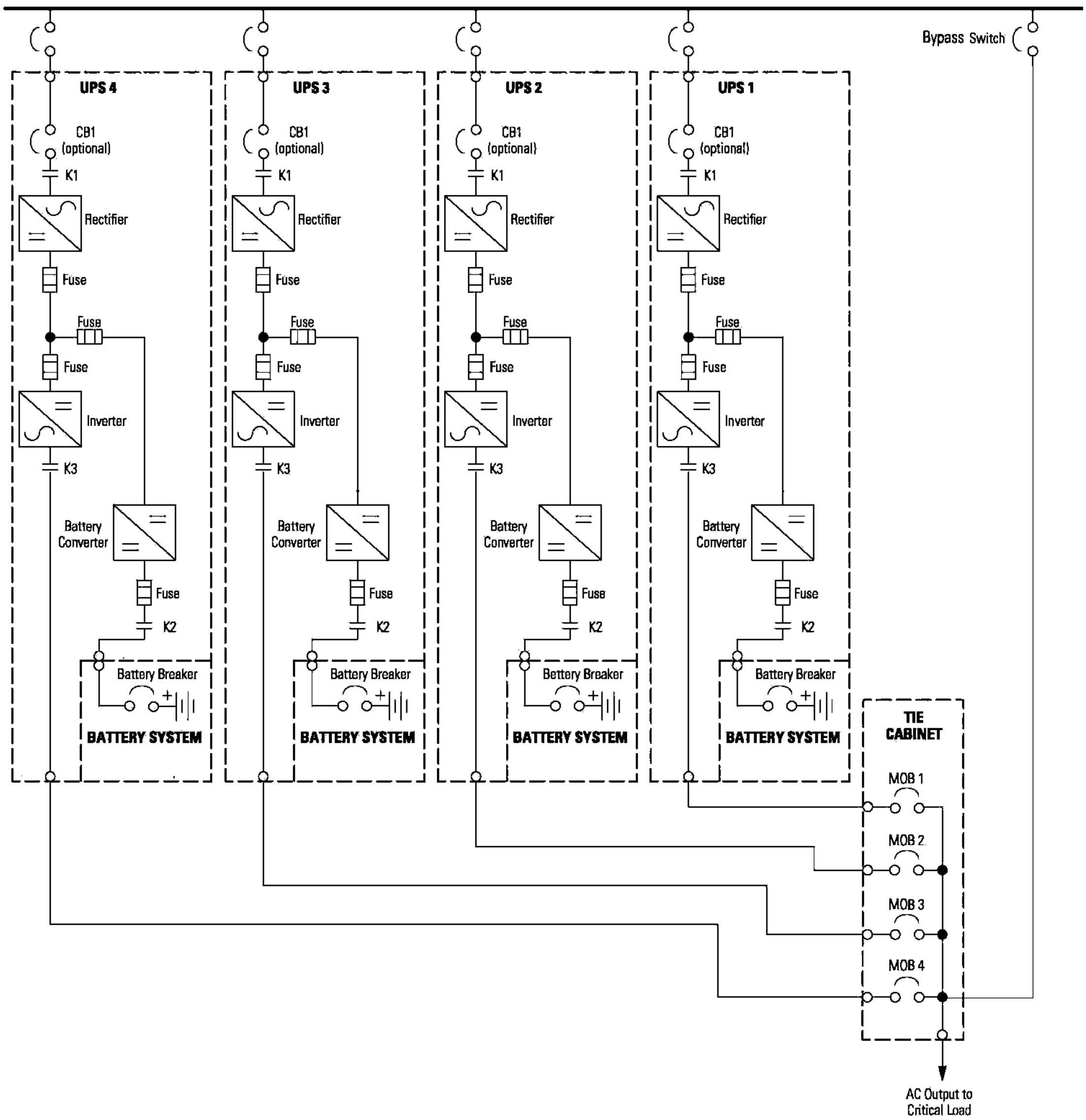


Figure 5.2.7: SUPS parallel system with centralized maintenance bypass

5.2.7.1 Centralized bypass system

The parallel configuration will have four SUPS units set to feed critical loads and processes via a single tie cabinet or parallel cubicle from the legacy RUPS, as shown in Figure 5.2.7 above. This parallel cubicle houses the centralized maintenance bypass switch (MBS). In this system, the four UPMs contained in each SUPS supply the output of the SUPS system. Multiple UPMs, 16 in total for the entire SUPS parallel system, are connected in parallel and tied together at the parallel cubicle to provide a load level greater than the nominal rating of one UPM. The paralleled UPMs will continue supplying the critical loads with protected and conditioned power as long as the downstream load level does not exceed the combined rating of the paralleled UPMs. The power system is redundant if one of the UPMs disconnects itself from the output bus. The remaining UPMs continue to supply power to the critical loads without exceeding their ratings. While the UPMs supply critical loads, the system output bus is continuously monitored for an over or under-voltage condition. If an out-of-limits condition is detected, the paralleled UPMs automatically transfer the critical loads to the bypass line. Communication is required between the SUPSs for system metering and mode control. System-level communication and control are accomplished using a controller area network (CAN). A single building alarm in each SUPS, connected to the other SUPSs in parallel and tied to the bypass contactor auxiliary contacts in each SUPS, is used for a secondary communication path. This arrangement ensures bypass control even if the CAN bus is lost.

5.2.7.2 SUPS system configuration features

The SUPS is constructed such that multiple internal UPMs can be combined and paralleled for redundancy and increased capacity. Through VMMS capability, the SUPS system is programmed and given an aptitude to identify the need to respond to capacity and redundancy issues paused by the variations in critical loads. The internal SUPS UPMs are programmed to function in a peer-to-peer model for accurate load distribution, improved tripping coordination and selectivity, and synchronization aptitudes. The SUPS system must exploit facility communication networks for its condition-based management and condition-based monitoring system. But the failure of this communication network must not affect its normal operation or functionality. The system must have the option to be inherently redundant when the load is less than 75% of the SUPS rated capacity. Under load conditions less than 75% of rated UPS capacity, at least one internal UPM must be redundant. VMMS feature of the Eaton Xpert 9395P High-Performance SUPS has the following configurable modes of operation selectable from the front panel:

- **Double-conversion mode**: Mode where the SUPS unit operates and supplies power to critical loads and processes through each of the power converters while providing equal load-share between all available UPMs.
- **Variable module management mode**: Mode where the unit operates in a traditional double-conversion configuration. However, the unit will place identified UPM(s) in idling but ready-state based on the number of UPMs required at a specific load rate. The total number of UPMs required can be calculated using Equation 5.2.7 below:

$$UPM_{required} = \frac{P_{UPS}(kVA)\,or\,System\,(kVA)}{P_{UPM}(kVA) \times VMMSLimit} + VMMSRedundancy \qquad (5.2.7)$$

- **High-alert mode:** This is the mode where all ready-state UPMs are active for 60 minutes (user adjustable). The SUPS functionality will then revert to VMMS mode once the 60 minutes period has lapsed. Reception of a new command during the first 60 minutes period will reset the timer and make it restarted its timing sequence.

The following result in the transfer of all ready state UPMs from VMMS to double-conversion mode: Any utility outage that results in the unit going to battery mode, any voltage variation greater than +/- 3 % on the output, any UPM that exceeds its current limit, any condition where SUPS or UPM load is greater than 80%, any initiation of the battery test, any battery charging requirement, and any UPM being serviced.

5.2.8 SUPS modes of operation

Each SUPS is a fully automated system functioning in the following modes:

5.2.8.1 Standard or normal operating mode

When the main utility supply is present, the inverter supply quality and conditioned power to critical loads at up to 97% efficiency while the rectifier maintains the charge on the BESS. This application places all four SUPS units preferably on VMMS operation mode and not on ESS mode. The modularity of the selected SUPS and its FI-UPM capability offers scalability options that allow the total system-rated capacity to be pushed up by a few kVA more.

5.2.8.2 Battery mode in parallel system configuration

SUPS units, 4 x 1100kVA online SUPS, must be capable of being paralleled to increase overall system power capacity to the facility's 4400kVA installed demand. The parallel system must have the intelligence to recognize the need for capacity increase automatically. The parallel SUPS system must utilize autonomous SUPS units that do not rely on any control interconnections for synchronized operation. The individual SUPS unit must operate in a peer-to-peer manner to provide automatic load sharing, synchronization, and selective tripping capabilities (master-slave configurations are not acceptable). The parallel SUPS system must utilize a communications network to provide system information and status, such as operating mode and meter data. This network must process information of each individual SUPS unit as well as information of the total system. Individual SUPS unit information must be available from any unit's front panel display or HMI. The loss of this system information network must not cause the parallel SUPS units to drop or transfer critical loads and processes to the bypass line.

The SUPS system will transfer critical loads to battery mode automatically when the utility power outage occurs or when the utility waveform does not conform to the SUPS system's specified parameters. The SUPS system inverter will instantly and seamlessly derive energy from the BESS to supply quality and conditioned power to these critical loads at up to 97% efficiency. The Eaton Power Xpert 9395P High-Performance SUPSs will sound an audible horn, illuminate a visual indicator lamp on the front panel to indicate an on-battery operation, and create an entry into the alarm event history. As the battery cells discharge, the boost converter and inverter constantly make minute adjustments to maintain a steady output. The SUPS system remains in this operating mode until the restoration of the utility power or the waveform input to the rectifier is again within the SUPS system's specified voltage or frequency acceptance windows. The BESS continues discharging until it reaches a cut-off voltage level if the input power fails to return or does not return within the required acceptance windows for normal operation. The cut-off stage is where the inverter output can no longer support the critical loads. During this event, SUPSs will issue a second set of audible and visual alarms to indicate a shutdown warning. Afterwards, paralleled UPMs will begin shutting down until there are no longer enough UPMs online to support critical loads. Upon the reinstatement of the mains supply line, in the case of a prolonged power interruption, the rectifier will automatically resume the supply of power to the battery charger and start the recharging process while synchronously supplying power to critical loads via the inverter. Rapid response time associated with this Eaton Power Xpert 9395P High-Performance SUPS ensures the uninterruptible transfer of critical loads upon power failure or power restoration.

5.2.8.3 Bypass operating mode

This bypass mode is achieved through a centralized or maintenance bypass circuit breaker installed in the paralleling cubicle as adopted from the existing RUPS system installation. To completely take the SUPS system out of service during a maintenance shutdown, the centralized bypass circuit breaker will be closed to transfer critical loads and processes to the main utility supply then proceed with the shutting down of SUPS units.

5.2.9 Environmental requirements

The selected SUPS system must endure external ecological situations while maintaining its operational performance or integrity level. The system operates between 5°C and 40°C. The storing temperature ranges between -25°C and 60°C, and the relative humidity (operational and storing) is between 5% and 95% maximum (non-condensing).

5.3 SUPS system ratings and operating characteristics

5.3.1 Rectifier/charger input

The rated input voltage to be 600VAC, 3-phase, 3-core + N + Earth (grounded wye source required). Regarding the acceptable input voltage deviation, +/- 10% maximum deviation to rated input voltage must be allowed without calling upon or discharging the battery backup system. For voltage tolerance at partial load, -30% of nominal voltage must be allowed without discharging the battery at loads less than 85%. The operating input frequency range must not exceed 50Hz +/- 5%. Table 5.3.1-1 details the corresponding UPS input specifications in compliance with NRS 048-2. Tables 5.3.1-2 & 3, respectively, detail the maximum voltage and frequency deviation as stipulated by NRS 048-2. The selected Eaton Power Xpert 9395P High-Performance SUPS unit has its input current parameters set to adjust rectifier input current from 100% to 115% of its rated full load current. The total harmonic distortion of its input current (THDi) does not exceed 5%, the power walk-in slope to full rated load is adjustable from 3 seconds to 1 minute, and the BESS charger current per SUPS unit is adjustable from 0A and up to 120A (Eaton, 2019a:10-1; NRS 048-2, 2003:12-14).

Table 5.3.1-1: UPS input specifications (Eaton, 2019a:10-1)

Operating Input Voltage	600 Vac and 575 Vac
Operating Input Frequency Range	50/60 Hz
Operating Input Current	See Table 3-6 for four UPM models. See Table 3-8 for three UPM models. Reduced for Generator Adjustable
Input Current Harmonic Content	3% THD at full load
Power Factor	Minimum 0.99
Line Surges	6 kV OC, 3 kA SC per ANSI 62.41 and IEC 801-4
Battery Voltage	480 Vdc
Battery Charging Capacity	Configurable per UPM at nominal line voltage: Up to 120A
Battery Shunt Trip	48 Vdc

Table 5.3.1-2: Maximum deviation from standard or declared voltages (NRS 048-2, 2003:12)

1	2
Voltage level V	**Limit** %
< 500	± 15
≥ 500	± 10

Table 5.3.1-3: Maximum deviation from standard frequency (NRS 048-2, 2003:14)

1	2
Network type	**Limit**
Grid	± 2,5% (± 1,25 Hz)
Island	± 5% (± 2,5 Hz)

5.3.2 Rectifier/charger output

The rated direct current voltage on BESS of the selected Eaton Power Xpert 9395P High-Performance SUPS is equal to 480V. The voltage regulation at steady-state condition is +/- 1%, and the acceptable peak-to-peak ripples on output voltage are less than 0.5%. The charger is designed and configured to incorporate a BMS to improve the battery cells' lifespan. The system has a redundant DC voltage detection for over-voltage protection on the BESS. The automatic shutdown of BESS is governed by the corresponding SUPS unit in relation to its loading and remaining capacity. The automatic disconnection of BESS by the corresponding SUPS unit is done via supply contactor to avoid an excess discharge that might originate from an extended power outage. The disconnection time and the minimum cut-off voltage are adjustable.

5.3.3 SUPS output in standard double-conversion mode

In standard double-conversion mode, the SUPS system has the specifications as illustrated below. Corresponding output specifications of the new Eaton Power Xpert 9395P High-Performance SUPS are detailed in Table 5.3.3 (Eaton, 2019a:10-2; Eaton, 2020b:1-18):

- 600V, 3-phase, 3-wire, and earth
- The steady-state inverter voltage regulation is equal to +/- 2% average from the rated output voltage. The transitory voltage response is compliant with SANS/IEC 62040-3 Class 1. The total harmonic distortion of its output voltage is less than 2% of its linear load harmonic distortion integrity at the corresponding full load. The total harmonic distortion of its output voltage is less than 5% of its non-linear load harmonic distortion integrity at full load. The output voltage is adjustable within +/- 0.03 rated voltage. The line synchronization range is +/- 3Hz adjustable at +/- 0.5Hz of rated frequency. The frequency regulation to be +/- 0.1Hz when not loaded. The frequency slew rate is adjustable up to 0.7Hz/sec.
- The phase angle control is +/- 1° from nominal 120° at a balanced linear load, and less than +/- 4° from average phase voltage at the full unbalanced linear load. The phase voltage control is +/- 1% from average phase voltage at balanced linear loads, and less than +/- 5% at a full unbalanced linear load
- Regarding the overload current capability at rated line capacity and fully charged battery, the Eaton Power Xpert 9395P High-Performance SUPS unit can operate with resistive/inductive load of 10% over its rated capacity for up to 600 seconds, 25% over its rated capacity for 30 seconds, and 50% its rated capacity for 10 seconds.
- Concerning the fault clearing current capability, Eaton Power Xpert 9395P High-Performance SUPS can carry 1000% of its root-mean-square (RMS) current value for

20ms and 600% of its RMS current value for 50ms with bypass intercession. The inverter can produce 350A RMS current per UPM (Each UPM rated 275kVA, 265A) for 10 cycles.

- Noise emitted by the Eaton Power Xpert 9395P High-Performance SUPS system under normal operating conditions is well below the specified maximum noise-rating limit of 85dBA a meter away from any operator standing point. As per OSH-Act (85 of 1993) and noise-induced hearing loss regulation, the maximum noise-rating limit can be defined as an 8-hour rating noise level, measured at ambient temperature, prone to cause hearing damage once reached or exceeded.
- The Eaton Power Xpert 9395P High-Performance SUPS has an electromagnetic compatibility (EMC) suppression that meets SANS/IEC 62040-2, Category C3. The system has an electrostatic discharge (ESD) that meets SANS/IEC 61000-4-2 level 3. It can achieve an efficiency of up to 97% while in double-conversion/VMMS mode and up to 100% in ESS operating mode.

Table 5.3.3: UPS output specifications (Eaton, 2019a:10-2)

UPS Output Capacity	100% rated current
Output Voltage Regulation	±1.5% (10% to 100% load)
Output Voltage Harmonic Content	1% maximum THD (linear load) 5% maximum THD (nonlinear load)
Output Current	See Table 3-6 for four UPM models. See Table 3-8 for three UPM models.
Output Voltage Balance	2.5% for 100% maximum load imbalance (linear load)
Output Voltage Phase Displacement	±4° for 100% maximum load imbalance (linear load)
Output Transients	Meets Class 1 IEC 62040-3 (10% to 100% load)
Frequency Regulation	±0.1 Hz free running
Synchronous to Bypass	+10% to -10%
Frequency Slew Rate	.7 Hz per second maximum
Load Compatibility	0.8 pF Leading 0.7 pF Lagging
Overload Capability (kVA or kW)	110% for 10 minutes 125% for 120 seconds 150% for 15 seconds

5.3.4 Uninterrupted power quality

The newly installed Eaton Power Xpert 9395P High-Performance SUPS system will need to ensure a continuous supply of electrical power to downstream critical systems while ironing any power disturbances and power quality events emanating from the main power utility. The design of the new SUPS system will size the SUPSs and BESSs to carry the full envisaged critical and their respective auxiliary loads. The redundancy approach is considered to the extent determined by the facility’s financial constraints. An allowance will be made to condition-based monitor the complete SUPS system both locally as well as remotely. The proposed solution will have to have full autonomy and enough capability to condition all NRS-048 defined imperfections and smooth any rapid voltage changes on the power utility network as illustrated in Table 5.3.4 below:

Table 5.3.4: Characterization of depth and duration of voltage dips (NRS 048-2, 2003:20)

1	2	3	4	5
Range of dip depth ΔU (expressed as a % of U_d)	**Range of residual voltage** U_r (expressed as a % of U_d)	**Duration** t		
		20 < t ≤ 150 ms	150 < t ≤ 600 ms	0,6 < t ≤ 3 s
$10 < \Delta U \leq 15$	$90 > U_r \geq 85$		Y	
$15 < \Delta U \leq 20$	$85 > U_r \geq 80$			Z1
$20 < \Delta U \leq 30$	$80 > U_r \geq 70$			
$30 < \Delta U \leq 40$	$70 > U_r \geq 60$	X1[a]	S	Z2
$40 < \Delta U \leq 60$	$60 > U_r \geq 40$	X2		
$60 < \Delta U \leq 100$	$40 > U_r \geq 0$	T		
NOTE In the case of measurements on LV systems it is acceptable to set the dip threshold at 0,85 pu.				
[a] A relatively large number of events fall into the X1 category. However, it is recognized that dips with complex characteristics (such as phase jump, UB, and multiple phases) might have a significant effect on customers' plant, even though these might be small in magnitude. Customers might not have the means to mitigate against the effects of such dips on their plant.				

5.4 SUPS system controls and indicators

5.4.1 Microprocessor-controlled circuitry and interface card

Microprocessor-controlled digital signal processing provides functional features to the SUPS system while offering complete automation of functionalities, eradication of tolerance discrepancies in components. It also delivers reliable and effective reaction to issues detected. The Microprocessor-controlled circuitry makes Eaton Power Xpert 9395P High-Performance SUPS parameters firmware-controlled, offers a system diagnostic capability that simplifies failure analysis, fault-finding process, and reliability-centred maintenance. The Eaton Power Xpert 9395P High-Performance SUPS system is also furnished with an interface card aimed to provide various signals and communication capabilities with its surroundings. The card is equipped with normally open (N/O) and normally closed (N/C) dry alarm contacts rated at 5A, 120Vac to connect permissive detection device from the SUPS system environment. The card is equipped with an RS232 and Ethernet communication port to communicate directly with the SUPS system for diagnostic, troubleshooting, and parameter setting. These communication ports are also very utile as they allow Eaton to make use of a PredictPulse™ to offer remote condition-based monitoring and condition-based management capability to the facility. The card is equipped with external auxiliary contacts to connect an external emergency or a remote-control pushbutton. The card is also equipped with battery control contacts to wire the BESS shunt trip and secondary signals from the BESS protection or isolating system.

The Eaton Power Xpert 9395P High-Performance SUPS is also provided with a Gateway card that permits the direct connection of the unit to the Ethernet network and the Internet. This built-in Web communication capability provides data exchange with numerous other SUPS in the centralised parallel system without requiring additional software. It can also be integrated into the facility's building and network management system (NMS). Remote monitoring of the SUPS system can, therefore, be achieved via standard communications devices. All noncompulsory hardware interfaces are hot-swappable, meaning they can be fit, changed, or replaced while the SUPS unit is in a full operating mode. The latter is executed without interfering with SUPS system capability to deliver conditioned and regulated power to critical loads and processes.

5.4.2 Human-machine interface

HMI displays are a communication medium that allows operators or technicians to dialogue with the machine. For the Eaton Power Xpert 9395P High-Performance SUPS, this HMI is 7 inches in size and has a digital colour touchscreen LCD. It plays a vital role in translating SUPS unit language to the language familiar to operators or technicians. Through programming, and as seen in Figures 5.4.2-1 & 2 below, this HMI can continuously be tailored or personalized to best suit the facility application. The HMI program can include animated statuses, display statistics and load profiles. It can also display functional parameters or data in real-time and the behavioural trend of critical components of the system. (Eaton, 2019a:7-3; Eaton, 2019b:9).

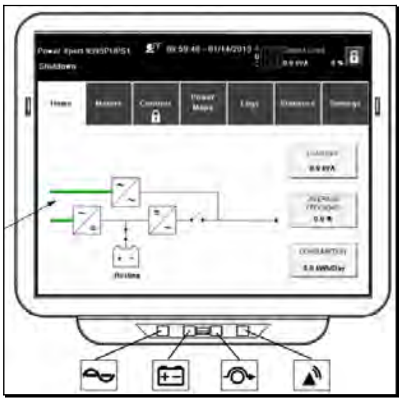


Figure 5.4.2-1: Power Xpert colour touchscreen control panel (Eaton, 2019a:7-3)

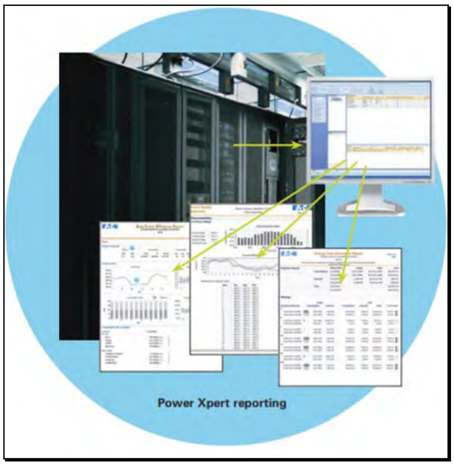


Figure 5.4.2-2: Power Xpert reporting (Eaton, 2019b:9)

5.4.2.1 Control panel's information

The Eaton Power Xpert 9395P High-Performance SUPS touchscreen LCD control panel has various pages described below programmed to display functions or information related to the unit. The home page displays the power map and data pertaining to the load and efficiency, indicates the power flow and the operating mode (online or bypass mode) of the local SUPS unit. The meters page displays the critical load's performance parameters of the local SUPS unit. When this page is selected, the HMI shows individual screens of input parameters, output parameters, voltage, current, and frequency in a graphical format. In addition, the meters and remaining runtime of the local SUPS, BESS and SUPSs in the centralized parallel system can also be viewed. The controls page lets operators select any operating mode required from the SUPS system, and individual UPMs can also be controlled through this screen. The power-maps page shows the power flow of the SUPS system via any SUPS power-map and the power flow of the UPM through the SUPS module-map. The system overview also displays the entire system and can access any SUPS unit information from a specific local SUPS. The logs page displays the functional performance incidents history of a pre-determined length that occurred through a pre-determined period. These logs are time-stamped, include a detailed sequence of events, description, source, type, and proposed solution, and can be extracted as a report by the operating team for further analysis. The BESS log possesses the total battery operation mode duration, runtime, average-time, and total-time-on-battery for each SUPS unit. The 'statistics page' summarizes the time on various modes for the current month, prior month, and since the last reset. These stats include online, online VMMS, on-bypass, and on-battery modes. The settings page allows configuration of the SUPS unit including, meter format, VMMS configuration, backlight adjustments, screen contrast, communication ports, and exhibition of control panel's firmware version, IP address, subnet mask, gateway. The status bar page displays the SUPS unit allocated name, date/time, running alarms, output and bus voltage, synchronization angle between SUPS output and bus, frequency, and remaining BESS capacity. Two interactive buttons on the status bar allow for language changes and passcode input.

5.5 SUPS system power distribution reticulation

The new SUPS system has a single 600V output combined at the paralleling cubicle and supplying a 4.5MVA step-up transformer that steps up the 600V voltage level from the paralleling cubicle of the SUPS system to 11kV. This transformer feeds the low voltage switch gears that, in turn, supply downstream critical loads and processes connected to it. The selection of the new SUPS system is made for equal power requirement as the redundant RUPS system. The project will maintain the following components from the existing installation to reduce the installation cost as they will be enough to accommodate the new SUPS system: Low voltage power distribution equipment, feeding panels, paralleling cubicle, external bypass system, circuit breaker (including the protection and coordination systems), the medium voltage switch gears and fuses. Some protection components might require setting adjustment.

5.5.1 SUPS unit protection

Fuses will protect battery charger and rectifier circuits. Inline thermal and magnetic moulded-case circuit breakers are used to protect the BESS. The inverter output circuit is protected by electronic current limiting circuitry and fuses.

5.5.2 Cabling and wiring

Existing main power cables and wireways will be maintained and used for the new SUPS system installation. Appropriate types of cables have already been selected based on the existing installation. All these cables have already been sized considering factors such as maximum continuous current, ambient temperature, grouping proximity, installation medium, 5% voltage drop limitations, and short circuit withstand criteria. Any new cables and wiring required must comply with the above specifications and all applicable standards.

5.5.3 Earthing and bonding

The earthing for the new SUPS system should be extended from the existing facility's earthing system. The earth busbar must be provided at various areas where all electrical pieces of machinery are installed. The bonding will bring all the bonded parts to the same electrical potential. The following must be earthed/bonded: The star points of the secondary winding of transformers, the earthing terminals of all permanently connected electrical equipment, instrument signal, system equipment, shielding to eliminates the radio frequency interference (RFI), noise and noise reduction systems, and all metal parts of roofs, gutters, and downpipes.

5.5.4 Equipment naming guide

The existing installation presents a huge ambiguity with regard to equipment recognition during maintenance or troubleshooting. This guide addresses this issue by adopting a proper naming convention to be used for this project. The list of equipment subjected to this naming convention will include substations, UPSs, distribution boards (DBs), Sub-DBs, cables, and busses. This naming convention must be standardized in this new project and later can become a new standard to use throughout the facility. The equipment's name must be displayed on the relevant equipment and reflected in the corresponding SLDs. It is the responsibility of the project team to ensure that this guide is followed and implemented.

5.5.4.1 Guidance for process implementation

The equipment naming will be implemented as follow. The substation that houses MV equipment will be named MV01-S/S, and any subsequent or future substations housing various other MV equipment must follow on from that (MV02-S/S, MV03-S/S, etc.). The substation that houses LV equipment will be named LV01-S/S, and any subsequent or future substations housing various other LV equipment must follow on from that (LV02-S/S, LV03-S/S, etc.). The substations that house emergency generators or related equipment will be named ES01-S/S, and any subsequent or future substations housing various other emergency equipment must follow on from that (ES02-S/S, ES03-S/S, etc.). The main distribution board inside an LV substation will be named MDB01, and all subsequent MDBs will follow from that numbering system (MDB02, MDB03, etc.). A distribution board that feeds directly from MDB01 must be named DB01, and a sub DB that supplies from a DB01 will be named SDB01-01. The numeral in the name will reference the supplying DB, and the second will be its unique number allocated sequentially (SDB01-02, SDB01-03, etc.). The Main DB fed from a standby generator will be named MEDB01, and all subsequent MEDBs will sequentially follow on from that numbering system (MEDB02, MEDB03, etc.). The Main DB fed from the SUPS unit will be named UPS-MDB01, and all subsequent UPS-MDBs will sequentially follow on from that numbering system (UPS-MDB02, UPS-MDB03, etc.). The DB that feeds from MEDB01 will be named EDB01. The numeral in the name will reference the DB adjacent to it (EDB02 if situated next to DB02, etc.). Circuit breakers in the main DB will be named Q01. The numeral will increase sequentially in the DB but reset to '01' in a new DB. To make the reference unique on the SLD, the DB in which the circuit breaker is installed will be referenced, i.e. MDB02-Q03, UPS-MDB02-Q18, MEDB01-Q20, etc. Circuit breakers in any other DB will be named starting at CB01. The numeral will increase sequentially in the DB but reset to '0'1 in a new DB. To make the reference unique in the SLD, the DB in which the circuit breaker is installed will be referenced, i.e. SDB02-01-CB03, EDB01-CB01, DB20-CB13, etc. Name tags on power cables will differ from the label in the SLD. In the field, the nametag will describe both terminations of the cable, i.e. C14-DB25-SDB25-02, to indicate 'Cable 14' which, terminates between DB25 and SDB25-02. This extra information is omitted in the SLD to reduce clutter. The cable will only be named 'CAB14' as the termination points will be clear from the SLD. The numeral will reference from the SLD, and it will be assigned sequentially.

5.6 Construction management

5.6.1 Electrical installation works

With regard to the management of the contractor's works and activities undertaken throughout this project, the following points need to be taken into consideration:

a) The contractor should supply a detailed on-job method statement detailing the order of works, activities, and any power outages envisaged. The contractor makes all applications to the local utility supplier related to the upgrade on behalf of the facility. The contractor must plan to have an authorized person to accomplish the required high voltage switching operations. A switching plan detailing which sections will go off and the duration of expected outages must be submitted to the facility.

b) All new SUPS units must be positioned, levelled, and correctly fixed into place. All cabling, including auxiliary wirings for communications, between SUPSs, BESSs, and MV switch gears are to be done by the contractor, and they should be correctly terminated and labelled on both sides. Phase conductors must be appropriately sized to the envisaged load and fault level with a full-sized neutral conductor and connection to the existing earthing system to be determined and investigated. The new SUPSs, BESSs, MV cables from the feeder to the new SUPSs and BESSs, busbars, and existing switch gears must be tested and commissioned per the manufacture's specifications and all applicable standards as illustrated in Section 5.6.3. The contractor has the responsibility to determine the protection settings, arc rating for the MV and LV switch gears. The contractor must submit a detailed commissioning program indicating all tests to be performed and their execution time. At the end of the project, the contractor will present all compliance certificates, test certificates, machinery documents, as-built drawings, and approval documents to the facility.

c) The contractor is responsible for the removal and disposal of the existing RUPSs and LA-BESSs. He is also responsible for the installation of the new SUPS and LI-BESSs. Fire-rated or firestop materials are used to seal any cable trays or cables penetrations holes.

5.6.2 Quality assurance and safety

A safety file from the principal contractor in terms of the Occupational Health and Safety Act, 1993 (Act 85 of 1993) is required before carrying out any work. All contractor staff must have undergone safety induction training and medically tested for the type of installation work. All personal protective equipment (hardhats, safety shoes, overall, arc-rated PPE when switching) required on the construction site must be issued. A qualified first aider and foreman whose skills are aligned with site and project requirements need to be deployed. They will be on-site for the duration of the project. A contract manager will need to be appointed to liaise with the facility, resolve any potential problems that might occur, monitor all the safety aspects of the project, and ensure that all work is carried out in accordance with both the facility and manufacture's recommendations. The contractor's workmanship must comply with regulations and standards that apply to the project and ensure considerable time is spent in housekeeping.

5.6.3 Applicable standards

All work undertaken should comply with local requirements and standards. The equipment, materials, and system implementation must comply with the latest SANS and IEC applicable specifications; unless specified otherwise. Design evaluation, system commissioning, functionality testing, and validation post the installation must comply with the latest specification stipulated by standards below:

- SANS 10142-1: The wiring of premises – Low-voltage installations
- SANS 10142-2: The wiring of premises – Medium-voltage installations
- SANS 10198: The selection, Handling & installation of electric power cables of rating not exceeding 33 kV
- NRS048: Electricity supply - Quality of supply
- SANS 984: IEEE guide for performing arc-flash hazard calculation
- SANS/IEC 60439: Low-voltage switchgear and control gear assemblies
- SANS/IEC 60947-4: Low-voltage switchgear and control gear
- SANS/IEC 62040-2: Uninterruptible power systems (UPS) Part 2: Electromagnetic compatibility (EMC) requirements
- SANS/IEC 62040-3: Uninterruptible power systems (UPS) Part 3: Method of specifying the performance and test requirements
- SANS/IEC 61000-4-2: Electromagnetic compatibility (EMC) Part 4-2: Testing and measurement techniques - Electrostatic discharge immunity test

5.7 Mechanical specifications

Figure 5.7-1 represents the overall Eaton Power Xpert 9395P High-Performance SUPS unit dimensions for both front and side view. Figure 5.7-2 illustrates the typical SUPS parallel system layout where line 1 is the utility power input to SUPS and line 2 is the CAN Network. Figure 5.7-3, on the other end, details a not-to-scale (NTS) top view of the proposed SUPS system layout.

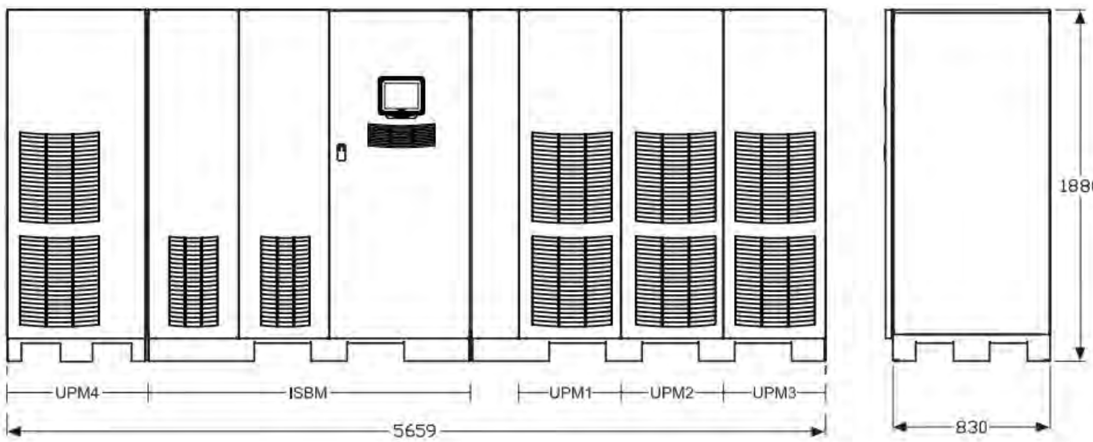


Figure 5.7-1: SUPS cabinet dimensions - Front and side view (Eaton Corporation)

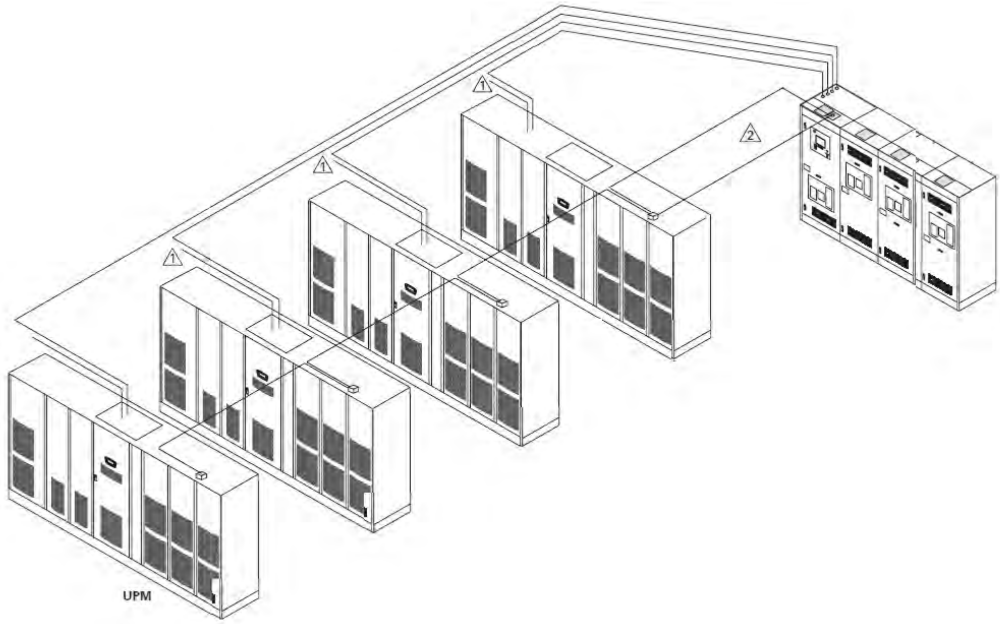


Figure 5.7-2: Typical SUPS parallel system layout (Eaton Corporation)

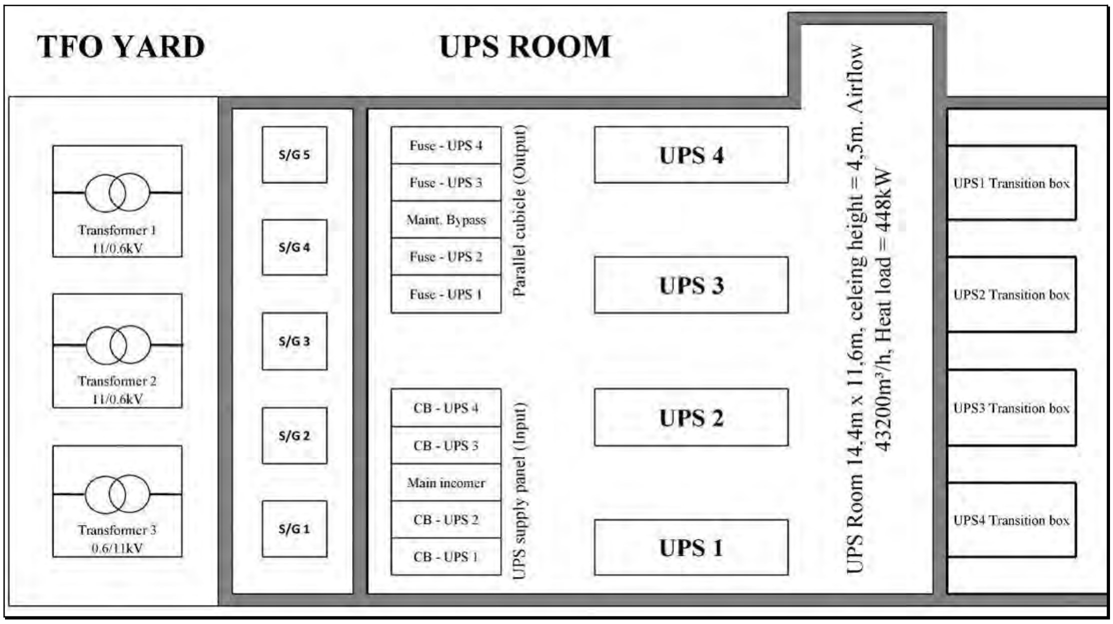


Figure 5.7-3: Current UPS parallel system layout - Top view (NTS)

5.7.1 Mechanical design

With regard to the ventilation, the SUPS system and UPS room must be of forced-air cooling design as specified in Table 5.7.1 below. The inlet of cool air is from the front side of the unit. The hot air exhausts from the top of the SUPS unit. The hot air dissipates into the environment through the roof in the same fashion as the existing RUPS. With regard to cable access, the Eaton Power Xpert 9395P High-Performance SUPS is designed such that incoming cables enter the enclosure from the top and outgoing leave from the bottom of the SUPS enclosure. Devoted cable trays or trunkings for running auxiliary I/O wirings can be supplied and installed inside the wiring cabinet. Concerning the component replacement access, all incorporated assembly components that can be repaired or overhauled are modular and front accessed with hot-swappable built-in capability to undergo planned-component-replacement process even while the SUPS unit is in operation. From the Eaton Power Xpert 9395P High-Performance SUPS cabinet design, the ejection of these components is executed from the front only. And concerning service or installation area requirements, the Eaton Power Xpert 9395P High-Performance SUPS unit requires at least 1m of front service access room but not requiring side or rear access. The existing UPS room, battery room, and switchgear will be maintained and used to accommodate the new SUPS system (Eaton, 2019a:3-4).

Table 5.7.1: SUPS ventilation requirements during full-load operation (Eaton, 2019a:3-4)

Model	Rating	Input/Output Voltage	Heat Rejection kW (1000 BTU/hr)	Ventilation Required for Cooling Air Exhaust
Eaton 9395P-1100/1100 (CSS or IOM)	1100 kVA 1100 kW	575/575 600/600	61 [207500] 61 [207500]	Approximately 4250 liter/sec (9000 CFM)
Eaton 9395P-1100/1000 (CSS or IOM)	1000 kVA 1000 kW	575/575 600/600	56 [188700] 56 [188700]	
Eaton 9395P-1100/825 (CSS)	825kVA 825 kW	575/575 600/600	46 [155600] 46 [155600]	Approximately 3300 liter/sec (7000 CFM)
Eaton 9395P-1100/750 (CSS)	750 kVA 750 kW	575/575 600/600	41 [138700] 41 [138700]	
Eaton 9395P-1100/675 (CSS)	675 kVA 675 kW	575/575 600/600	38 [127400] 38 [127400]	
NOTE CSS = Continuous Static Switch; IOM = Input Output Module				

5.7.2 Mechanical installation

The SUPS system implementation must follow the guiding principle that the SUPS units are placed and anchored on the suitably levelled floor capable of supporting the exerted mechanical loading. The UPS room has been designed to prevent the ingress of any debris and has its internal humidity and temperature fully monitored and controlled.

5.7.3 SUPS footprint and floor loading

Length of the SUPS unit = 5.659m

Width of the SUPS unit = 0.873m

Height of the SUPS unit = 1.88m

Surface area occupied by the SUPS unit = 5.659 x 0.83 = 4.94m²

The total area occupied by all four SUPS units = 4.94 x 4 = 19.76m²

Weight of each SUPS unit = 5239kg

The total weight of all four SUPS units = 5239 x 4 = 20956kg

5.8 SUPS system commissioning

The motive to have an electrical system commissioned is to conduct a static and dynamic process checkout of all components through a well-determined checkout guide to ensure normal prospective functionality. It is also to have initial system configuration data developed comparable with future test results to identify equipment deterioration. The new SUPS system is initially checked for damage, deterioration and component failures using a well-defined check, inspections, and test procedures as defined by the equipment manufacturer. The interconnection of system components should also be checked using de-energized and energized methods to verify for proper incorporation of the assembly and functionality of on-off control, system process interlocks, and protective relaying functions. The system is energized, operationally tested, and measurements performed after the above tests and inspections.

All steps and results of all testing processes should be carefully reviewed, documented, and later used as a comparative baseline for future test results. The commissioning of any electrical system uses dangerously high tensions and currents. These high electrical energies are susceptible to cause danger of electrocutions to personnel performing the tests or to others who are exposed to the hazard. Safe work practice and safety measures, established and laid out in the management of change (MOC), must be followed to prevent such injury. Test procedures should also be designed to ensure that no intentional damage to commissioned equipment or electrical system will result from any testing process.

5.8.1 Static SUPS system test

The newly installed SUPS system must undergo a visual inspection to check its compliance to applicable standards, facility requirements, agreed design principles, system architecture and identify any safety hazards. Things to check are any loose parts, insulation damage, proper settings, components damage and cleanliness, insulators cracking, components nameplates, mechanical installation, alignment of hardware, interlocking, possible mistakes in the wiring. The termination of each cable, shown on the cable block and wiring diagrams, should be checked to ensure each conductor matches the wiring and schematic diagrams. A visual inspection of each connection, wire number, colour, terminal, and checking point-to-point continuity or ringing-out each wire from end to end, including grounds, should be conducted.

5.8.2 Dynamic SUPS system test

A sequential energization of each component of the SUPS system from the input through to the output takes place after visual and electrical wiring inspections. All hardware logic, controllability functions, system interlocking, system protection, and alarms are tuned as the individual component is powered up. At each stage, voltage, phasing, phase rotation, and current must be measured and recorded as the load is linearly increased to a nominal rating. Following the discussion in Section 5.2.4, the commissioning of the Eaton Power Xpert 9395P High-Performance SUPS is made easier through its ECT capability programmed to process power in a recirculating pattern, using its rectifiers and inverters as an internal load bank. This functionality allows users to perform a full-load test and full battery discharge test without the connection of a load bank.

5.9 SUPS system maintenance procedures

Periodic or preventive maintenance is needed to maintain the performance integrity level and improve the lifespan of the SUPS system. Even though electronically constructed components often do not experience physical wear and tears in the same grade as electromechanical components, they also need to be included in the maintenance scheduled program. Some scheduled tasks in the preventive maintenance may necessitate that the SUPS system be completely halted and put out of service for a while. The facility has its general maintenance structure guided by the existing RUPS system repair history, failure analysis, or functional maintenance structure. Although all this maintenance structure exists, reference to the overall equipment manufacturers (OEM) user manual is essential as it stipulates proficient maintenance, troubleshooting, and diagnostics guiding principle. The facility must ensure that any person performing these maintenance tasks demonstrates that he/she has been trained, has knowledge and experience related to specific equipment.

5.9.1 Detailed maintenance specifications

Preventative maintenance on the SUPS system will involve checking the electrical installation, operating environment, controlled start-up, and testing as per the following specifications:

1) Perform a visual inspection of the SUPS system for any damage, ingress of dust, or liquids, and every SUPS unit for tightness and condition of all its terminals connections.
2) Conduct a full SUPS system functionality test to determine if the system still complying with its designed performance level. It is important to note that, full functionality test of the SUPS system includes bypass operations or transfer of critical loads from the SUPS system to the utility main supply and operation of all its associated switch gears. Check the overall functioning of each SUPS unit, UPMs, inverters, rectifiers, charging equipment, BESS; perform a simulation of a power outage to prove automatic bypass functionality. Perform a complete operational test of the SUPS+BESS system to determine system functionality and monitor battery-rundown test to determine battery strings or cells health condition. Conduct functional performance test of the UPMs (load, unload, and load sharing test) to determine their integrity. Conduct parameters-based performance tests to determine their controllability. Measure, record, and analyse all test results and measurements (current, voltage, frequencies, and battery float charging and ripple current, rectifier charger output current and voltage) corresponding to each testing phase.
3) Check and review event logs and operations alarms. Clear, correct, adjust alarms activation level or range where necessary. Inspect protective device settings, calibrate measuring equipment, and calibrate transducers (detection limits, mission time, response time, demand rate, test rate).

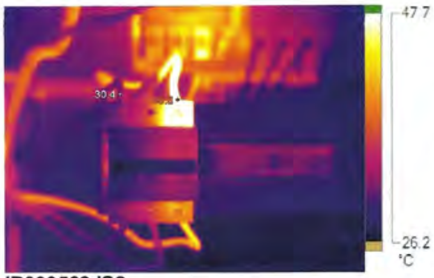
4) Check functionality of air ventilation system and confirm temperature inside the machine room, and ensure that air circulation within the SUPSs' enclosures is maintained, replace any air filter elements in the SUPS enclosure as required.

5.9.2 Thermographic testing survey

Over time, even under normal operating conditions, equipment's terminal connections can become loose as the rate of currents flowing through them and temperatures (causing expansion and contraction of terminals) around them continuously vary. Loose connections introduce high-resistance points in the circuit that resist the flow of electric currents. This phenomenon then produces heat and causes thermal energy loss. Other phenomena such as bearing failure, blocked cooling vents, phase unbalance are also prone to cause thermal energy loss in any electrical systems drawing, supplying, transforming, converting, or storing electrical energy. Because thermographic testing is the measurement process used to depict these hot spots, it is needed to be structured as part of the preventative maintenance schedule. An infrared thermometer is a contact-free thermal imaging device used to measure the surface temperature of in-service electrical equipment without touching or disturbing the functionality of that equipment. The detected images can easily be exhibited, printed, or placed in a user-friendly format. When conducting a thermographic survey, the background temperature around specific equipment or machinery is considered a reference. Any intensifications of temperature from this background temperature will designate a poor connection or current resistant point. Faults classification base on the temperature difference between the exception and the reference, as shown in Table 5.9.2. This standard derives from experience, both locally and abroad. It is recognized by all principal thermal inspection authorities worldwide. ANSI/NETA ATS-2017 and MIL-STD-2194 (SH) states guidelines, procedures, and specifications.

Table 5.9.2 below shows an example of a thermal imaging report. The background or ambient temperature is the room and or atmospheric temperature. The spot temperature is the maximum temperature of the region of interest located on the thermal profile, ΔT is the delta difference between reference and spot temperatures. The 'target distance' is the distance from the object when measuring temperature data (critical when the spot size becomes part of the equation). 'Emissivity' is the ability of the measured object to emit radiant thermal energy (1 = perfect blackbody or perfect emitter). Materials having an emissivity value less than 0.6 act as thermal mirrors and are difficult to measure accurately.

Table 5.9.2: Thermal imaging report



IR000563.IS2
11/30/2011 10:34:02 AM

LV ROOM – OLD GENSET PANEL

Image Info

Background temperature	23.5°C
Emissivity	0.95
Camera serial number	Fluke Ti32-10070196
Lens description	Standard
Image Time	11/30/2011 10:34:02 AM

Main Image Markers

Name	Temperature	Emissivity
Hot	46.8°C	0.95
P0	30.4°C	0.95

PRIORITY / FAULT CLASSIFICATION

PRIORITY	DESCRIPTION	COMMENT	DELTA T in Deg C
1	CRITICAL	IMMEDIATE REPAIR NECESSARY	> 75
2	SERIOUS	URGENT REPAIR	35 to 75
3	INTERMEDIATE	REPAIR WHEN POSSIBLE	10 to 35
4	MINOR	MAINTENANCE REPAIRS	1 to 10
5	NORMAL	NO REPAIR	0

5.10 Summary

The newly selected Eaton Power Xpert 9395P High-Performance SUPS is built on a reliable reputation that offers up to 20% more power than the existing Piller UB1100S RUPS. The system reaches an efficiency of up to 97% from a load as low as 20% of its full load. Unlike conventional converter technology used by the legacy Piller UB1100S RUPS making use of SCRs, the Eaton Power Xpert 9395P High-Performance SUPS uses a three-level converter technology making use of IGBTs. This SUPS topology operates its major converting elements (rectifier and inverter) at less than 50% stress compared to the traditional RUPS system. Component stress being directly proportional to the current flowing through these components, its reduction decreases the electrical energy lost and, consequently, improves the overall SUPS system efficiency.

Scalability in the RUPS system is achieved only by supplementing a new RUPS unit, thus limiting its flexibility to adapt to future variations in the facility's load demand. Its initial design size is normally pre-escalated by 20% or more, facility-dependent, to cater to the envisaged facility's future growth. This pre-escalation increases the initial capital investment of a RUPS system compared to the SUPS system. In contrast, the SUPS system is scalable and flexible given its available capacity from FI-UPMs. Therefore, the facility can select a SUPS system with an installed capacity closer to critical load requirements without worrying about future variations. This matching-size strategy enables the facility to pay-as-you-grow and adapts to its future expansions. While the RUPS system uses only a standard redundancy mode, the current SUPS system has introduced ESS and VMMS features. This design adopts the VMMS operating mode for SUPSs. In this mode, the units operate in traditional double-conversion, automatically placing identified UPM(s) in the ready state based on the number of UPMs required to support current facility loading to enhance system efficiency even at a low load rate. The SUPS technology has developed and improved its flexibility, availability, and modularity. The system has reduced repair time, eased maintenance and component replacement, offered space-saving, and improved redundancy, scalability, and upgradeability.

Electromechanical machinery necessitates higher maintenance than power electronic machinery to guarantee a certain level of availability. Some of the routine maintenance tasks required to be performed in electromechanical machinery such as the RUPS system involve, for example bearing temperature monitoring and lubrication which (done frequently), RUPS system maintenance (done yearly), and bearing replacement (done 5-yearly).

On the other end, the SUPS system is typically as well subjected to annual scheduled maintenance. It also requires investments, but this investment is minimal compared to the one allocated to the RUPS system. The number of installed RUPS systems around the world is less compared to SUPS systems. This statement is founded on the installed base evaluation data around the world. The number of site service or field-support entities available out there is also directly proportional to the types of systems installed. The high number of installed SUPS systems had drastically increased the robustness of their site service or field-support system. Maintaining a SUPS system, to some extent, presents no difficulty due to the modularity construction of its components. These components have self-diagnostic capabilities, are hot-swappable, and can be easily replaced or exchanged. In the case of a RUPS system, the motor-generator block weighs about 7tones making their handling very difficult and requires bearing replacement every 5years with mean-time to repair ranging from 24 to 36 hours. This task requires a stringent and well-elaborated plan to be executed safely and necessitates a higher workforce due to the number of personnel allocated.

Due to electromechanics components (motor, generator, and transformers) and SCRs used, the RUPS system generates more heat than the SUPS system. UPS system must operate at a daily average of 35°C. A required relative humidity limit is also required to be controlled and maintained in the room to avoid degradation of equipment's insulation resistances and their premature failure. A controlled passive ventilation system is installed to provide temperature and humidity control and maintain them within specified limits. A thermostatically controlled heater is installed to prevent condensation from damaging the unit by degrading the insulation resistances of its components during cold climates and when the UPS system is not operating.

CHAPTER SIX
LITHIUM-ION BATTERY ENERGY STORAGE SYSTEM

6.1 Scope

An energy storage system must be called upon to maintain the supply of electrical energy to the facility's critical loads and processes in the event of a power outage. This backup energy must be securely stored and promptly accessible whenever required. Once depleted, the mains power supply recharges the storage system when restored. The facility currently uses the flooded lead-acid-based energy storage system. However, various battery technologies have since been developed into commercially worthwhile alternatives to LABs. Amongst these technologies are LIBs. This chapter designs, sizes, and specifies the LI-BESS associated with Eaton Power Xpert 9395P High-Performance SUPS selected.

6.2 Introduction to lithium-ion battery

A protected energy supply is the underlying basis or principle for the prosperity and progression of any facility. For some of these facilities, power outages can be expensive. The curbing of this situation involves the use of a SUPS system that will ensure an uninterrupted supply of power to the facility. The most vital section of a SUPS system is its energy storage system aimed to deliver the required energy to guarantee continuous conditioned power feed to the critical loads or processes. This statement leads to say a SUPS system is only as good as the energy storage or battery system. Self-sufficiency, rated power, the efficiency of the inverter, depth of discharge, and disposable are the desired parameters amongst several other aspects that must be carefully considered during energy storage or battery system selection and configuration. LIBs are becoming more common due to their high energy density, and they can be charged or discharged at a higher rate than LABs. Researches show a high degree of development in safety, storage capacity, energy density, lifespan, self-discharge reduction, rate of charge and discharge enhancement even though LIB technology is comparatively new to LAB technology (made a market entry in the year 1990). These enhancements have made them compatible battery types for use in business facilities requiring power optimization. Their charging efficacity has since drastically improved, reaching an efficiency of up to 99% for some chemistries. They do not contain toxic liquid (sulphuric acid electrolyte) or environmentally pollutant elements (lead) used in their construction like is the case for LABs. To ensure high performance and safety integrity level, even though presenting good advantages, a correct system design implementation, improved condition-based monitoring, and condition-based management must be achieved. LIBs, if overcharged, allowed to overheat, short-circuited, or accidentally damaged, they more likely to cause a fire hazard or explosion and have their lifespan severely reduced. The battery charger must then be designed to limit the overcharging of LIBs by not more than 50mV.

6.3 Fundamentals of lithium-ion battery

Fundamentally, LIB cells are composed of four principal parts: a liquid electrolyte, a separator, a cathode (positive electrode), and an anode (negative electrode), as shown in Figure 6.3 below. Each cell has its positive electrode (cathode) made of metal oxide, while its negative electrode (anode) is made of porous carbon graphite. Both positive and negative electrodes are absorbed in a liquid electrolyte containing lithium salt and organic solvent. In LIBs, lithium ions are reversibly inserted into electrode materials' structure by the intercalation process. Inside the battery cell, lithium ions migrate from cathode to anode during the charging process and from anode to cathode during the discharging process. The movement of electrons through an external circuit is done in a similar way as the lithium ions. This movement is instigated in two ways; first by the release of potential chemical energy stored in the battery cell during the discharging process, and second by the SUPS charger during the charging process. The separator is usually a polymeric membrane saturated with a liquid electrolyte that permits the migration of lithium ions while preventing direct contact between electrodes. The functionality of LIB cells is, therefore, based on lithium ions transfer from negative to positive electrodes with no chemical reactions between electrolyte and electrodes and no gas emission during charge and discharge (Ana et al., 2016:47-49; Lighting Global, 2019:1 – 12; Mayo, 2018:15; Patrick & Martin, 2018:1-11; Tianmei et al., 2020:208 - 2017).

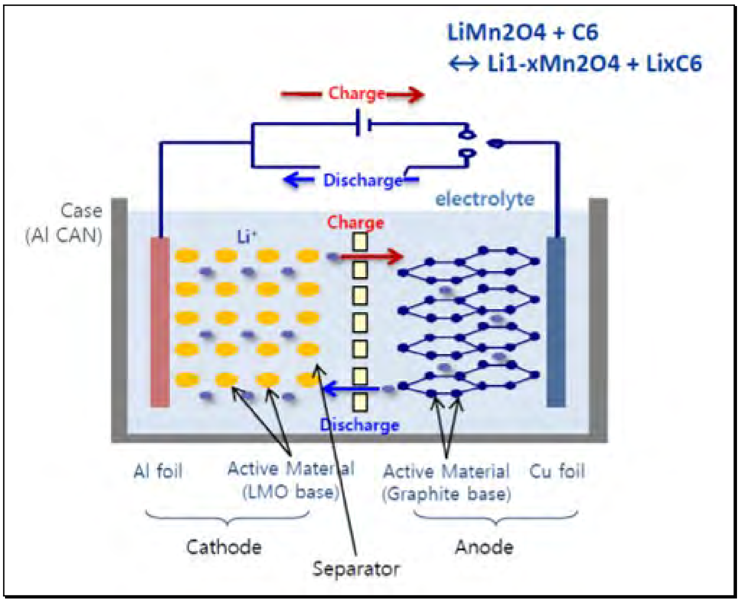


Figure 6.3: LIB cell charging and discharging mechanism (Mayo, 2018:15)

A common way to distinguish the main types of LIBs is to consider their cathode composition. The selection of well-suited battery chemistry depends on factors, including cell voltage, cell constructions, capacity, energy and power capabilities, cycle life, form factors, sizes, and operating temperature. Five principal chemistries based on their cathode or anode materials composition are considered from the long list of LIB chemistries available out there.

6.3.1 Cathode materials

The categorization of LIBs often bases on how their cathodes (positive electrodes) are composed. The selection of cathode materials is mainly driven by safety, cost, and energy density considerations more than anything else. Table 6.3.1-1 below enumerates various positive electrode materials type commercially obtainable nowadays, and Table 6.3.1-2 gives their general characteristics (Lighting Global, 2019:2-12).

Table 6.3.1-1: Common cathode materials (Lighting Global, 2019:2)

Material	Abbr.	Description
Lithium cobalt oxide $LiCoO_2$	LCO	Original commercial type; expensive raw materials.
Nickel cobalt aluminum $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	NCA	Highest energy density per unit mass.
Nickel manganese cobalt $LiNi_{1-x-y}Mn_xCo_yO_2$	NMC NCM	Safer and less expensive than LCO. Good cycle life. Promising technology.
Lithium manganese oxide $LiMn_2O_4$	LMO	Safer and less expensive than LCO, but poor cycle life.
Lithium iron phosphate $LiFePO_4$	LFP	Very safe, high power, but lower energy density. Best high-temperature stability.

Table 6.3.1-2: Typical properties of various lithium-ion chemistries (Lighting Global, 2019:12)

Positive electrode	LCO and NCA	NMC	LMO		$LiFePO_4$
Negative electrode	Graphite	Graphite	Graphite	Lithium titanate	Graphite
Optimized for	Energy	Energy or Power	Power	Cycle life	Power
Operating voltage range	2.5-4.2 (rarely 4.35)	2.5-4.2 (rarely 4.35)	2.5-4.2	1.5-2.8	2.0-3.6
Nominal voltage	3.6-3.7	3.6-3.7[21]	3.7-3.8[21]	2.3	3.3
Specific energy (Wh/kg)	175-240 cyl 130-200 polymer	100-240	100-150	70	60-110
Energy density (Wh/L)	400-640 cyl 250-450 polymer	250-640	250-350	120	125-250
Discharge rate (continuous)	2-3*C*	2-3*C* (power cells >30*C*)	>30*C*	10*C*	10-125*C*
Cycle life (100% DOD to 80% capacity)	500+	500+	500+	4000+	1000+
Ambient temperature during charge (°C)	0-45	0-45	0-45	-20-45	0-45
Ambient temperature during discharge (°C)	-20-60	-20-60	-30-60	-30-60	-30-60

6.3.1.1 Lithium cobalt oxide

Lithium cobalt oxide (LCO) is the cathode material first extensively marketed and still commonly used in consumer products. Even though it possesses a high energy density, it is not suited for use in the off-grid system because of its poorer safety, lower cycle life, and thermal steadiness.

6.3.1.2 Lithium manganese oxide

Unadulterated lithium manganese oxide (LMO) batteries possess good safety records and thermal stability but lower cycle life; their commercial use has since been weakened. LMO is nowadays substituted by merging the manganese oxide with nickel and cobalt (NMC), as described in Section 6.3.1.4.

6.3.1.3 Nickel cobalt aluminium

Nickel cobalt aluminium (NCA) batteries possess a lower thermal steadiness than their rivals. They are not well-suited for off-grid products because of the high cost, lower cycle life, and lower thermal steadiness.

6.3.1.4 Lithium nickel manganese cobalt oxide

Various merges of nickel, manganese, and cobalt (NMC or NCM) are an efficacious and auspicious perspective for LIBs. The proportion of these three components is now and then listed in the electrode name. An equivalent proportion would be chemically denoted as LiNi1/3Mn1/3Co1/3O2 and be recorded as NMC 111. NMC mixtures provide blends with good lifecycle, safety, and high energy density. The tailoring of component proportions can greatly accentuate potentials to suit targeted applications. Samsung LIB uses this technology to optimize the advantages of both chemistries. This combination brings out the best in each system, and the LMO/NMC is chosen for electric vehicles.

6.3.1.5 Lithium-iron phosphate

Symbolized as LiFePO4, these batteries display an excellent standard level increasing their suitability for off-grid products where safety, cost, lifecycle, and steadiness are key prerequisites. In comparison to other competing lithium-ion chemistries, they possess inferior energy density and output voltage of 3.2V. But this still satisfactory since countless effective off-grid products utilize this chemistry.

6.3.1.6 Cathode amalgamation

The research to merge diverse cathode materials is underway to try and ameliorate battery cell performance and cheapen them. As described in Section 6.3.1.4, lithium NMC 111 is combined with other cathode blends to reduce the quantity of cobalt (cobalt being the most expensive material) used while enhancing some of its capabilities and abate cost. The advancement and testing of the like of NMC 811, NMC 532, and NMC 442, and so forth are conducted presently for application in automotive industries. For market competitiveness, cheapened cells with excellent qualities will need to be produced. The amalgamation of the cathode can also consist of LiFePO4 and NMC (Daisuke et al., 2012:1-6).

6.3.2 Anode materials

6.3.2.1 Carbon-based anodes

Graphite formulations are utilized for the negative electrode in most LIB cells commercially available. These formulations could be pure graphite, unnatural graphite, or amorphous carbon. Lithium ions become intercalated in the carbon sheet structures when the cell is charged and released during discharge. When the cell is first charged, a solid electrolyte interphase (SEI) layer will form on the graphite surface. The SEI layer stabilizes the anode by preventing reactions between the graphite and the electrolyte. SEI layer integrity assumes a measure role in the overall performance of the cell.

6.3.2.2 Lithium titanite

Lithium titanite (LTO) anode materials can be used with LMO or NMC cathodes to make a lithium-ion cell. LTO cells provide very high cycle life, exceptional safety, and thermal stability and offer good low-temperature operation. However, they have a much lower energy density than other lithium-ion technologies and a low cell voltage of 2.4V.

6.3.3 Lithium-ion cell construction

Lithium-ion cells are obtainable in firm rectangular-shaped (prismatic-shaped) and cylinder-shaped constructions. Cylinder-shaped cell technology is most popular, and the shape is utilized in several other battery kinds. Prismatic-shaped cells have their usage well-established in communication devices (e.g. mobile phones) and many other electronic devices. Prismatic-shaped cells are usually designed with built-in safety mechanisms permitting them to interrupt the flow of current out of the battery cells if their temperature has heightened to a perilous level. These safety mechanisms, equally, provide battery cells with a capability to release their internal pressure from stockpiling of gas emanating from the mishandling or misusing of battery cells or from an internal short-circuit. Also, newly available in the market are pouch battery (polymer or lithium-polymer) cells. These polymers or lithium-polymers (Li-Poly or LiPo) cells are packaged in a flexible plastic pouch and have similar chemistry to firm LIBs. Pouch cells are of similar shape to prismatic cells and use a thin, flexible laminate to substitute a firm cover. They are, most commonly, used in portable digital music devices and communications devices. They are miniaturized and of cost-effective construction but less durable than prismatic cells.

6.3.3.1 Cylindrical cells

Cylindrically shaped LIB cells are fabricated by having long pieces of cathode and anode foil and a separator rolled together and housed into a can made of firm stainless steel or aluminium materials. The can is replenished with liquid electrolytes, and the insertion of safety disks into the top is made. The positive and negative electrodes are soldered to the external connecting terminals. The can is hermetically sealed by pressing the upper disk assembly.

6.3.3.2 Prismatic cells

Prismatic cells illustrated in Figure 6.3.3.2 and cylindrical cells are alike in terms of their construction but utilize a flat rectangular-shaped cover for an overall decrease in cell thickness. The electrode-separator assembly can either be rolled like cylindrical cells or have their electrodes rectangularly stacked. Battery terminals, placed as contact pads, can be situated on the side or top of the battery cover. The design aspect, shape, and size of a prismatic make them easily replaceable batteries and increase their suitability in the UPS system and electronics devices (Lighting Global, 2019:4).

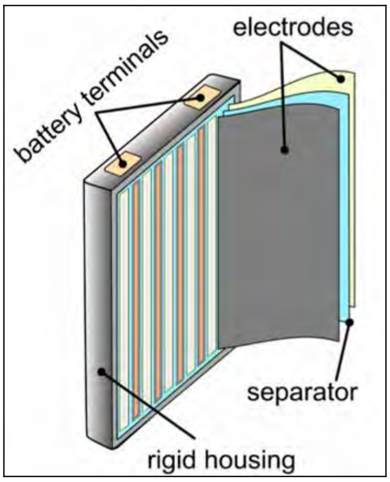


Figure 6.3.3.2: Prismatic lithium-ion cell (Lighting Global, 2019:4)

6.3.3.3 Pouch cells or lithium polymer

Pouch cells are made of a thin rectangular form factor framed by rectangular stacks of discrete electrode and separator layers. A laminated yielding polymer/aluminium bag is utilized as a replacement for firm housing. The electrodes comprise tabs along one side; these heat-sealed tabs are fused with terminals that protrude to the upper section. The assembly is soaked in a liquid electrolyte. Contrary to prismatic cells, the elimination of the firm casing achieves the salvation of weight, thickness, and cost of pouch cells. The use of yielding case can create swelling and reduce their lifetime, capacity, and safety integrity.

6.3.4 Charging and discharging process

LIBs charger system requires very stringent control and protection if batteries lifespan and safety are to be maintained. Overcharging or over-discharging a LIB can, respectively, explode or be harmful to it. LIBs use a two-stages UI-characteristic charging process as illustrated in Figure 6.3.4 below. Stage 1 is the constant electric current charging phase (I-phase), where constant-current 30% to 100% of its designed ampere-hours capacity is applied until LIB cell voltage reaches its maximum voltage of between 4.1 and 4.2 volts.

Stage 2 is the constant voltage charging phase (V-phase), where the charger voltage is held constant while the battery current decreases. This voltage remains constant until the battery current decreases to between 2% to 10% of its ampere-hour rating capacity for a predetermined period of approximately 2 hours.

If the LIB is excessively over-discharged, a sluggish charge of about 10% of its ampere-hour rating capacity is required to bring up its voltage to the level between 2.5 and 3VPC before its submission to the stage 1 charging process. Nevertheless, trying to charge an excessively over-discharged battery presents a dangerous condition and damages the battery. Partial charging of LIBs will not harm them; submitting them to a lower charge voltage will prolong their life cycle but substantially compromising their stored capacity. Automatic and precise regulation of the charger's output voltage of utmost importance in the safe charging of LIBs without compromising the stored capacity. For charging of series-connected cells, the battery charger must have a built-in capability to constantly even its output voltage to prevent any chance of exceeding the maximum voltage of any single cell connected (Lighting Global, 2019:6 – 7).

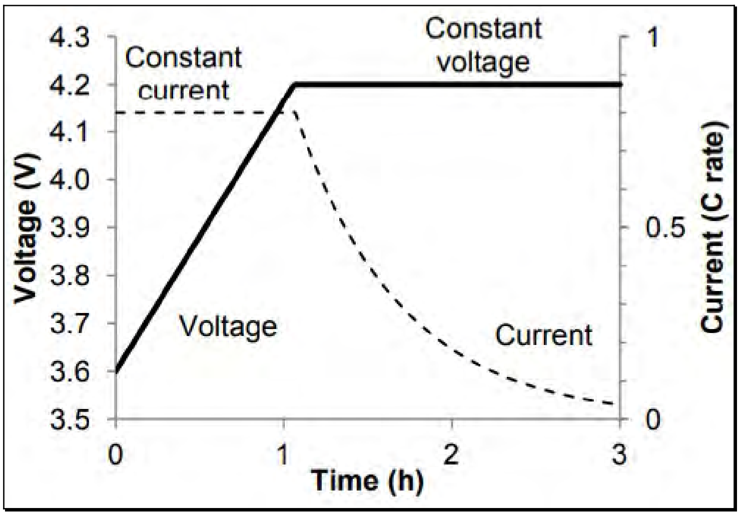


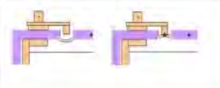
Figure 6.3.4: LIB charging process (Lighting Global, 2019:7)

The charging of most LIBs should not be conducted at surrounding temperatures below 0°C or above 45°C ranges. LIBs charged at surrounding temperatures above 45°C will decrease their lifecycle and lead to a hazardous condition. And LIBs charged at surrounding temperatures below 0°C will lead to the evolution of lithium metal dendrites that may possibly cause a fire hazard by internally short-circuiting and destroying the battery. Furthermore, unlike NiCad and NiMH cells, LIBs do not possess a memory effect; their submission to a full discharge cycle (discharge under 2.5 to 3VPC) will endorse a reduction in the lifecycle and permanently damage or short-circuit them. It is also important to note that operating voltages and temperature boundaries are specific to each battery type or chemistry. Refer to the manufacturer's catalogue for those specifications.

6.3.4.1 LIB cell overcharging protection mechanism

Charging beyond specific battery voltage limits is dangerous since this could stimulate a reaction between the electrolyte and charged positive electrode material, thus, resulting in the venting of electrolyte solution to form an explosion atmosphere around the battery room. The stability and safety integrity level presented by positive electrode materials are specific to battery chemistry. LFP chemistry has a high safety integrity level, trailed by NMC, LMO, and LCO. There is a similarity between the safety integrity level of NCA and LCO chemistry. The built-in battery protection switch, specified in Table 6.3.4.1, provides an isolation capability of the battery system from the charger during the overcharging condition. Upon the failure of this protection mechanism, a second protection system in the form of a safety vent that acts as a circuit interrupter to prevent the continuance of excessive charging or heating process opens and activates the release of the battery's internal pressure. The activation of this system will consequently destroy the battery (Mayo, 2018:26).

Table 6.3.4.1: LIB cell safety and physical protection mechanism (Mayo, 2018:26)

Item		Function description
OSD (Overcharge Safety Device)		to cut overcharge current into electrode by activation of OSD (cut at 4kgf of Internal Pressure)
Fuse		to cut abnormal current flow
SFL (Safety Functional Layer)		to maintain electronic isolation by additional heat resistant ceramic layer on Anode
Gas Vent		to vent generated gas in case of emergency (venting at 7kgf of Internal Pressure) 2/3 CO2 and 1/3 CO, H2 and CH4

6.3.4.2 LIB cell over-discharging

Draining of lithium-ion cell below specific voltage limit can dissolute the copper current-collector on the cell anode ending up deposited in the cathode and separator and feasibly short-circuiting the battery cell. An over-discharged battery cell can lose its ampere-hours capacity and swell. Since various electronic devices may still draw leakage current even though shut down, it is crucial to incorporate a BMS in each battery racks or cabinet for complete isolation of battery cells beforehand to prevent hazardous discharge.

6.3.4.3 LIB cell overheating

Letting LIBs heated up beyond specific battery temperature limits is equally dangerous as this could stimulate a reaction between the electrolyte and cathode material. This reaction will result in the venting of electrolyte solution to form an explosion atmosphere around the battery room with the risk to cause a fire. The BMS system must then contain temperature probes to halt the charging process prior to reaching thermal runaway conditions.

6.3.4.4 LIB cell short circuit

Short-circuiting a LIB can cause the battery to overheat, resulting in a fire. The separation or recession of terminals preventing them from touching extraneous metal objects and the assurance that battery leads insulation will not degrade at any operating condition are some of the best design practices to reduce possible short-circuit. LIBs make use of a porous plastic shutdown separator which, partly dissolves to interrupt the conduction of electricity and positive temperature coefficient (PTC) devices that prevents the flow of currents of a magnitude greater than designed limits. The effectiveness of these detective devices does not guarantee protection against internal short-circuits caused by inherent manufacturing defects. Crushing or puncturing a cell can also short-circuit it.

6.3.5 LIB cell safety overview

LIBs are significantly sensitive to any abnormalities falling out of their design specifications. They are usually designed to have integral safety mechanisms that permit them to avert any hazardous situations from happening. Installation or utilization of batteries that do not incorporate these safety measures must be prohibited (Patrick & Martin, 2018:1-11). Strick adherence to additional safety measures specified below is also recommended:

- LIBs' two-stage UI-characteristic charging process must be done under stringent control and protection as specified by the manufacturer. Avoid overcharging, over-discharging, and short-circuiting of lithium-ion cells categorically. These factors have the potential to cause an acute loss or major defect to them. BMS must provide condition-based monitoring and management even to individual cells inside the battery pack to prevent any risky condition from arising.
- Do not operate LIB cells (charge or discharge) at temperatures exceeding 45°C or at temperatures below 0°C. Their packs must offer enough natural and passive ventilation gaps between adjacent cells to avert inter-cells propagation of thermal runaway situation. Do not mishandle, dismantle, or mechanically stress LIBs in their charged state.
- The storage of LIB cells must be performed while moderately discharged, usually between 20 to 40%. Fires caused by any defect in LIBs can be put off using a normal fire extinguisher.

6.3.6 LIBs disposal

Materials used in LIBs, including cobalt, nickel, manganese, iron, and aluminium, are not as poisonous as it is in the case of materials used in LABs. Most countries around the world permit their disposal at any disposal site or facility. Although all materials used in LIBs are recyclable, since they are a new technology in the market, their recycling can be costly compared to LABs. LABs have already a prevalent recycling infrastructure established. Furthermore, mishandling or dismantling charged LIBs can dangerously lead to a fire or explosion hazard. Thus, before any disposal process is undertaken, one should ensure that they are in their fully discharged state.

6.4 LIB selection characteristics

LIB can be a good choice for UPS applications if the correct chemistry is made with safety and performance requirements in mind. There are many choices of lithium chemistries and cell designs that could potentially be used in UPS applications. Focal characteristics where that choice is fundamentally based are: the power and energy performance, battery shelf life, beginning-of-life (BOL) and end-of-life (EOL) performance, temperature limits, depth of discharge and cut-off voltage while retaining rated lifecycle, overall cells condition monitoring and management, charging time, back-up or autonomy time, footprint, and safety.

6.4.1 Energy and power performance

Properties of LIB chemistries can best be shown and compared using the chart in Figure 6.4.1. The selection of a well-suited LIB chemistry and the sizing of an LI-BESS depends on various factors, including ampere-hour capacity, energy, power capabilities, and operating temperature within its self-sufficiency time. The constant discharge power and current handling capability directly control the number of parallel strings needed to support the critical loads and processes requirements. The nominal ampere-hours capacity of a battery cell is its definite discharging capacity expressed as a product of its discharge current delivered and self-sufficiency period through which the discharge current will be sustained while avoiding any possibility of being over-discharged. From Figure 6.4.1 and Table 6.4.1 below, the most promising choices applicable to UPS systems would then be LFP, NCA, and LMO (ABB, 2017:6; Ana et al., 2016:17-28; Mayo, 2018:12).

Table 6.4.1: LIB chemistry application selection (Mayo, 2018:12)

Main Li-ion Variant	Principal use	Typical 100% DOD Cycle Life	Shortest Discharge	Potential (voltage)	Start of Thermal Run Away	Relative Price
LCO	Cell phones - laptops	600	60 min.	3.6	170°C	100%
NCA	Tesla	1300	30 min.	3.6	180°C	150%
LMO	Elec. Car - UPS	1100	12 min.	3.8	255°C	125%
NMC	Elec. Car - UPS	1300	6 min.	3.7	215°C	150%
LFP	Power tools – Hybrid - UPS	3000	5 min.	3.2	270°C	135%
LTO	Grid storage and hybrid cars	12000	6 min.	2.5	Not applicable	300%

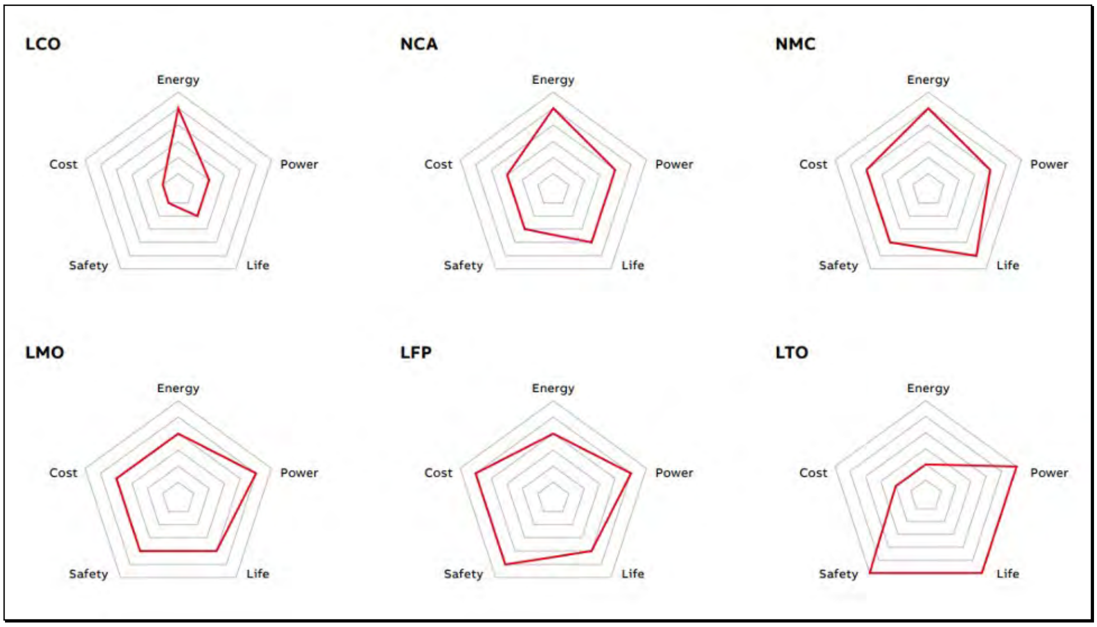


Figure 6.4.1: LIB chemistries' properties (ABB, 2017:6)

6.4.2 Shelf life and battery storage

LIBs will have a longer shelf life than some of the lead-acid models used in today's battery-based UPS systems. The reason LIBs have a longer shelf life is because they can self-discharge to a greater depth of discharge (DOD) and still recharge to the rated capacity. LIBs hardly self-discharge themselves; their utmost discharge emanates from leakage currents flowing through their built-in surveillance circuitries and electronics. These leakage currents are mostly design-based. Currents consumed by all battery-connected electronics needs to be specified by the manufacturer. The manufacturer must recommend storage conditions such as the discharge state, current reserve, temperature to prevent batteries from over-discharging. An increase in battery cell stress, a reduction in lifespan or lifecycle, and an upsurge in thermal runaway energy are some of the detrimental consequences when LIBs are stored in fully charged or elevated temperature conditions.

Identical to all other batteries, LIBs are also prone to self-discharge at a monthly rate of approximately 2% to 10% while stored. Their charge must be brought back to an acceptable storage level regularly. Leaving them discharged to voltages below manufacturer-specified values can be detrimental, but storage made under perfect conditions can make them last for over five years. To obtain a long shelf life with LIBs, the BMS must not operate while storing battery strings. The current drain of the BMS can be of enough magnitude to discharge the battery cells rather quickly compared to the self-discharge rate. Many of today's manufacturers have the means to either disconnect the BMS or put it into a sleep mode where the current drain is small relative to the self-discharge rate.

6.4.3 Performance at the beginning and end of life

The selection of well-suited LI-BESSs depends mainly on its capacity, energy, and power, self-sufficiency capabilities. The knowledge of performance at the beginning and the end of their life (BOL and EOL) is necessary. An oversizing factor, typically 125% as per IEEE 485, must be accounted for to mitigate ageing influences.

6.4.4 Operating temperature

Of considerable importance when developing a battery system for a UPS application is the thermal management of heat generated in the cells during charging and discharging for their optimal efficiency and state of health (refer to Figure 6.4.4-1). Lithium chemistries are exothermic on charge and discharge; that is, the internal chemical reactions themselves release heat as a by-product. This heat is in addition to the heat generated from losses in the connections and wiring, sometimes referred to as Joule heating. The additional heat generated must be managed to prevent the cell's temperature from exceeding the limit above which its permanent degradation will occur, possibly leading to thermal runaway. In a general sense, it is desirable, regardless of the rating of the battery system, to avoid using fans for cooling. The ventilation system will then add cost to the battery pack and potentially increases the volume and spatial footprint of the LI-BESS, as space for both the fan and airflow must be created. The lithium battery system expected to last up to 10 years in a float service application with no maintenance. Adding a fan having a fixed life, which is generally shorter than a lithium battery system, will nullify some of the great benefits of choosing a lithium battery solution. For reasons elaborated above and to alleviate consequences and inefficiencies on LI-BESS that arise because of thermal conditions, active cooling of the battery system room is preferred. The smaller HVAC unit from the two existing units, used with the LAB-RUPS system, will be retained to ventilate and manage the LIB room temperature.

The LIBs lifetime degradation is determined by how the battery storage capacity decreases with the number of charge and discharge cycles. This degradation, shown in Figure 6.4.4-2, follows a calendar degradation that includes a linear declination in the capacity over time 't', regardless of cycling. That is dominantly due to the environment (temperature and humidity) in which the battery system is installed. This decay in battery system capacity can mathematically be represented by Equation 6.4.4 below, where 'k' is a constant (Mayo, 2018:36-37):

$$Q_{Actual\ capacity} = Q_{Initial\ capacity} - (k)\xi\,\bar{t} \qquad (6.4.4)$$

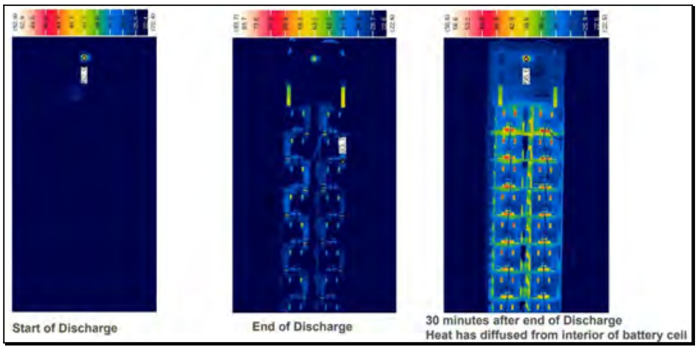


Figure 6.4.4-1: Thermal imaging of rack heat dissipation (Mayo, 2018:37)

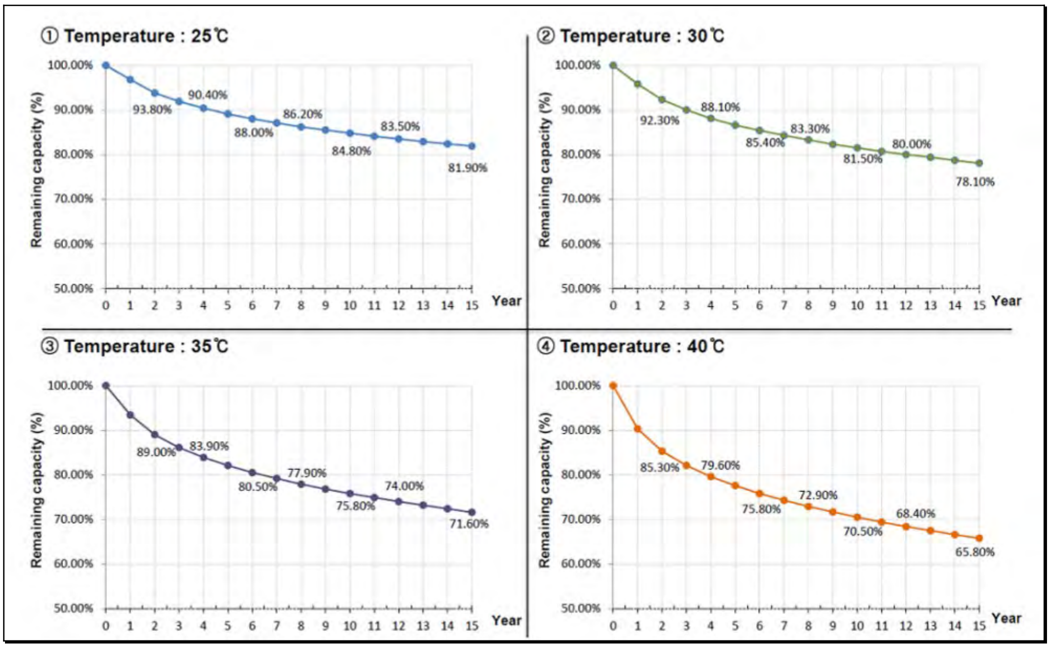


Figure 6.4.4-2: LIB periodical capacity degradation (Mayo, 2018:36)

6.4.4.1 LI-BESS thermal management

In this section, three means to manage the heat are discussed. The first means is to oversize the battery system by adding parallel strings. Since the heat generated from the reactions is a function of the current, the temperature rise of each cell will be less when more parallel strings are sharing the total current required to serve the facility's critical loads and processes. This choice increases the cost, volume, and spatial footprint of the complete BESS. But the BESS discharge time will consequently increase which, may or may not be desirable by the facility. The second means is achieved by increasing the number of cells in series. The increase in the number of these cells translates into a reduction in service power taken from each battery cell and temperature rise of cells. But it is important to note that; increasing the number of cells in series will increase the operating voltage of the string which, may or may not be accepted by the SUPS. Noting again, the load on the battery system is constant power, P= V x I = constant. If the voltage (V) increases, by necessity, the current (I) must decrease (a lower current generates less heat). A third means to manage the heat is to modify the cut-off voltage based on the rated BESS power. With many designs, the available discharge time is longer than the desired discharge time. Raising the cut-off voltage will shorten the discharge time, reduce cells' temperature, and prevent it from reaching or exceeding the maximum limit where the BESS disconnects itself from the UPS system to avoid battery cells degradation. The same approach can be taken by sensing the ambient temperature around the battery system. This method requires some characterization of the battery system that will help determine the specific cut-off voltages that should be used to limit the temperature rise of the battery cells.

6.4.5 Depth of discharge and cut off voltage

Depth of discharge is defined as a ratio between the quantity of charge removed from the battery cell at the given state to its maximum stored charge expressed in Equation 6.4.5 below:

$$DoD = \frac{Removed\ quantity\ of\ charge}{Maximum\ stored\ charge} \times 100\% \qquad (6.4.5)$$

Like most equipment, there are characteristics of LIBs that are considered less beneficial and must be dealt with when designing or selecting an LI-BESS for a UPS system application. Lithium chemistries are not very tolerant of operating conditions outside the recommended limits. Discharging below the minimum cut-off voltage (over-discharging), small departures of the float voltage above the maximum recommended (overcharging), and exceeding the maximum temperature limit of the cell either from ambient conditions or from high a charge or discharge current can all induce thermal runaway. These events are generally catastrophic for most lithium chemistries. As elaborated in Section 6.3.4.2 and illustrated in Figure 6.4.5 below, over-discharging a lithium-ion cell below its depth of discharge will lead to a loss of its ampere-hours capacity and swelling. The lower the battery surpasses its discharge state per cycle, the lower its lifecycle. It is, therefore, important that module, rack or cabinet, and system BMSs provided on the LI-BESS prevent the depth of discharge limits be surpassed (Mayo, 2018:29).

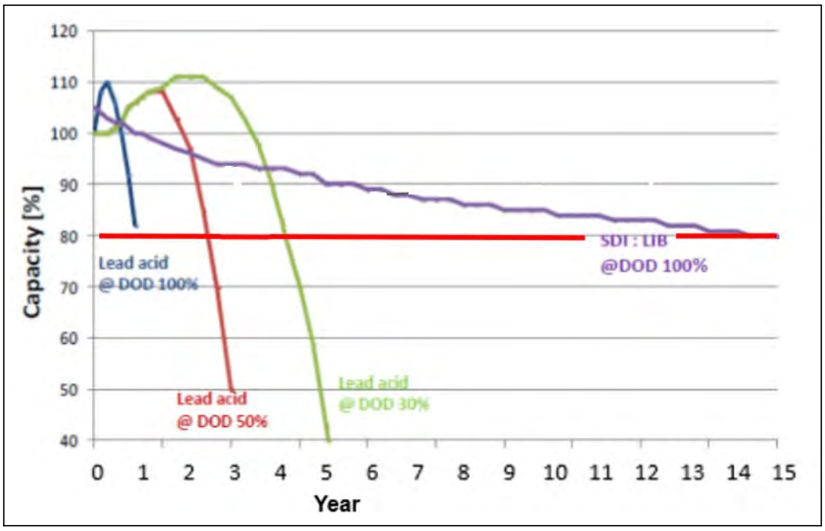


Figure 6.4.5: Depth of discharge - DOD (Mayo, 2018:29)

6.4.6 The role of the BMS as a means of protection

LI-BESS will influence the overall performance of the SUPS System. It needs to be charged after being used during a power failure and kept charged when the power utility voltage is present. So, part of the energy absorbed by the SUPS system is delivered to the LI-BESS with additional heat loss and dissipation. The battery chargers have efficient electronic-controlled circuitries loaded with intelligent software algorithms based on the actual operating conditions of the battery cells and LI-BESS in general to reduce the energy losses associated with the LI-BESS. Intelligent charging and discharging management and monitoring algorithms allow the battery charging process to be done accurately and effectively. This intelligent operation reduces energy consumption, limiting the charging time and using the battery cells and consequently the LI-BESS in the best possible operating way. Using the battery cells properly extends their life resulting in savings on the number of battery cells or modules needing to be replaced during the lifetime period of the SUPS system.

For the reasons detailed above, LI-BESS requires BMSs to maintain the cells operating conditions within their limits. These battery management controls range in complexity from just cell balancing to ones that monitor cell voltage, temperature, current. They use either semiconductor switches or relays to disconnect the battery pack from the SUPS system if any of the monitored cell variables exceed their operating limits. Thus, when interfacing an LI-BESS with a SUPS system, it is vital to know and understand the battery limits at which BMS will disconnect the LI-BESS and ascertain that the SUPS system will not exceed these limits in its normal operating condition. Verifying that SUPS system settings will not exceed pre-configured limits is a good practice and system design. Many BMSs provide a warning signal if the running conditions approach their pre-set operating limits before any action is taken. In this manner, it is possible to take preventive action and avoid nuisance LI-BESS disconnection from the SUPS system during normal operation. To prevent any catastrophic system failure, the BMS will generally not reconnect the LI-BESS until the condition that caused the action is removed (Webb, 2018:3 – 4).

6.4.6.1 Brief description of functions contained in a typical BMS

The first of these functions is cell balancing, either passive or active. The purpose of cell balancing is to maintain the terminal voltage of each cell, or bank of parallel cells, in the series string approximately equal. This voltage equalization assists in maintaining the capacity of each cell the same since cell voltage bears some relationship to its capacity. This voltage equalization prevents weaker cells or those cells with lower capacity from being over-discharged and cells with higher capacity from becoming overcharged to their thermal runaway conditions.

The second group of functions is what may be called the measurement functions. The first measurement is of the cell voltages; the purpose of this measurement is to make sure the cell voltages are balanced and close enough to each other and that the LI-BESS can be charged and discharged over its intended range of operation. In some instances, the BMS may not allow charging or discharging, at least not at rated load, until the cell voltages are within some predetermined range of each other. The second measurement is of the current through the cells. There are usually maximum charge and discharge current limits that, if exceeded, will trigger a warning and possibly disconnect the LI-BESS from the SUPS system if the condition persists for some prescribed period. The third measurement is of the cell temperature; when evaluating a battery system for use with a SUPS system, it should be a requirement that the case temperature of battery cells in the LI-BESS is measured. Due to the rapid temperature rise during the thermal event, an internal air temperature measurement inside the LI-BESS enclosure may not be proportionally rising fast or be sensitive enough to detect the onset of thermal runaway and trigger the disconnection of the LI-BESS. The BMS will protect the LI-BESS from excessive temperatures by signalling when the cell temperature is nearing or has reached the maximum and ultimately disconnect the LI-BESS from the SUPS system if the maximum is reached. Another action taken by a BMS is to limit or postpone charging of the LI-BESS until the temperature has decreased sufficiently from the unsafe limit.

Some BMS models may also provide a measurement of the state of charge (SOC) and indicate the state of health (SOH) of the battery system. The SOC measures the battery charges in ampere-hours (Ah) removed during the discharging process and replaced during the charging process. The battery charge is usually measured by imaging the current into or out of the battery system with respect to time. Starting with a known value of available battery charge, the SOC is just the ratio of the net battery charge (discharged Ah – charged Ah) to the overall available battery charge. With some lithium chemistries, the cell voltage provides a reasonable indication of its SOC. On the other end, the SOH is the state of health measurement or an indicator of the amount of degradation or ageing that has occurred since the battery was new. The basic approach of this measurement is to determine how much the battery cell available charge is decreasing with age. Capacity loss as the battery ages is sometimes referred to as capacity fade. A discharge test, starting from the fully charged state, is usually used to estimate the level of this fade. Another ageing mechanism that can occur with some chemistry is referred to as power fade which, is of more concern in high current discharge rate applications, such as in a UPS system. This power fade is a result of an increase in resistance of the cell as it ages; with a high current discharge rate, the increased resistance will cause the cell voltage to decrease and thus reach the cut-off voltage earlier than anticipated resulting in a shorter discharge time. Some BMSs have the means to make a resistance measurement and estimate the decrease in discharge time.

6.4.7 LI-BESS charge time

Another reason for choosing lithium-ion technology over lead-acid technology is because of its shorter charge time. This shorter charge time is due to the higher charge efficiency of the lithium chemistry compared to lead-acid. Charge times less than 5 hours have been obtained over a range of discharge times that are typically acceptable in most UPS system applications with relatively low charge currents in the order of 0.55C. In most African countries where the grid is quite unstable and unreliable, this may be a deciding factor for using lithium-ion technology.

6.4.8 LI-BESS backup or autonomy time

Another important consideration related to the selection of an appropriate BESS is the determination of its backup or autonomy time at various UPS system load rates. This autonomy time characterizes the discharge time of the installed BESS and the ability of the entire SUPS system to continue supplying conditioned and uninterrupted power to critical loads and processes during a power disturbance or outage. Like any other BESS, LI-BESSs are retailed in differently-sized cabinets or racks correspondingly rated at different ampere-hour capacities. Design to specify the correct number of cabinets and, consequently, ampere-hour capacity required in relation to the facility's power and required backup or autonomy time need to be performed.

6.4.9 LI-BESS footprint

Another benefit of using lithium-ion technology is its capability to reduce spatial footprint and volume compared to an equivalent lead-acid solution. A significant decrease in size is the most far-reaching benefit a UPS technology offers to a facility implementing or planning to implement it. Reduction in the total footprint plays a major role in the overall future development, improvement, flexibility, and power protection philosophy in general. It is also worth mentioning that the correlation between the UPS system's capacity and the space they occupy forms a significant aspect of their market sustainability and appraisal in many applications where floor space is at a premium.

6.4.10 LI-BESS safety and fire hazards

Another criterion for selecting lithium chemistry is safety. The primary concern here is the management of thermal runaway conditions. Overcharging, over-discharging, excessive discharge current, or an internal cell defect can push a LIB cell into a thermal runaway. With some chemistry, a thermal event will be significantly more intense than others. Temperatures more than 300°C to 500°C can be reached in a short period when thermal runaway occurs; the heat generated and the temperatures reached can, in some cases, auto-ignite adjacent cells, causing the damage to spread even further within the LI-BESS. The reason for the intense heat generated is that some chemistries release oxygen at temperatures within the range of the thermal event. Like illustrated in Section 3.3.4.2, this oxygen then becomes the fuel that will sustain the burning.

6.5 Battery system configuration

6.5.1 Serial strings

In this configuration, shown in Figure 6.5.1, a pre-determined number of similar LIB cells are series-connected to make a battery bank. The total voltage at the terminals of the battery bank, which is the nominal cabinet or rack voltage, is found by summating voltages of each discrete cell voltages. The total ampere-hour capacity of the cabinet or rack remains the same as the ampere-hour capacity of each discrete cell.

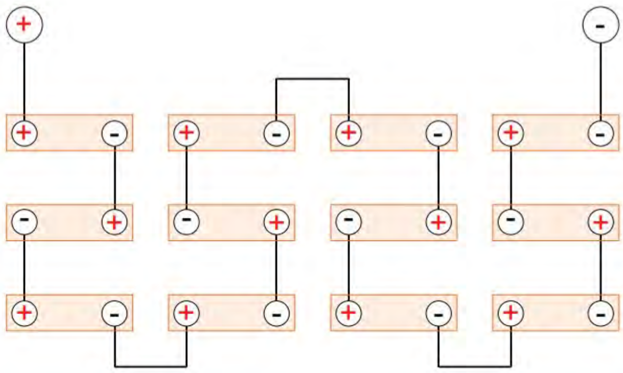


Figure 6.5.1: Serial battery string connection (12S1P layout)

6.5.2 Parallel strings

In this configuration, shown in Figure 6.5.2, a pre-determined number of similar LIB cabinets of racks are parallel-connected. The total ampere-hour capacity is found by summating the ampere-hour of each discrete cabinet or rack ampere-hour capacity. The voltage at the terminals of the paralleled system remains the same as the voltage of each discrete cabinet.

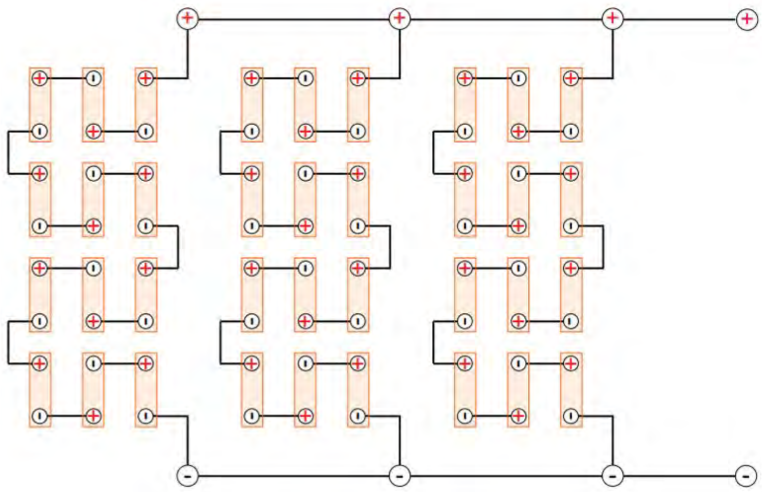


Figure 6.5.2: Parallel battery string connection (12S3P layout)

6.5.3 Transition boxes

Transition boxes are utile when multiple battery strings are to be coupled to the same UPS system. These transition boxes achieve the simplicity of BESS-to-UPS cable connections and terminations by providing enough working space for installation and maintenance personnel, as shown in Figures 6.5.3-1 & 2. They are also used to house protection devices and auxiliary control systems of each battery bank and allow safe isolation of each battery bank, cabinet, or rack during reliability-centred maintenance or repair without putting the entire UPS system offline. During system implementation or installation, care must be made to the equalization of cable lengths to the BESS to equalize their impedances and create an equal current divider that delivers the same current in each of its branches.

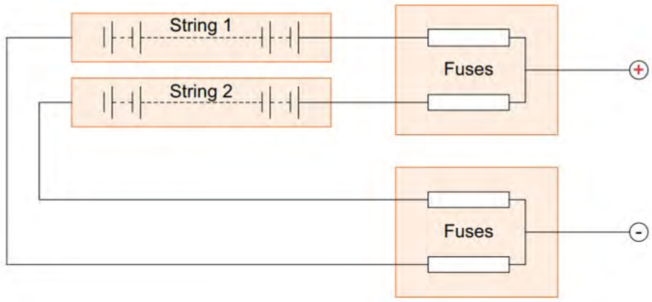


Figure 6.5.3-1: Typical fused transition boxes for two batteries strings

Figure 6.5.3-2: Current fused LA-BESS transition box

6.6 Battery system specifications and requirements

This section specifies an energy storage system using LIB strings that are housed in cabinets or racks, together with its BMS and switch gears. The LI-BESS will concurrently function with the selected Eaton Power Xpert 9395P High-Performance SUPS to provide battery backup power to critical loads and processes. Each of the four Eaton Power Xpert 9395P High-Performance SUPS units forming the SUPS system will be associated with several paralleled cabinets or racks to achieve 20 minutes of backup or autonomy time (refer to Appendixes F and H for more details). In this research work, the LI-BESS using prismatic LMO lithium-ion cells - Samsung SDI and 128S1P cabinets will be configured.

6.6.1 Battery system components

The followings are the main components forming the LI-BESS. The first components are the battery cabinets or racks that contain multiple LIB modules, as shown in Figure 6.6.1-1. The second components are the BMSs, as shown in Figures 6.6.1-2, 3, 4 & 5. Three types of BMS are given in order of their control hierarchy, namely Module BMS (MBMS), rack BMS (RBMS), and bank or system BMS (BBMS or SBMS). MBMS is an intrinsic BMS to the battery module inside the string. Each cabinet or rack containing this battery string possesses an RBMS with internal communication capabilities and a function to monitor battery charging or discharging current while preventing battery cells from going into a thermal runaway condition. Status or alarms are communicated back to the SUPS system. RBMS will request the battery protection units (BPU) to active protective devices supplying the specific rack circuit if a major alarm is detected. The other function of the RBMS is also to provide a level of supervision to all respective MBMSs. The BBMS offers the entire system management. This BBMS is housed in one of the racks or cabinets and is used to broadcast system information to all peripheral infrastructures to the SUPS system and the building management system. The function of a BBMS is also to provide a level of supervision to all connected RBMSs. BMS monitoring matrix and protective functions for the 128S1P cabinet are stipulated in Tables 6.6.1-1 & 2. The third components are the BPUs. Each cabinet or rack possesses an intrinsic BPU composed of protection devices such as circuit breaker, contactor, fuses and disconnect devices to isolate each battery string within a cabinet. As a measure of safety compliance, automatic isolation and disconnection of the battery cabinet from the UPS system must exclusively be dependent upon disconnecting or protection devices intrinsic to the cabinet or rack (Samsung SDI, 2017c:16 & 2014:1-2; Mayo, 2018:38; Samsung SDI, 2017b:19-20; Schneider Electric, 2018:2).

Figure 6.6.1-1: LI-BESS cabinet (Schneider Electric, 2018:2)

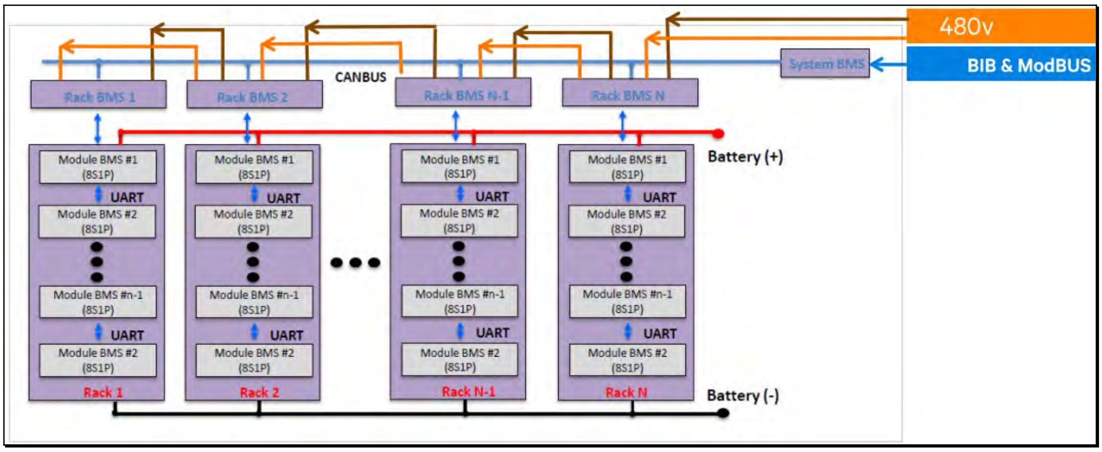


Figure 6.6.1-2: General system configuration block diagram-1 (Mayo, 2018:38)

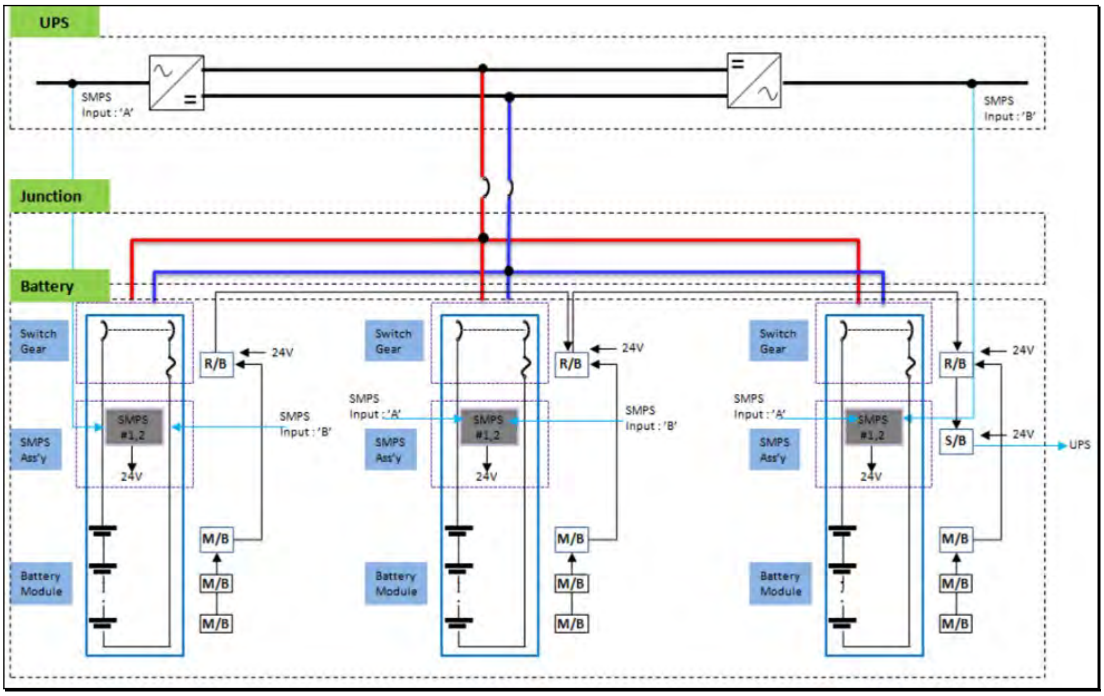


Figure 6.6.1-3: General system configuration block diagram-2 (Samsung SDI, 2017c:16)

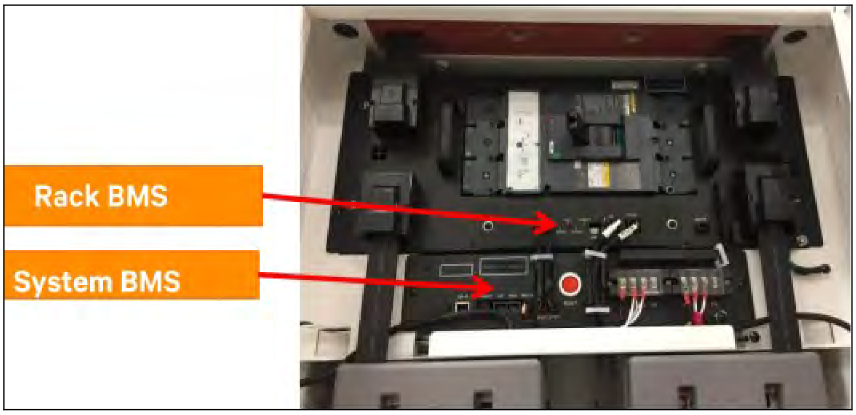


Figure 6.6.1-4: Rack and system BMS (Mayo, 2018:38)

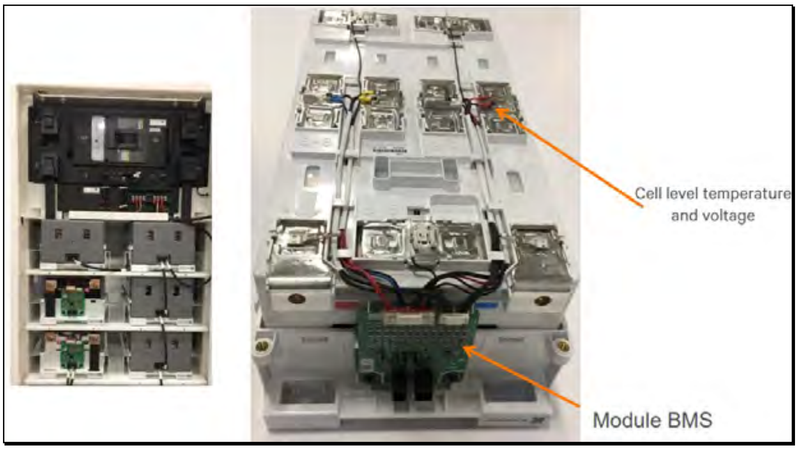


Figure 6.6.1-5: Module BMS (Mayo, 2018:27)

Table 6.6.1-1: Protective functions - 128S1P configuration (Samsung SDI, 2017b:19-20)

No	Items	Level	SET Condition	Time (Sec)	MCCB	Release Condition	Time (Sec)	MCCB
1	Over Voltage Protection - Cell	Major	Max Cell ≥ 4.28V	5	OFF	Max Cell < 4.25V & Reset	5	ON
2	Under Voltage Protection - Cell	Major	Min Cell ≤ 2.5V	3	OFF	Min Cell > 2.70V& Reset	3	ON
3	Over Voltage Protection - Rack	Major	Rack Voltage ≥ 547.84V	5	OFF	Rack Voltage < 544V & Reset	5	ON
4	Under Voltage Protection - Rack	Major	Rack Voltage ≤ 320	3	OFF	Rack Voltage > 345.6V & Reset	3	ON
5	Voltage Imbalance	Major	Max Cell ≥ 3.80V & ΔVcell ≥ 100mV	5	OFF	ΔVcell < 30mV & Reset	5	ON
6	Voltage Sensing Error (Rack)	Minor	|Rack V - Cell Sum V| ≥38.4V	10	ON	|Rack V - Cell Sum V| < 19.2V & Reset	3	ON
7	Voltage Sensing Error (Module)	Minor	|Module V - Cell Sum V| ≥190mV	5	ON	|Module V - Cell Sum V| < 190mV & Reset	3	ON
8	Over Temperature Protection	Major	Max Temp ≥ 75℃	3	OFF	Max Temp < 65℃ & Reset	3	ON
9	Under Temperature Protection	Minor	Min Temp ≤ 0℃	3	ON	Min Temp > 5℃ & Reset	3	ON
10	Temperature imbalance	Major	Max Cell T - Min Cell T ≥ 40℃	30	OFF	Max Cell T - Min Cell T < 20℃ & Reset	3	ON
11	Over Current Protection (Charge)	Major	Level2 Current ≥ 250A	2	OFF	|Current| < 10A & Reset	3	ON
		Major	Level1 Current ≥ 200A	60	OFF	|Current| < 10A & Reset	3	ON
12	Over Current Protection (Discharge)	Major	Lvel4 |Current| ≥ 600A	1	OFF	|Current| < 10A & Reset	3	ON
		Major	Level3 |Current| ≥ 540A	10	OFF	|Current| < 10A & Reset	3	ON
		Major	Level2 |Current| ≥ 495A	30	OFF	|Current| < 10A & Reset	3	ON
		Major	Level1 |Current| ≥ 470A	60	OFF	|Current| < 10A & Reset	3	ON
13	Communication Failure (Module ↔ Rack)	Major	No Communication	30	OFF	Re Communication & Reset	-	ON
14	Communication Failure (Rack ↔ System)	Major	No Communication	30	OFF	Re Communication & Reset	-	ON
15	SW Failure - MCCB	Minor	MCCB OFF & |Current| ≥ 2.4A	3	ON	(MCCB OFF & (|Current| < 2.4A) & Reset	-	ON
16	SW Sensor Failure - MCCB	Minor	MCCB contact ON = MCCB Trip ON	3	ON	(MCCB contact ≠ MCCB Trip) & Reset	-	ON
17	Current Sensing Error	Minor	No communication with Current IC	3	ON	Re communication with Current IC	-	ON
18	Fuse Failure	Minor	Fuse Blown	10	ON	Fuse ON & Reset	-	ON

Table 6.6.1-2: BMS monitoring matrix (Mayo, 2018:40)

Function		System BMS	Rack BMS	Module BMS
Measurement	Rack Voltage / Current	-	○	-
	Cell Voltage / Temp	-	-	○
Calculation	SOC Estimation	-	○	-
	SOH Estimation	-	○	-
Control	Switching Control	-	○	-
	Cell Balancing	-	○	○
Communication	UART	-	○	○
	CAN	-	○	-
	RS-485 or MODbus-TCP/IP	○	-	-
	Dry Contact	○	-	-

6.6.2 LI-BESS modes of operation

The LI-BESS functions continuously and autonomously as follows. During normal operating mode, the LI-BESS is supplied by the Eaton Power Xpert 9395P High-Performance SUPS charger under the surveillance of various BMSs which, manage and monitor its key parameters, namely, temperature, current, voltage, SOC, and SOH. The discharge mode is such that, during a power disturbance or outage, the Eaton Power Xpert 9395P High-Performance SUPS inverter will still maintain supply to critical loads and processes. This transition in energy acquisition from the utility main to the LI-BESS is seamlessly and automatically executed. The BMSs will still maintain their monitoring capabilities over battery discharge current and thermal runaway. The discharging process will be concluded when the BMS detects an excess in supplied electrical current or battery temperature. The nominal voltage level required by the LI-BESS, provided by or to the SUPS system, is rated at 480V. The recharge mode is such that, upon the restoration of the utility power, the servicing of critical loads by the inverter which, takes now power from the utility main via the rectifier, will still be maintained. Drained LI-BESS ampere-hour capacity will now be replenished by connecting them back to the SUPS charger. Transition in energy acquisition from the LI-BESS to utility main is as well seamlessly and automatically executed. Like in the discharge mode, the BMSs will keep their monitoring capabilities over battery charging current while preventing thermal runaway conditions.

6.6.3 LI-BESS environmental requirements

The LI-BESS selected must endure external environmental conditions such as the recommended operating temperature ranging between 18°C and 28°C, storage temperature ranging between 18°C and 28°C, and operating and storage relative humidity ranging between 5% and 85% (non-condensing) while maintaining its designed performance, integrity, and safety level.

6.7 Design and sizing of the LI-BESS

Like the LA-BESS system previously discussed, the design and sizing of the LI-BESS are based on load demand. The most important step when sizing a battery system is to determine the desired amount of energy storage. The design and sizing of an appropriate LI-BESS suitable for a given SUPS application are made through the following steps:

1. Determine which load will be backed up (critical load).
2. Perform a power balance analysis between the LIB-SUPS and the critical load. The amount of electrical power to be considered is the power delivered by that LI-BESS when called upon ($P_{bat\ SUPS}$). For that reason, the LI-BESS rating should be calculated starting with the SUPS apparent power required to support critical loads (S) while also considering the overall SUPS system efficiency (η_{SUPS}) and power factor ($\cos\varphi$) as per Equation 6.7-1.
3. Determine self-sufficiency, backup, or autonomy period at various load rates following the analysis of the facility's energy usage of critical equipment.
4. The most salient approach in determining the size of the LI-BESS is to bring up its project planning datasheet. This project planning datasheet details the rack's constant power discharge ratings based on its autonomy time and at a predetermined operating temperature.
5. Depending on the LIB-SUPS system DC voltage, determine the system Ah capacity and cells string configuration.
6. Identify how many battery racks are needed to achieve a specific DC voltage based on the bank voltage and the target Ah capacity.
7. Design and size the LI-BESS based on the facility load requirement. It is imperative to ensure uniformity of battery type throughout the battery storage system.

The LI-BESS uses Samsung SDI prismatic LMO lithium-ion battery cells installed inside 128S1P cabinets. Each cabinet contains 16 battery modules forming a single string, and each module has eight battery cells in an 8S1P configuration (8 x 1S1P cells per module). These battery modules are connected in series via provided busbar DC links, as shown in Figures 6.7-1 & 2. The battery cell voltage is 3.8V, the nominal capacity is 67Ah, and the constant discharge energy is 67Ah x 3.8VPC = 254Wh. Given these cell parameters, the module voltage is equal to 30.4V (8 x 3.8VPC). The nominal module capacity and discharge energy are, respectively, equal to 67Ah and 2.036kWh (8 x 254Wh/cell or 67Ah x 30.4V), the cabinet voltage is equal to 486.4V (16 x 30.4V/module), and the nominal cabinet capacity and discharge energy are, respectively, found to be equal to 67Ah and 32.6kWh (16 x 2.036kWh/module or 67Ah x 486.4V). Similarly, from using Equation 3.2.3-1 and based on the maximum installed capacity of 1100kVA per SUPS, the battery power is determined as per one of the two options below (Eaton, 2019c:1-3; Samsung SDI, 2017c:9 & 2014:1-2; Mayo, 2018:33; Samsung SDI, 2017a:37):

a) Option 1 - Calculation based on full installed kVA

This design opts to design a system that will provide a 20 minutes backup time at 100% SUPS unit loading. By sizing the new SUPS system with the same capacity as the old RUPS system and with the efficiency and power factor of the SUPS unit given to be 0.97 and 1, respectively, the LI-BESS power required is determined as per Equation 6.7-1 below:

$$P_{bat\text{-}SUPS}=\frac{S\times cos\varphi}{\eta_{SUPS}}=\frac{1100\times 1}{0.97}=1134.02kW \quad (6.7\text{-}1)$$

Based on the technical data in Table 6.7, for a backup time not exceeding 20 minutes, the initial and final constant power discharge power are 77.6kW and 61.5kW, respectively. To ensure that the facility is supplied with the required power through LIBs lifetime degradation, the final constant power discharge or final battery capacity of 61.5kW is considered. From Equations 6.7-1, we can deduce that the number of parallel battery racks or cabinets associated with each SUPS unit is equal to 1134/61.5 = 18.44 which, can be rounded up to 20. The total designed storage or amp-hours capacity for LI-BESS is equal to 67Ah x 20 = 1340Ah, and its total designed constant power discharge rating is 61.5kW/rack x 20 racks = 1230kW.

b) Option 2 – Calculation based on full kW of critical loads

Each of the existing RUPS units was designed to take up the full critical load in the facility while running at an efficiency and power factor of 0.92 and 0.8, respectively. The power delivered by the LA-BESS is equal to 956.522kW, as determined in Equation 3.2.3-2. With future expansion set at approximately 25%, the new LIB-SUPS power can be calculated as shown in Equation 6.7-2 below:

$$P_{bat\text{-}SUPS}=956.522\times 1.25=1195.65kW \quad (6.7\text{-}2)$$

Based on the technical data in Table 6.7 and Equations 6.7-2, for a backup time not exceeding 20 minutes, we can deduce that the number of parallel battery racks or cabinets associated with each SUPS unit is equal to 1195.65/61.5 = 19.44 which, can be rounded up to 20. The total designed storage capacity for the LI-BESS is equal to 67Ah x 20 = 1340Ah. Its total designed constant power discharge rating is equal to 61.5kW/rack x 20 racks = 1230kW.

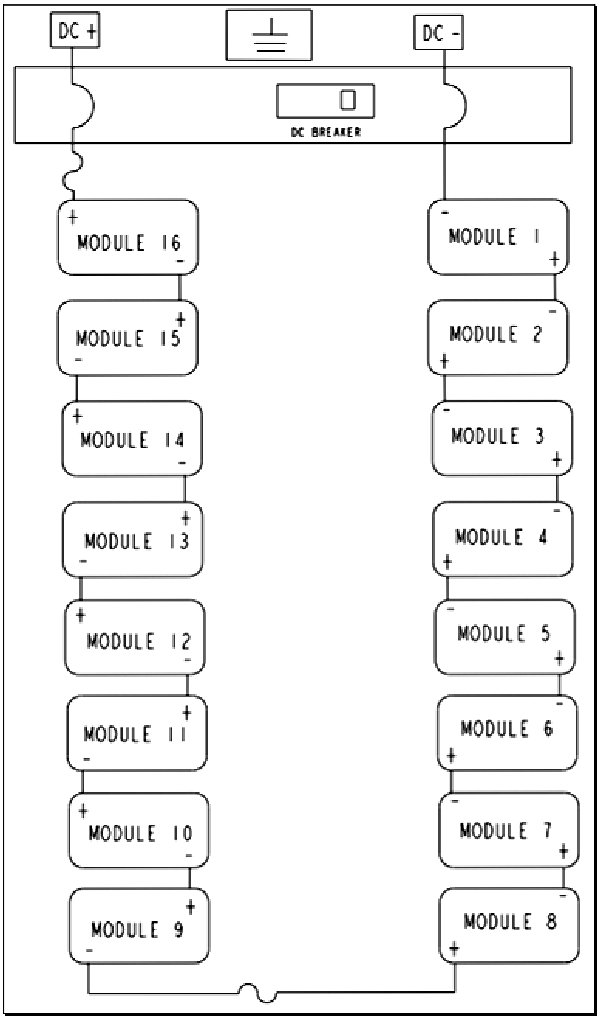


Figure 6.7-1: String configuration - 128S1P LI-BESS (Eaton, 2019c:3)

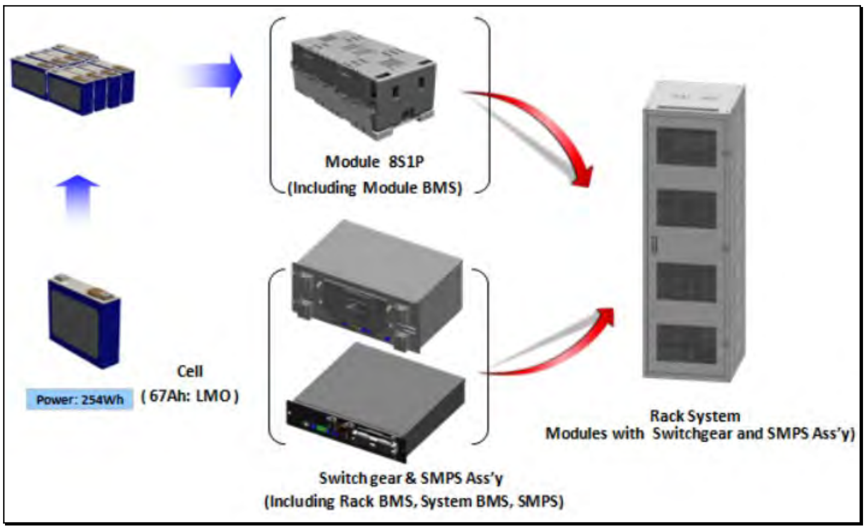


Figure 6.7-2: Composition layout of the LI-BESS rack (Samsung SDI, 2017c:9)

Table 6.7: Samsung 128S1P rack technical data (Mayo, 2018:33)

CONSTANT POWER DISCHARGE RATINGS - kW PER STRING @ 25°C																				
MUNUTES	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
INITIAL CAPACITY	213.0	210.0	207.0	204.0	201.0	195.0	190.0	184.0	172.9	154.5	140.7	129.2	119.4	110.2	103.0	96.8	91.2	86.2	81.7	77.6
FINAL CAPACITY	210.0	201.0	195.0	190.0	177.0	162.0	155.0	147.0	135.0	122.9	111.7	102.4	94.6	87.8	81.9	76.8	72.3	68.3	64.7	61.5
MUNUTES	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
INITIAL CAPACITY	74.5	71.4	68.4	65.3	62.2	60.1	58.0	55.9	53.8	51.7	50.5	49.4	48.2	47.1	45.9	44.8	43.6	42.5	41.3	40.2
FINAL CAPACITY	59.0	56.6	54.1	51.7	49.2	48.1	46.4	44.8	43.1	41.0	40.1	39.2	38.3	37.3	36.4	35.5	34.6	33.7	32.8	31.9
MUNUTES	**41**	**42**	**43**	**44**	**45**	**60**	**90**	**120**	**180**	**240**	**300**	**360**	**420**	**480**						
INITIAL CAPACITY	39.0	37.9	36.7	35.6	34.4	25.8	17.2	13.0	8.6	6.5	5.2	4.3	3.7	3.2						
FINAL CAPACITY	31.0	30.0	29.1	28.2	27.3	20.5	13.7	10.2	6.8	5.1	4.1	3.4	2.9	2.6						

ITEM	SPECIFICATION	REMARKS
NUMBER OF CELLS PER CABINET	128	8 CELLS PER MODULE
NOMINAL CAPACITY PER CABINET	32.6kWh	1/3C @ R.T.
NOMINAL VOLTAGE	486.4VDC	3.8V/CELL
MAXIMUM VOLTAGE	537.6VDC	4.2V/CELL
END OF DISCHARGE VOLTAGE	384VDC	3.0V/CELL
MAXIMUM DISCHARGE CURRENT	600A	1-SECOND PULSE
SHORT CIRCUIT CURRENT	7400A	
FLOAT CHARGE VOLTAGE	537.6VDC	4.2V/CELL
RECOMMENDED CHARGE CURRENT	22.3A	PER CABINET
MAXIMUM CHARGE CURRENT	250A	2-SECOND PULSE
RECOMMENDED OPERATING TEMPERATURE	23°C +/- 5°C	AMBIENT
STORAGE TEMPERATURE	0 - 40°C	
STORAGE HUMIDITY	LESS THAN 60% RH	NON-CONDENSING
ELECTROLYTE WEIGHT PER CELL	343g	128 CELLS PER CABINET

OVERCURRENT PROTECTION TRIGGER CURRENT	
600A	1 SECOND
540A	10 SECONDS
495A	30 SECONDS
470A	60 SECONDS

6.7.1 Backup time at different loading rates

Based on the LI-BESS rating determined above, the backup or autonomy time profile of each Eaton Power Xpert 9395P High-Performance SUPS unit in terms of various loading rates can be deduced as shown in Table and Figure 6.7.1 below.

Table 6.7.1: SUPS unit backup time vs. percentage loading

Percentage loading (%)	Loading power (kW)	Loading power per rack/string (kW)	Backup time (Minutes)
100	1134.00	56.70	21
90	1020.60	51.03	24
75	850.50	42.53	29
60	680.40	34.02	37
45	510.30	25.52	45
30	340.20	17.01	60
20	226.80	11.34	105

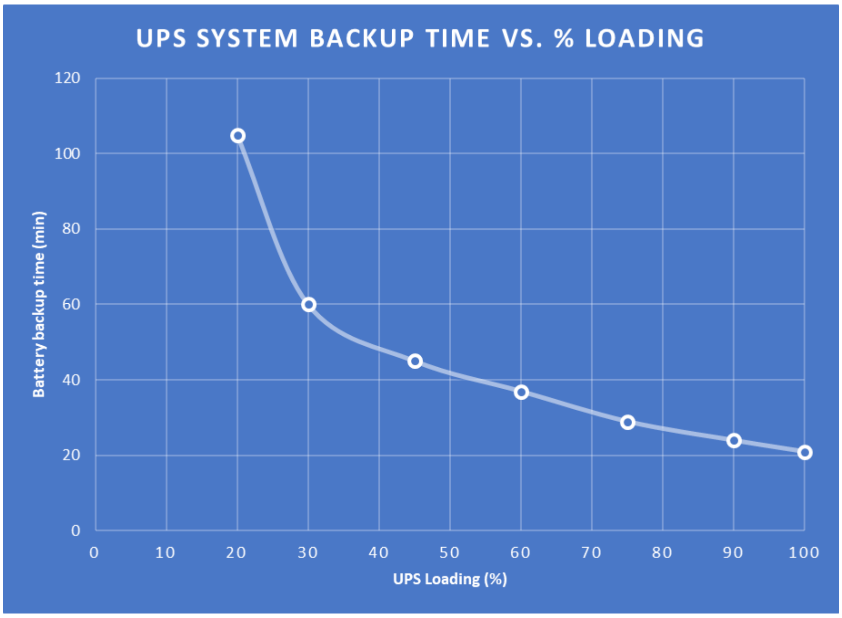


Figure 6.7.1: SUPS unit backup time vs. percentage loading trend

6.7.2 Battery cabinet features

The battery cabinet will consist of standard components, as described below, housed in a metal frame cabinet. Each cabinet will contain 16 x 8S1P Samsung battery modules, one BPU, and one switched-mode power supply (SMPS) assembly. Control, communication, and power cables land into the cabinet through a wiring platform placed at the top of the cabinet.

6.7.2.1 Operation status for 128S1P configuration

Table 6.7.2.1 below details typical and maximum state of charge and discharge conditions to keep the battery system in normal operation (Samsung SDI, 2017b:18).

Table 6.7.2.1: Range of operation - 128S1P configuration (Samsung SDI, 2017b:18)

No.	Item	Specification	Remarks
1	Nominal Capacity	32.6kWh	1/3C@R.T
2	Nominal Voltage[1]	486.4V DC	3.8V/cell
3	Maximum Voltage[1]	537.6V DC	4.2V/cell
4	Discharging Method	Constant Power	
	End of Discharge Voltage[1]	384V DC	3.0V/cell
	Recommended End of Discharge Voltage	409.6V DC	3.2V/cell
	Standard Discharging Current	22.3A	1/3C@R.T
	Maximum Continuous Discharge Power	173kW	Peak 450A @ EODV
5	Charging Method	CC-CV, Floating	
	Floating Charge Voltage	537.6V DC	4.2V/cell
	Standard Charge Current	22.3A	1/3C
	Maximum Peak Charge Current	250A	2 second pulse
	Maximum Continuous Charging Current	67A	1C
6	Recommended Operation Temperature	23±5°C	
7	Storage Temperature	0 ~ 40°C	
8	Storage Humidity	Less than 90 % RH	Noncondensing
9	Recommended Storage Humidity	Less than 60 % RH	Noncondensing
10	Storage Period[2]	Less than 6 months	

6.7.2.2 Battery cabinet main characteristics

The main characteristics of the lithium-ion battery cabinet are specified below:

Nominal input voltage (128S1P model) = 486.4VDC (16 x 30.4V) at 3.8VPC

Nominal output voltage (128S1P model) = 486.4VDC

Float voltage (128S1P model) = 537.6VDC

Minimum tripping-point voltage = 409.6V

End-of-discharge voltage (128S1P model) = 384VDC

Nominal input current: Up to 22.3A (state-of-charge dependent)

Discharging mode: Constant power discharge

Cabinet's weight = 17kg

Cabinet's dimension: Length = 414mm; Width = 216mm; Height = 163mm

6.7.2.3 Battery protection unit assembly

The switchgear or BPU assembly, as shown in Figure 6.7.2.3 below, consists of an RBMS and protection devices. The electrical characteristics of the BPU are specified below (Samsung SDI, 2017a:7):

Maximum continuous current rating = 460A

Fuse rating = 500A

Moulded-case circuit breaker rating = 600A

Switchgear's weight = 15kg

Switchgear's dimension: Length = 583 mm; Width = 235 mm; Height = 411 mm

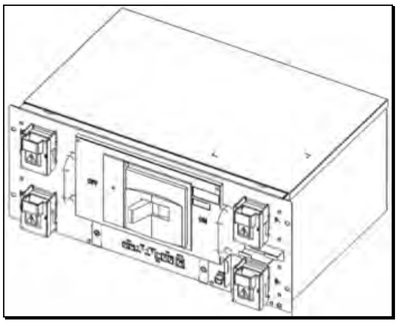


Figure 6.7.2.3: Front view of a BPU assembly (Samsung SDI, 2017a:7)

6.7.2.4 Switched-mode power supply assembly

The SMPS assembly, shown in Figure 6.7.2.4 below, provides power to the RBMS and BPU systems that assume rack and bank management and protection. Two types of SMPS exist; Type A (with BBMS or SBMS) and type B (without BBMS or SBMS). The SBMS assembly provides information to all peripheral systems (building management system and SUPS system) while maintaining a condition-based control and monitoring of all connected RBMSs. SMPS assembly also provides an RS485 (via RJ-45) port used as an optional user monitoring software connection. The evaluation of the economic performance of the battery storage system considers two main financial metrics, namely, the capital expenditure and payback period. A key element in the energy storage system is the capability to protect battery banks while in operation, thus, prolonging their life expectancy to safeguard the facility's direct investment. The LI-BESS that includes levels of BMS has long-term economic sustainability and fiscal impact from the construction and operation. Premature battery degradation and capital replacement costs can remove the value provided to customers and make it difficult to justify the capital expenditure. The system selects Type A-SMPS to optimize the financial requirement of the energy storage system.

Weight (Type A - SMPS) = 5kg

Dimension: Length = 397mm; Width = 338mm; Height = 86mm

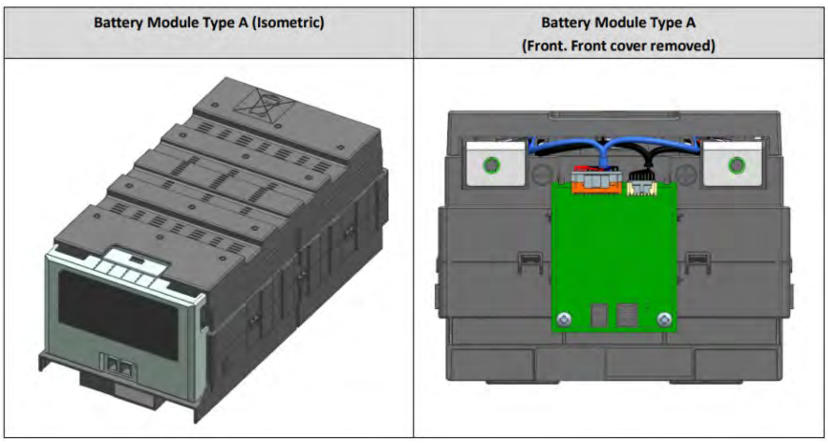


Figure 6.7.2.4: Battery module with Type A - SMPS (Samsung SDI LIB)

6.7.2.5 Battery rack-frame

Rack-frames or cabinets, shown in Figures 6.7.2.5-1 & 2 below, house battery modules, the BPU, and SMPS assembly. The standard cabinet used in this study has the following parameters:

Battery cabinet model: 128S1P

DC output nominal voltage = 486.4V

Battery nameplate = 32.6kWh

Heat output = 567BTU

Dimension: Length = 650mm; Width = 530mm; Height = 2281mm

Weight installed (for 128S1P configuration): 482kg

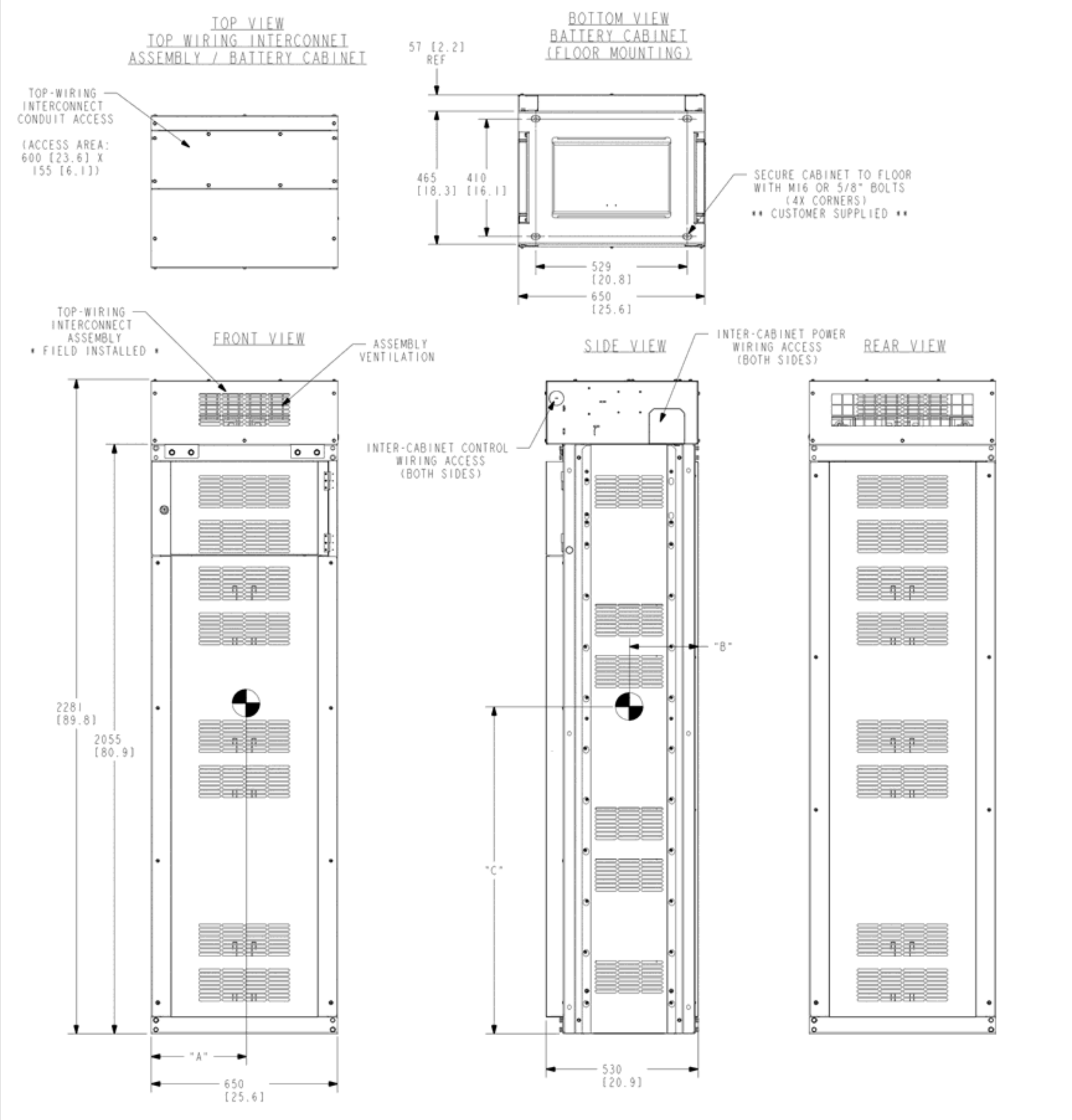


Figure 6.7.2.5-1: LI-BESS rack or cabinet layout (Eaton, 2019c:1)

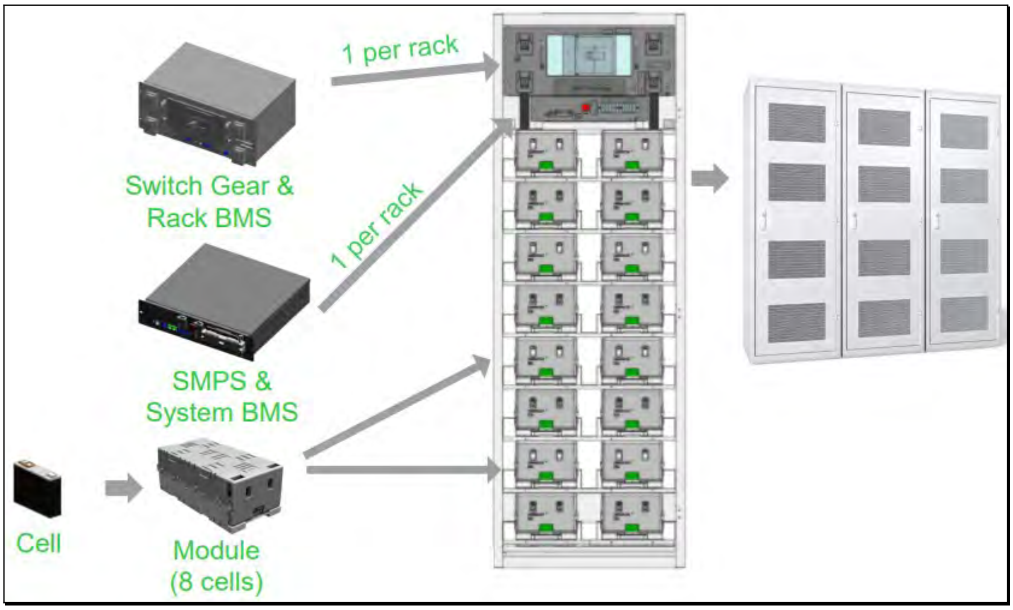


Figure 6.7.2.5-2: LI-BESS rack or cabinet composition (Samsung SDI LIB)

6.7.6 Protective and monitoring devices

This section describes devices and components offering system status (fault and alarm) and monitoring capabilities to the LI-BESS, as per Tables 6.7.6-1 & 2. The status panel, situated at the operator side of the BPU assembly, uses LED-type lamps to annunciate the functionality status of the LIB cabinet or rack; e.g. major or minor alarms of fault conditions, warning conditions, battery charge or discharge status, protective devices status, state of charge, battery bank voltage, power, current or temperature. Causes of indicators are reachable through the monitoring software incorporated in the battery system. Communication with this monitoring software can be realized by connection to the battery BBMS using the Modbus data communications protocol. There is also an SMPS on/off status located on the SMPS box. It has a green LED on the lower and upper of the power supply(s) labelled SMPS #1 and SMPS #2. The BPU power switch located inside the battery cabinet features LED status lamps for functionality status indication of the RBMS. A rocker switch energizes the RBMS controls for the associated battery string. Concerning the battery communication protocol, the RS-485 and RJ-45 connectors or communication ports, placed on the front side of the BBMS module, accommodate the Modbus TCP communication protocol of the entire SUPS system. The integration of this battery communication protocol into the facility's building management system and network management systems (NMS) is preferred. The BBMS or SBMS provides two hard-wired signal outputs to indicate a summary alarm and the battery system status (Samsung SDI, 2017b:14-15).

Table 6.7.6-1: Indicated codes (Samsung SDI, 2017b:15)

LED Status	Battery Status	Remarks
FAULT CURRENT POWER ALARM POWER steady	Normal status	MCCB Off
FAULT CURRENT POWER ALARM POWER blinking	Normal status	MCCB On
FAULT CURRENT POWER ALARM POWER blinking CURRENT steady	Normal Status	Discharge
FAULT CURRENT POWER ALARM POWER blinking CURRENT blinking	Normal Status	Charge
FAULT CURRENT POWER ALARM POWER steady FAULT blinking	Major Protection MCCB tripped	Over-Voltage Protection Under-Voltage Protection Over-Temperature Protection Over-Current Protection
FAULT CURRENT POWER ALARM POWER blinking ALARM blinking	Minor Protection MCCB on	Voltage Imbalance Error Voltage Sensing Error Under Temperature Protection Temperature Imbalance Error

Table 6.7.6-2: LED indicator (Samsung SDI, 2017b:14)

Items	POWER(Green)	FAULT(Red)	ALARM(Yellow)	CURRENT(Green)
Location	FAULT CURRENT POWER ALARM	FAULT CURRENT POWER ALARM	FAULT CURRENT POWER ALARM	FAULT CURRENT POWER ALARM
Status	On : MCCB Off Off : Power Off Blink : MCCB On	On : N/A Off : Power Off Blink : Major Protection	On : N/A Off : Power Off Blink : Minor Protection	On : Discharge Off : Idle Blink : Charge

6.7.7 Battery cabinet wirings

The battery cabinet has landing plates to ease the penetration of wiring cables into the enclosure. The BPU module contains positive and negative power connection terminals. The SMPS module has three terminals: power connection terminals for 480VAC or 120-240VAC cables originating from the input and output busses of the SUPS unit, shunt trip and auxiliary contact terminals for cabinet's protective devices, and communication terminals. Each LI-BESS cabinet will require a separate breaker for its 480VAC or 120-240VAC connection terminals. Bank battery monitoring module or BBMS contains plug connections for Modbus TCP communication and relay contacts connection to/from the SUPS system and building management system.

6.7.8 Battery racks mechanical design and installation

The battery cabinet enclosures are of steel construction. They are installed according to the clearance distances listed in Table 6.7.8 and Figure 6.7.8-1 below. These enclosures house battery modules, BMS, SMPS, BPU, and all supply and interconnect cablings. They are made to be accessed from the front or operator side and sufficiently guarded by access doors constructed and safety-signed to prevent illegal entries. In this installation, only a clearance distance of 1 metre on the front or operator side of the battery rack enclosure is necessary, as referred to in Table 6.7.8 Figure 6.7.8-1 below. No provision for side or rear clearance is needed. The front or operator side of the racks is cleared for installation, maintenance, service access, ventilation, and cooling. Supply cables enter the battery cabinet enclosure through the top. All functional sub-assemblies and components that are serviceable are of modular design. The ejection, replacement, or installation of these sub-assemblies or components is executed from the front or operator side of the cabinet enclosure. The 20 x 128S1P battery cabinets or racks associated with each Eaton Power Xpert 9395P High-Performance SUPS unit will be installed side-by-side and rear-to-rear in two rows in a so-called '128S20P' configuration or layout shown in Figure 6.7.8-2. (Samsung SDI, 2017a:26).

Active or air-forced ventilation system is required to maintain battery cabinet enclosures and battery room temperatures to an acceptable level that is desirable to avoid thermal runaway and maximize battery cell lifespan. Cabinets are designed to let air in from the front side and exhaust from the top side. To comply with the manufacturer recommendations for racks installed with no rear clearance, part of the existing air-conditioning system illustrated in Section 3.3.1 will be maintained.

Table 6.7.8: Rack clearance distance (Samsung SDI LIB)

Configuration	Anchor points per rack	Clearance Distance (mm)			
		Side (end)	Side (adjacent)	Rear	Front
Single Rack	2 (Front) not rated for seismic event	0	n/a	0	1000
	4 (All) – Telcordia Zone 3	800	n/a	800	1000
Multiple Racks (Side-to-Side)	2 (Front) not rated for seismic event	0	0	0	1000
	4 (All) – Telcordia Zone 3	800	0	800	1000
Multiple Racks (Side-to-Side and Rear-to-Rear)	2 (Front) not rated for seismic event	0	0	0	1000
	4 (All) – Telcordia Zone 3	800	0	800	1000

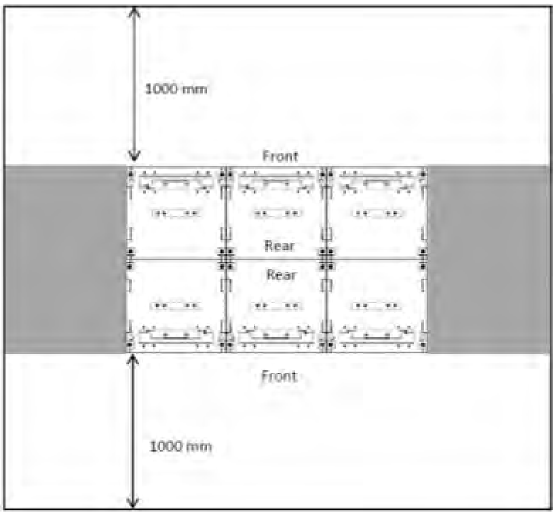


Figure 6.7.8-1: Rack installation and clearance distance (Appendix H; Samsung SDI, 2017a:26)

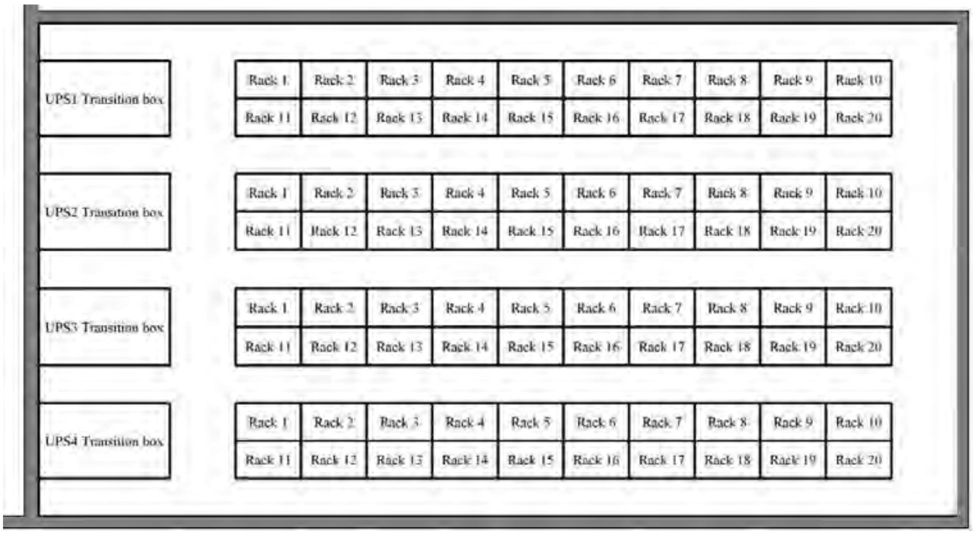


Figure 6.7.8-2: SUPS system - 4 x 128S20P racks installation layout (NTS)

6.7.8.1 LI-BESS spatial footprint and floor loading capacity

The 20 battery cabinets of the LI-BESS associated with each Eaton Power Xpert 9395P High-Performance SUPS unit are stacked into two rows as described above. Each row contains ten battery cabinets installed side-by-side and rear-to-rear in a so-called '128S20P' configuration or layout. The LI-BESS spatial footprint and floor loading capacity are determined below:

Battery cabinet model: 128S1P

Length of the battery rack = 0.65m

Width of the battery rack = 0.53m

Height of the battery rack = 2.281m

Surface area occupied by each rack or cabinet = 0.65 x 0.53 = 0.3445m²

The total area occupied by the LI-BESS associated with SUPS = 0.3445 x 20 = 6.89m²

The total area occupied by all LI-BESSs associated with SUPS system = 6.89 x 4 = 27.56m²

Weight of each battery rack = 482kg

The total weight of each LI-BESS associated with SUPS = 482 x 20 = 9640kg

The total weight of all four LI-BESSs associated with SUPS system = 9640 x 4 = 38560kg

6.7.9 Commissioning

The following pre-start inspections and performance tests are to be carried out by technical personnel in charge of the commissioning process. With standardized commissioning procedure for LI-BESSs not fully developed yet, their commissioning process is expected to draw similarity from that of the LA-BESSs. This procedure will contain subsequent steps:

6.7.9.1 Pre-start inspections

Inspect all components to identify any sign of mechanical damage or ingress of any foreign material into battery enclosures must be conducted. Conduct a hazard identifications and risk assessment of the battery system. Inspect all safety signs and the cooling system on various sections of the battery system. Verify and ensure that all power connection terminals are secure and sound and that the terminations of all control cables are correct. Verify and ensure that the installation of the DC bus is compliant and no risk of short-circuiting is present. Verify routings of all control and power cables for correctness.

6.7.9.2 Recommended testing protocols

LIB-SUPS system configuration parameters and dynamic testing results must be recorded and kept as baseline data for future reference. Perform a static checkout to verify that installation has been conducted correctly and safely per the manufacturer's specification. Refresh batteries charges to ensure voltages of each respective battery strings are perfectly balanced and within recommended limits. Perform a full discharge test at various load rates to verify autonomy time, temperature, constant discharge power, constant discharge current, and voltages through the BMS system. Perform full charge test to assess various LI-BESS limits and their correct programming. Verify proper functioning of automatic disconnection or protective devices in each rack and communication statuses. Incorporate battery cabinets into the SUPS system using the service configuration software. Carry out a dynamic, on-power, or energized test to check the full functionality and operation of the LIB-SUPS system. Verify settings and limits of all critical parameters. Confirm permissive conditions and functionalities of all configured major and minor alarms.

6.8 Summary

The development of LIB chemistry compared to LAB has introduced enhanced features in the LI BESSs. These features result in energy density boosting, lifecycle enhancement, extended warranty on service life, and flexibility in their implementation. These LI-BESSs provide a greater cycle life with the number of charge-discharge cycles ranging from 3000 (8 years) and extending to 6000 (15 years), versus approximately 500 - 1000 (2 to 3 years) for LA-BESSs. These features have equipped LI-BESS with improved and advanced backup energy storage predictability and manageability by incorporating battery management systems into the LI-BESS cabinets or racks for condition-based monitoring and management of currents, voltages, temperature, state of health, state of charge, capacity, cell balancing, performance status of battery cells, modules, and strings. Furthermore, the lithium-ion chemistry development has made LI-BESSs have their EOL capacity typically dropping only by 20% versus 50% for LA-BESSs. They have become less sensitive to temperatures, thus, offering a reduced cooling and thermal management constraint. In addition, the facility can easily deploy LIBs technology without continuous maintenance and replacement challenges shown in LABs, saving labour and replacement costs. Besides many advantages, the principal drawback of LIB technology derives from the fact that it is modern. Some UPS system manufacturers still have little involvement in introducing LIB into their applications. Nevertheless, this has been evolving speedily with effective LI-BESS deployments into various rotary or static UPS systems for some years.

A significant decrease in weight and size is the most far-reaching benefit a LIB system offers to a facility implementing or planning to implement the technology over the LAB system. Substantial reduction in the total footprint of LIB technology has significantly impacted the overall development of the facility's power protection philosophy. Chapter seven conducts this comparative analysis of the two battery technologies. The LIB technology development has improved its flexibility, availability, and modularity. It offers reduced repair time, ease of maintenance, ease of battery module replacement, space-saving, scalability, and upgradeability.

The sizing of LI-BESS is slightly different from that of an LA-BESS as the hold-up time of critical loads and processes is limited by both the battery cells' voltage boundaries and operating temperatures. The statement above implies that the discharge cut-off time for LIB cells is imposed not only by low cell voltage like in lead-acid but also by their internal temperatures to avoid thermal runaway. The quantity of service charge collected from the lithium-ion technology at the given state of its maximum stored charge doubles compared to lead-acid technology. This deep energy collection is safely conducted using innovative battery management systems implanted at the module, cabinet, and system level to offer condition-based monitoring and management of cells' functionality, state of charge, and health.

The recharge rate of LIBs is higher than that of LABs. LI-BESSs are considerably recharged quicker as compared to LA-BESSs. A reliable and monitored backup solution with easily accessible battery health data is necessary for today's connected facility's environment. The lithium-ion solution meets this demand through its innovative battery management system implanted at the module, cabinet, and system level to offer condition-based monitoring and management of batteries system's functionality and health. During the battery cell recharge region, the BMS monitors SOC, SOH, voltage levels, and the internal temperature of each LIB cell to allow automatic control of the charging process and avoid potential thermal runaway. This controllability feature might extend the recharge time to their capacity.

LABs have a limited lifetime by design. It is essential to keep the battery at room temperature of around 20°C and 25°C to optimize this lifetime. While all batteries will age faster at higher temperatures, the LIBs' nominal lifetime and ageing characteristics are such that they will tolerate higher operating temperatures or occasional spikes and still retain much longer battery life versus LABs. This thermal tolerance of lithium-ion technology allows a significant reduction in the battery room cooling and ventilation capacity needed to remove the heat load emitted in the summer seasons. LABs have a limited lifetime, especially when subject to temperature fluctuation. To ensure runtime availability, many customers replace even the highest quality LABs every three to six years, driving up maintenance costs. Lithium-ion technology has a service life that is double compared to that of the LAB technology. The extended battery service life reduces the burden and cost of battery cell replacement, risk of possible downtime, and risks associated with the temporary removal of the facility power protection system.

Numerous safety measures must be considered when dealing with the RUPS system. Exceptional alertness to the LA-BESS connected to the RUPS system is needed. The monitoring and prevention of excessive accumulation of hydrogen gas in the battery room need to be established to avoid the risk of fire or explosion. Materials used in LIBs, including cobalt, nickel, manganese, iron, and aluminium, are not as poisonous as LABs, and their disposal does not cause any environmental concern. Charged LIB cells can dangerously lead to a fire or explosion if mishandled or dismantled. They need to be in a fully discharged state before any disposal process is undertaken. Another drawback of LIBs is that they can go into thermal runaway if operated at excessive temperatures. However, in the LI-BESS applications, the presence of the BMS provides condition-based monitoring and management over the battery system to reduce the possibility of thermal runaway conditions. LIB cells have safety mechanisms protecting them even in abnormal situations. LIBs will not get into thermal runaway if designed and configured to achieve a high heat-dissipation rate than the heat generated when overcharged. The LI-BESS system requires an active ventilation system to maintain operating temperatures within specified ranges that will prevent degradation of its capacity and reduction in lifespan.

CHAPTER SEVEN

COMPARATIVE ANALYSIS – LIB-SUPS VS. LAB-RUPS SYSTEM

7.1 UPS systems main characteristics

The main characteristics of both UPS systems are summarised in Table 7.1 to allow comparative electrical analysis between the LAB-RUPS and LIB-SUPS system.

Table 7.1: LAB-RUPS and LIB-SUPS systems main details

UPS Details	RUPS system	SUPS system
UPS type	Piller UB1100S RUPS	Eaton Xpert 9395P SUPS
BESS type	LA-BESS	LI-BESS
UPS modules in parallel	4	
Input and output voltages	600/600VAC	
UPS module rating	1100kVA	
UPS module efficiency	92%	97%
UPS input power factor	0.8	1
UPS output active power	1100 x 0.8 = 880kW	1100 x 1 = 1100kW

7.2 LIB-SUPS system CAPEX

For the success of this project, it is necessary to consider the financial implication from the start. The effectiveness of the implementation objective will take a positive approach that achieves the best outcome within the agreed budget. System design made with cost-effective ideas in mind creates a concept that might exceed the facility's expectations. The estimate CAPEX in Table 7.2 below approximates the implementation cost of this upgrade with the following services and works excluded: local authority approvals, fire detecting and protecting system, and integration of the new SUPS system into the local facility building management system. Pricings on the SUPS units and LI-BESSs indicated on lines 4 and 5 were obtained from the quotation provided by Eaton Electric (Pty) Ltd in 2020/2021 financial year and are based on this design. The prices on them in the 2021/2022 financial year are given in Table 7.6-3.

Table 7.2: LIB-SUPS system upgrade cost estimate

Installation Estimate Summary					
Appropriation Title:	**UPS SYSTEM UPGRADE**				
	Feature	**Capital Spending**		**Expense**	
Number	**Title**	**Material**	**Labour**	**Material**	**Labour**
000001	**General**: Documentation, Certification, Testing commissioning, Delivery		R 150 000		
000002	**Civil and structural works**: Allowance for remedial works, Rigging, UPS and battery racks installation		R 105 000		
000003	**Cable Management**: Cable trays, Cable ladders, Mountings. Existing Mains cables, Control cables re-routing and terminations. Earthing and bonding	R 60 000	R 85 000		
000004	**UPS Power plant:** 4 X 1100kVA Eaton Xpert 9395P static UPS's with control panel, remote view software, Modbus interface, extraction fans, Air conditioning	R 8 977 528			
000005	**Energy storage system**: 20 x 4 - 128S1P Li-Ion battery racks with BMS, BPU, Factory acceptance tests, Supplier site commissioning and tests.	R 28 791 920			
000006	Consulting fees (Electrical & structural)		R 3 500 000		
		R 37 829 448	R 3 840 000		
	5% Allowance for Contingency & Escalation	R 1 891 472	R 192 000		
	TOTAL	R 39 720 920	R 4 032 000		
	Total Material and Labour (Excl. VAT)	R 43 752 920			
			Capital Spending:		**R 43 752 920**
			Expense:		
			GRAND TOTAL		**R 43 752 920**
					$ 3 017 442,79
Remarks:					
Exchange Rate	**1 USD = ZAR 14.5**				

7.3 Assumptions

All calculations are done on the average number of days per month = 365 days a year / 12 months a year = 30.417; thus, the total number of hours a month equals 24 x 30.417 = 730 hrs. Based on data obtained from Eskom, the facility had 67 interruptions sustained above 5 minutes in the past 10 years (Appendix I; Eskom, 2021b), giving an average of 7 interruptions per year. For that, we assume to have 7 complete battery discharges and recharges a year. The discharge is made through a full 15 minutes design backup time to translate to a monthly discharge period of 0.146 hours (7 x 15 min/12 x 60). Each charging process takes 6 hours and translates to a monthly charge period of 3.5 hours (7 x 6 hours/12 = 3.5 hours). With the average number of hours per month taken to be 730 hours and based on monthly discharge and charge periods determined above, we can deduce that LAB will be in floating operation for the rest of the time when not discharging or charging, and this is equivalent to 726.35 hours a month. Two ventilation units are used to control battery room temperature and prevent the unsafe accumulation of hydrogen gas. The system is designed to run both ventilation units for LA-BESS and only one single unit for LI-BESS at full capacity during summertime or low-demand season to compensate for their winter or high-demand season consumptions. Through energy transformation, from electrical to heat developed in the UPS system, we will assume that of every Watt of dissipated heat energy by any equipment, 60% Watt of electrical power is consumed.

The facility uses the 'Miniflex' electricity tariff structure from the power utility. This tariff structure is one of the time-of-use (TOU) electricity tariffs for urban customers with a notified maximum demand (NMD) from 25kVA up to 5MVA. TOU tariff means a tariff with energy charges that change during different TOU periods and seasons. This TOU tariff is commonly used in developed economy countries as it is structured to incentivise consumers who lower their consumption during peak periods. The TOU periods typically are peak, standard, and off-peak periods and differ during high and low demand seasons. As more critical loads add to the UPS system, a high amount of power will need to be processed by various main components (inverter, rectifier). The losses emanating from these components will vary in proportion to critical loads, so are the energy charges during TOU periods and seasons. With this TOU electricity tariff structure having an economic impact on the wasted energy costs from both UPS systems, the accurate energy losses costs in alignment with the facility consumption profile or behaviour will need to be determined. Unfortunately, the main concern from previous researches while evaluating UPS system losses was to consider a fixed average energy charge in their annual energy losses calculations. UPS system annual energy losses costs specification based on an average energy charge will unfortunately not be load-profiled to the facility's energy consumption profile nor adapted to the power utility's charges through various seasons and time of the day. To specify these energy losses costs more accurately, the wasted energies distribution must follow the realistic energy profile or consumer behaviour and get charged per their time of use. The total cost of ownership bases on energy costs from Eskom's time of use (TOU) tariff and the 2020/2021 Miniflex tariff structure that include all ancillary charges (Eskom, 2021a). Energy distribution through this comparison is made in alignment with facility load profile obtained from the existing online metering infrastructure hosted and managed by http://www.silkamr.com as per Appendix J. Distribution ratio both during high and low-demand seasons as specified below:

<u>High-demand season energy distribution ratios</u>

Peak energy average = 0.309X

Standard energy average = 0.794X

Off-peak energy average = X

(X + 0.309X + 0.794X) = Y

X = Y/2.103

Y = Total seasonal energy calculated

X = Multiplying factor = Off-peak energy

Low-demand season energy distribution ratios

Peak energy average = 0.297X

Standard energy average = 0.759X

Off-peak energy average = X

(X + 0.297X + 0.759X) = Y

X = Y/2.056

Y = Total seasonal energy calculated

X = Multiplying factor = Off-peak energy

7.4 LAB-RUPS system losses calculation and energy distribution

All energy distributions based on calculations below are tabulated in Tables 7.4-1 & 2, and their respective costs are tabulated in Tables 7.4-3 & 4 shown below:

a) UPS heat energy losses: With the maximum heat dissipation of each RUPS unit given to be 87kW, 60% of this heat represents electrical power consumed and equal to 87 x 0.6 = 52.2kW. For all four RUPS units running throughout 730 hours of the month, the monthly electrical energy is equal to 52.2 x 730 x 4 = 152 424kWh.

b) Battery room cooling losses: For the LAB room, it was assumed above to run both ventilation units at full capacity during summertime. The total cooling power of both air-conditioning units used is (21 + 16) = 37kW leading to a monthly electrical energy of 37 x 730 = 27 010kWh.

c) Rated operation losses: Equations 7.4-1 & 2 below determines these losses. The rated loss of each RUPS unit is equal to 76.5kW, and for all four RUPS units running throughout 730 hours of the month, the monthly electrical energy is equal to 76.5 x 730 x 4 = 223 380kWh.

$$\eta = \frac{P_{out}}{P_{out} + P_{rated\text{-}losses}} \rightarrow P_{rated\text{-}losses} = \frac{P_{out}}{\eta} - P_{out} \qquad (7.4\text{-}1)$$

$$P_{rated\text{-}losses} = \frac{880}{0.92} - 880 = 956.522 - 880 = 76.5kW \qquad (7.4\text{-}2)$$

d) Batteries floating operation losses: As calculated in Section 3.2.2, the heat load during floating operation per cell was 1.275W, 60% of this heat represents electrical power consumed, and for all 1056 cells floating 726.35 hours a month as demonstrated in Section 7.3, the monthly electrical energy will then be equal to 1.275 x 0.6 x 1056 x 726.35 = 587kWh.

e) Batteries discharge operation losses: As calculated in Section 3.2.2, the heat load during discharge operation per cell was 299.32 W, 60% of this heat represents electrical power consumed, and for all 1056 cells discharging 0.146 hours on average a month as demonstrated in Section 7.3, the monthly electrical energy will then be equal to 299.32 x 0.6 x 1056 x 0.146 = 27.7kWh.

f) Batteries recharge operation losses: As calculated in Section 3.2.2, the heat load during recharge operation per cell was 46.521W, 60% of this heat represents electrical power consumed, and for all 1056 cells charging 3.5 hours on average a month as demonstrated in Section 7.3, the monthly electrical energy will then be equal to 46.521 x 0.6 x 1056 x 3.5 = 103.165kWh.

g) High-demand season wasted energy distribution

Y = 152.42 + 223.38 + 0.587 + 0.028 + 0.103 = 376.518MWh

X = Off-peak energy = 376.518 / 2.103 = 179.04MWh

Peak energy = 179.04 x 0.309 = 55.32MWh

Standard energy = 179.04 x 0.794 = 142.16MWh

h) Low-demand season wasted energy distribution

Y = 152.42 + 27.01 + 223.38 + 0.587 + 0.028 + 0.103 = 403.528MWh

X = Off-peak energy = 403.528 / 2.056 = 196.27MWh

Peak energy = 196.27 x 0.297 = 58.29MWh

Standard energy = 196.27 x 0.759 = 148.97MWh

i) High-demand season backup energy distribution

Y = 4400 x 0.8 x 0.146 = 514kWh

X = Off-peak energy = 514 / 2.103 = 244.41kWh

Peak energy = 244.41 x 0.309 = 75.52kWh

Standard energy = 244.41 x 0.794 = 194.1kWh

j) Low-demand season backup energy distribution

Y = 4400 x 0.8 x 0.146 = 514kWh

X = Off-peak energy = 514 / 2.056 = 250kWh

Peak energy = 250 x 0.297 = 74.25kWh

Standard energy = 250 x 0.759 = 189.75kWh

Table 7.4-1: LAB-RUPS system energy losses distribution per year

RUPS energy losses distribution per year					
Month	**Season**	**Total Energy (kWh)**	**Peak Energy (kWh)**	**Standard Energy (kWh)**	**Off-peak Energy (kWh)**
April	Low Demand	403528	58292	148968	196268
May	Low Demand	403528	58292	148968	196268
June	High Demand	376518	55323	142157	179039
July	High Demand	376518	55323	142157	179039
August	High Demand	376518	55323	142157	179039
September	Low Demand	403528	58292	148968	196268
October	Low Demand	403528	58292	148968	196268
November	Low Demand	403528	58292	148968	196268
December	Low Demand	403528	58292	148968	196268
January	Low Demand	403528	58292	148968	196268
February	Low Demand	403528	58292	148968	196268
March	Low Demand	403528	58292	148968	196268
Total kWh per year		4761306	690594	1767180	2303532

Table 7.4-2: LAB-RUPS system off-grid backup-time saving

RUPS Off-grid backup-time saving (distribution coefficients as per Appendix J)					
Month	**Demand Season**	**Total Energy (S x Cosφ x t) S = 4400kVA Cosφ = 0.8 t = 0.146hrs**	**Peak Energy (kWh)**	**Standard Energy (kWh)**	**Off-peak Energy (kWh)**
April	Low Demand	514	74	190	250
May	Low Demand	514	74	190	250
June	High Demand	514	76	194	244
July	High Demand	514	76	194	244
August	High Demand	514	76	194	244
September	Low Demand	514	74	190	250
October	Low Demand	514	74	190	250
November	Low Demand	514	74	190	250
December	Low Demand	514	74	190	250
January	Low Demand	514	74	190	250
February	Low Demand	514	74	190	250
March	Low Demand	514	74	190	250
	Total kWh per year	6167	895	2290	2983

Table 7.4-3: Total LAB-RUPS system energy losses cost per year

High demand vs low demand cost for 2020/2021 rates (RUPS)					
Customer Name:	**XXXXX**	**Consumption Data**	**HDS**	**LDS**	
Point of delivery ID	**0**	Sum of Utilised Capacity	15 000	45 000	kVA
Tariff	Miniflex	Sum of Chargeable Demands	13 500	40 500	kVA
Tariff Category	Urban	Peak Consumption	165 969	524 626	kWh
Supply voltage	≥ 500V & < 66kV	Standard Consumption	426 470	1 340 710	kWh
Transmission zone	> 900km	Off Peak Consumption	537 116	1 766 416	kWh
Tariff Classification	Non-Local Authority	Total Consumption	1 129 554	3 631 752	kWh
No of PODS	1	Excess Reactive Energy	-	-	kVArh
Size of supply	>1MVA & ≤5MVA	Days	92	273	days

		Miniflex (HDS)		**Miniflex (LDS)**		**Total 2020/2021 Charges**
Network charges	**Rate Units**	**2020/2021 Rates**	**2020/2021 Charges**	**2020/2021 Rates**	**2020/2021 Charges**	
Distribution network demand charge	R/kVA	0.00	R -	0.00	R -	R -
Network demand charge	c/kWh	8.03	R 47 573	8.03	R 149 786	R 197 359
LV Subsidy Charge	R/kVA	0.00	R -	0.00	R -	R -
Network capacity charge	R/kVA	28.65	R 429 750	28.65	R 1 289 250	R 1 719 000
Total network charges			**R 477 323**		**R 1 439 036**	**R 1 916 359**
Energy charges	**Rate Units**	**2020/2021 Rates**	**2020/2021 Charges**	**2020/2021 Rates**	**2020/2021 Charges**	
Peak	c/kWh	367.85	R 610 516	119.97	R 629 393	R 1 239 909
Standard	c/kWh	111.42	R 475 173	82.56	R 1 106 890	R 1 582 063
Off-Peak	c/kWh	60.48	R 324 847	52.39	R 925 426	R 1 250 273
Sub Total (TOU)			**R 1 410 536**		**R 2 661 709**	**R 4 072 245**
Total energy charges			**R 1 410 536**		**R 2 661 709**	**R 4 072 245**
Other charges	**Rate Units**	**2020/2021 Rates**	**2020/2021 Charges**	**2020/2021 Rates**	**2020/2021 Charges**	
Ancillary service charge	c/kWh	0.47	R 5 309	0.47	R 17 069	R 22 378
Reactive energy charge	c/kVArh	7.27	R -	0.00	R -	R -
Electrification and rural subsidy charge	c/kWh	9.22	R 104 145	9.22	R 334 848	R 438 992
Affordability subsidy charge	c/kWh	4.34	R 49 023	4.34	R 157 618	R 206 641
Administration charge	R/day	106.69	R 9 815	106.69	R 29 126	R 38 942
Service charge	R/day	236.74	R 21 780	236.74	R 64 630	R 86 410
Total other charges			**R 190 072**		**R 603 291**	**R 793 363**
Total excl VAT			**R 2 077 931**		**R 4 704 037**	**R 6 781 967**
VAT	15%		R 311 690		R 705 606	R 1 017 295
Total account			**R 2 389 620**		**R 5 409 642**	**R 7 799 263**
Average price	c/kWh		**181.23**		**132.26**	**145.15**

Table 7.4-4: Total LAB-RUPS system off-grid backup-time savings per year

High demand vs low demand cost for 2020/2021 rates (RUPS)					
Customer Name:	**XXXXX**	**Consumption Data**	**HDS**	**LDS**	
Point of delivery ID	**0**	Sum of Utilised Capacity	15 000	45 000	kVA
Tariff	Miniflex	Sum of Chargeable Demands	13 500	40 500	kVA
Tariff Category	Urban	Peak Consumption	227	668	kWh
Supply voltage	≥ 500V & < 66kV	Standard Consumption	582	1 707	kWh
Transmission zone	> 900km	Off Peak Consumption	733	2 250	kWh
Tariff Classification	Non-Local Authority	Total Consumption	1 542	4 625	kWh
No of PODS	1	Excess Reactive Energy	-	-	kVArh
Size of supply	>1MVA & ≤5MVA	Days	92	273	days

		Miniflex (HDS)		**Miniflex (LDS)**		**Total 2020/2021 Charges**
Network charges	**Rate Units**	**2020/2021 Rates**	**2020/2021 Charges**	**2020/2021 Rates**	**2020/2021 Charges**	
Distribution network demand charge	R/kVA	0.00	R -	0.00	R -	R -
Network demand charge	c/kWh	8.03	R 65	8.03	R 191	R 256
LV Subsidy Charge	R/kVA	0.00	R -	0.00	R -	R -
Network capacity charge	R/kVA	28.65	R 429 750	28.65	R 1 289 250	R 1 719 000
Total network charges			**R 429 815**		**R 1 289 441**	**R 1 719 256**
Energy charges	**Rate Units**	**2020/2021 Rates**	**2020/2021 Charges**	**2020/2021 Rates**	**2020/2021 Charges**	
Peak	c/kWh	367.85	R 833	119.97	R 802	R 1 635
Standard	c/kWh	111.42	R 649	82.56	R 1 410	R 2 058
Off-Peak	c/kWh	60.48	R 443	52.39	R 1 179	R 1 622
Sub Total (TOU)			**R 1 925**		**R 3 390**	**R 5 315**
Total energy charges			**R 1 925**		**R 3 390**	**R 5 315**
Other charges	**Rate Units**	**2020/2021 Rates**	**2020/2021 Charges**	**2020/2021 Rates**	**2020/2021 Charges**	
Ancillary service charge	c/kWh	0.47	R 7	0.47	R 22	R 29
Reactive energy charge	c/kVArh	7.27	R -	0.00	R -	R -
Electrification and rural subsidy charge	c/kWh	9.22	R 142	9.22	R 426	R 569
Affordability subsidy charge	c/kWh	4.34	R 67	4.34	R 201	R 268
Administration charge	R/day	106.69	R 9 815	106.69	R 29 126	R 38 942
Service charge	R/day	236.74	R 21 780	236.74	R 64 630	R 86 410
Total other charges			**R 31 812**		**R 94 405**	**R 126 217**
Total excl VAT			**R 463 552**		**R 1 387 236**	**R 1 850 788**
VAT	15%		R 69 533		R 208 085	R 277 618
Total account			**R 533 085**		**R 1 595 321**	**R 2 128 406**
Average price	c/kWh		**30 366.42**		**29 992.47**	**30 010.96**

7.5 LIB-SUPS system losses calculation and energy distribution

Like in Section 7.4, all energy distributions based on calculations below are tabulated in Tables 7.5-1 & 2, and their respective costs are tabulated in Tables 7.5-3 & 4 shown below.

a) <u>SUPS system heat energy losses</u>: With the maximum heat dissipation of each SUPS unit given to be 61kW, 60% of this heat represents electrical power consumed and equal to 61 x 0.6 = 36.6kW. For all four SUPS units running throughout 730 hours of the month, the monthly electrical energy is equal to 36.6 x 730 x 4 = 106 872kWh.

b) <u>Heat output from battery cabinets</u>: With the maximum heat dissipation of each LI-BESS cabinet or rack given to be 567BTU/hr, with 1BTU/hr equal to 0.293W, the heat dissipation in Watt will then be 567 x 0.293 = 166.131W = 0.166kW. With 60% of this heat representing electrical power consumed, the active power consumed will then be 0.166 x 0.6 = 0.0996kW. For all 80 (20 x 4) cabinets running throughout 730 hours of the month, the monthly electrical energy is equal to 0.0996 x 730 x 80 = 5 816.64kWh.

c) Battery room cooling losses: For the LIB room, it was assumed above to run only one single ventilation unit (16kW) at full capacity during summertime. The monthly cooling energy is, therefore, equal to 16 x 730 = 11 680kWh.

d) Rated operation losses: Equation 7.5 below determines these losses. The rated loss of each SUPS unit is equal to 34.02kW, and for all four SUPS units running throughout 730 hours of the month, the monthly electrical energy is equal to 34.02 x 730 x 4 = 99 338.4kWh.

$$P_{rated\text{-}losses}=\frac{1100}{0.97}-1100=1134.02-1100=34.02kW \quad (7.5)$$

e) Batteries waste heat energy during floating, discharge, and recharge operation is zero as cell operation is controlled by the BMS modules.

f) High-demand season wasted energy distribution

Y = 106.87 + 5.817 + 99.34 = 212.027MWh

X = Off-peak energy = 212.027 / 2.103 = 100.82MWh

Peak energy = 100.82 x 0.309 = 31.15MWh

Standard energy = 100.82 x 0.794 = 80.05MWh

g) Low-demand season wasted energy distribution

Y = 106.87 + 5.817 + 11.68 + 99.34 = 223.707MWh

X = Off-peak energy = 223.707 / 2.056 = 108.807MWh

Peak energy = 108.807 x 0.297 = 32.316MWh

Standard energy = 108.807 x 0.759 = 82.58MWh

h) High-demand season backup energy distribution

Y = 4400 x 1 x 0.146 = 642.4kWh

X = Off-peak energy = 642.4 / 2.103 = 305.47kWh

Peak energy = 305.47 x 0.309 = 94.4kWh

Standard energy = 305.47 x 0.794 = 242.54kWh

i) Low-demand season backup energy distribution

Y = 4400 x 1 x 0.146 = 642.4kWh

X = Off-peak energy = 642.4 / 2.056 = 312.45kWh

Peak energy = 312.45 x 0.297 = 92.8kWh

Standard energy = 312.45 x 0.759 = 237.15kWh

Table 7.5-1: LIB-SUPS system energy losses distribution per year

SUPS energy losses distribution per year					
Month	**Season**	**Total Energy (kWh)**	**Peak Energy (kWh)**	**Standard Energy (kWh)**	**Off-peak Energy (kWh)**
April	Low Demand	223707	32316	82584	108807
May	Low Demand	223707	32316	82584	108807
June	High Demand	212027	31154	80052	100821
July	High Demand	212027	31154	80052	100821
August	High Demand	212027	31154	80052	100821
September	Low Demand	223707	32316	82584	108807
October	Low Demand	223707	32316	82584	108807
November	Low Demand	223707	32316	82584	108807
December	Low Demand	223707	32316	82584	108807
January	Low Demand	223707	32316	82584	108807
February	Low Demand	223707	32316	82584	108807
March	Low Demand	223707	32316	82584	108807
Total kWh per year		2649444	384302	983416	1281726

Table 7.5-2: LIB-SUPS system off-grid backup-time saving

SUPS Off-grid backup-time saving (distribution coefficients as per Appendix J)					
Month	**Demand Season**	**Total Energy (S x Cosφ x t) S = 4400kVA Cosφ = 1 t = 0.146hrs**	**Peak Energy (kWh)**	**Standard Energy (kWh)**	**Off-peak Energy (kWh)**
April	Low Demand	642	93	237	312
May	Low Demand	642	93	237	312
June	High Demand	642	94	243	305
July	High Demand	642	94	243	305
August	High Demand	642	94	243	305
September	Low Demand	642	93	237	312
October	Low Demand	642	93	237	312
November	Low Demand	642	93	237	312
December	Low Demand	642	93	237	312
January	Low Demand	642	93	237	312
February	Low Demand	642	93	237	312
March	Low Demand	642	93	237	312
Total kWh per year		7709	1118	2862	3728

Table 7.5-3: Total LIB-SUPS system energy losses cost per year

High demand vs low demand cost for 2020/2021 rates (SUPS)

Customer Name:	**XXXXX**	**Consumption Data**	**HDS**	**LDS**	
Point of delivery ID	**0**	Sum of Utilised Capacity	15 000	45 000	kVA
Tariff	Miniflex	Sum of Chargeable Demands	13 500	40 500	kVA
Tariff Category	Urban	Peak Consumption	93 461	290 841	kWh
Supply voltage	≥ 500V & < 66kV	Standard Consumption	240 156	743 260	kWh
Transmission zone	> 900km	Off Peak Consumption	302 464	979 262	kWh
Tariff Classification	Non-Local Authority	Total Consumption	636 081	2 013 363	kWh
No of PODS	1	Excess Reactive Energy	-	-	kVArh
Size of supply	>1MVA & ≤5MVA	Days	92	273	days

		Miniflex (HDS)		**Miniflex (LDS)**		**Total 2020/2021 Charges**
Network charges	**Rate Units**	**2020/2021 Rates**	**2020/2021 Charges**	**2020/2021 Rates**	**2020/2021 Charges**	
Distribution network demand charge	R/kVA	0.00	R -	0.00	R -	R -
Network demand charge	c/kWh	8.03	R 26 789	8.03	R 83 038	R 109 828
LV Subsidy Charge	R/kVA	0.00	R -	0.00	R -	R -
Network capacity charge	R/kVA	28.65	R 429 750	28.65	R 1 289 250	R 1 719 000
Total network charges			**R 456 539**		**R 1 372 288**	**R 1 828 828**
Energy charges	**Rate Units**	**2020/2021 Rates**	**2020/2021 Charges**	**2020/2021 Rates**	**2020/2021 Charges**	
Peak	c/kWh	367.85	R 343 797	119.97	R 348 922	R 692 719
Standard	c/kWh	111.42	R 267 582	82.56	R 613 635	R 881 217
Off-Peak	c/kWh	60.48	R 182 930	52.39	R 513 035	R 695 965
Sub Total (TOU)			**R 794 309**		**R 1 475 593**	**R 2 269 902**
Total energy charges			**R 794 309**		**R 1 475 593**	**R 2 269 902**
Other charges	**Rate Units**	**2020/2021 Rates**	**2020/2021 Charges**	**2020/2021 Rates**	**2020/2021 Charges**	
Ancillary service charge	c/kWh	0.47	R 2 990	0.47	R 9 463	R 12 452
Reactive energy charge	c/kVArh	7.27	R -	0.00	R -	R -
Electrification and rural subsidy charge	c/kWh	9.22	R 58 647	9.22	R 185 632	R 244 279
Affordability subsidy charge	c/kWh	4.34	R 27 606	4.34	R 87 380	R 114 986
Administration charge	R/day	106.69	R 9 815	106.69	R 29 126	R 38 942
Service charge	R/day	236.74	R 21 780	236.74	R 64 630	R 86 410
Total other charges			**R 120 838**		**R 376 231**	**R 497 069**
Total excl VAT			**R 1 371 686**		**R 3 224 112**	**R 4 595 799**
VAT	15%		R 205 753		R 483 617	R 689 370
Total account			**R 1 577 439**		**R 3 707 729**	**R 5 285 168**
Average price	c/kWh		**213.23**		**165.44**	**177.89**

Table 7.5-4: Total LIB-SUPS system off-grid backup-time savings per year

High demand vs low demand cost for 2020/2021 rates (SUPS)

Customer Name:	**XXXXX**	**Consumption Data**	**HDS**	**LDS**	
Point of delivery ID	**0**	Sum of Utilised Capacity	15 000	45 000	kVA
Tariff	Miniflex	Sum of Chargeable Demands	13 500	40 500	kVA
Tariff Category	Urban	Peak Consumption	96 046	268 094	kWh
Supply voltage	≥ 500V & < 66kV	Standard Consumption	246 797	685 128	kWh
Transmission zone	> 900km	Off Peak Consumption	310 828	902 672	kWh
Tariff Classification	Non-Local Authority	Total Consumption	653 671	1 855 894	kWh
No of PODS	1	Excess Reactive Energy	-	-	kVArh
Size of supply	>1MVA & ≤5MVA	Days	92	273	days

		Miniflex (HDS)		**Miniflex (LDS)**		**Total 2020/2021 Charges**
Network charges	**Rate Units**	**2020/2021 Rates**	**2020/2021 Charges**	**2020/2021 Rates**	**2020/2021 Charges**	
Distribution network demand charge	R/kVA	0.00	R -	0.00	R -	R -
Network demand charge	c/kWh	8.03	R 81	8.03	R 238	R 320
LV Subsidy Charge	R/kVA	0.00	R -	0.00	R -	R -
Network capacity charge	R/kVA	28.65	R 429 750	28.65	R 1 289 250	R 1 719 000
Total network charges			**R 429 831**		**R 1 289 488**	**R 1 719 320**
Energy charges	**Rate Units**	**2020/2021 Rates**	**2020/2021 Charges**	**2020/2021 Rates**	**2020/2021 Charges**	
Peak	c/kWh	367.85	R 1 042	119.97	R 1 002	R 2 044
Standard	c/kWh	111.42	R 811	82.56	R 1 762	R 2 573
Off-Peak	c/kWh	60.48	R 554	52.39	R 1 473	R 2 027
Sub Total (TOU)			**R 2 407**		**R 4 237**	**R 6 644**
Total energy charges			**R 2 407**		**R 4 237**	**R 6 644**
Other charges	**Rate Units**	**2020/2021 Rates**	**2020/2021 Charges**	**2020/2021 Rates**	**2020/2021 Charges**	
Ancillary service charge	c/kWh	0.47	R 9	0.47	R 27	R 36
Reactive energy charge	c/kVArh	7.27	R -	0.00	R -	R -
Electrification and rural subsidy charge	c/kWh	9.22	R 178	9.22	R 533	R 711
Affordability subsidy charge	c/kWh	4.34	R 84	4.34	R 251	R 335
Administration charge	R/day	106.69	R 9 815	106.69	R 29 126	R 38 942
Service charge	R/day	236.74	R 21 780	236.74	R 64 630	R 86 410
Total other charges			**R 31 866**		**R 94 568**	**R 126 433**
Total excl VAT			**R 464 104**		**R 1 388 293**	**R 1 852 397**
VAT	15%		R 69 616		R 208 244	R 277 860
Total account			**R 533 719**		**R 1 596 537**	**R 2 130 257**
Average price	c/kWh		**24 081.76**		**24 012.27**	**24 029.64**

7.6 Results

Tables 7.6-1 & 2 summarises footprint and weight analysis between SUPS and RUPS systems and the respective BESS they employ. Table 7.6-3 summarises the net variance in the total annual running costs between LIB-SUPS and LAB-RUPS systems. Table 7.6-4 summarises the storage capacities and usable energy densities comparisons between LIB-SUPS and LAB-RUPS systems. It is worth mentioning that, in most of the previously cited researches, the comparison of the energy density between LAB and LIB refers to the weight of the battery system (W/kg), like in the case of Patrick, 2018 and Victor, 2018. In contrast, this thesis work will express this energy density differently based on the cell amp-hour or energy storage capacity (W/Ah). The expression will represent the actual depth of energy collection by each battery technology; the result will best highlight the development that the LIB chemistry has introduced in the usable energy density boosting compared to the LAB chemistry (Carl, 2011:1-15; Eaton, 2020a:1-15; John & Patrick, 2015:1-11; Richard, 2012:1-21; Patrick & Martin, 2018:1-11):

Table 7.6-1: Spatial footprint comparisons

UPS system	UPS footprint	BESS footprint	Total footprint
LAB-RUPS	27.245m²	114.8m²	142.045m²
LIB-SUPS	19.76m²	27.56m²	47.32m²

Table 7.6-2: Weight comparisons

UPS system	UPS weight	BESS weight	Total weight
LAB-RUPS	47 560kg	162 713.76kg	210 273.76kg
LIB-SUPS	20 956kg	38 560kg	59 516kg

Table 7.6-3: Costing summary analysis

Energy details and charges	2020/2021 Cost of losses		2021/2022 Cost of losses	
	RUPS	SUPS	RUPS	SUPS
Total cost of energy losses per year	R 7 799 263	R 5 285 168	R 8 972 796	R 6 080 395
Off-grid backup savings	R 2 128 406	R 2 130 257	R 2 448 619	R 2 450 748
Actual annual LAB-RUPS losses cost (operation losses – off-grid savings)	R 5 670 857		R 6 524 177	
Actual annual LIB-SUPS losses cost (operation losses – off-grid savings)	R 3 154 911		R 3 629 647	
Annual TCO savings	R 2 515 946		R 2 894 530	
4 x SUPS purchasing price	R 8 977 528		R 10 128 128	
4 x LI-BESS purchasing price	R 28 791 920		R 30 463 920	
Return on investment period (SUPSs only)	3.57 years		3.5 years	
Return on investment period (SUPSs + LI-BESSs)	15.01 years		14.02 years	

Note: The payback or return on investment period is a ratio between the investment cost to the total cost of ownership savings per year as per Equation 7.6 below:

$$Return\ on\ investment\ period = \frac{Investement\ cost\ of\ SUPS\ or\ SUPS+BESS}{Total\ cost\ of\ ownership\ savings\ per\ year} \tag{7.6}$$

Table 7.6-4: Storage capacity and energy density comparisons

Details	LA-BESS	LI-BESS
Usable system power	880kW	1100kW
Designed power	3.456kW/cell x 264 = 912.4kW	61.5kW/rack x 20 = 1230kW
Designed Ah capacity	2000Ah	67 x 20 = 1340Ah
	2000/1340 = 1.4925	
	LAB designed Ah capacity = (1.4925 - 1) x 100 = 49.25% of LIB	
Designed energy density	912.4/2000 = 0.456kW/Ah	1230/1340 = 0.918kW/Ah
	0.456/0.918 = 0.497	
	LAB designed density = (0.497 - 1) x 100 = - 50.3% of LIB	
Usable energy density	880/2000 = 0.44kW/Ah	1100/1340 = 0.821kW/Ah
	0.44/0.821 = 0.536	
	LAB usable density = (0.536 – 1) x 100 = - 46.4% of LIB	

a) <u>RUPS power density</u>: Referring to the main characteristics of both UPS systems in Table 7.1-1, the total active output power that each RUPS can deliver is 880kW. With the space footprint that takes up the system's weight found to be 142.045m², the power density will be equal to 880 ÷ 142.045 = 6.2kW/m².

b) <u>SUPS power density</u>: Referring to the main characteristics of both UPS systems in Table 7.1-1, the total active output power that each SUPS can deliver is 1100kW. With the space footprint that takes up the system's weight equal to 46.36 m², the power density will be 1100 ÷ 47.32 = 23.24kW/m².

c) From the results above, the percentage power density of the LAB-RUPS system is [(6.2 ÷ 23.73) – 1] x 100 = 73.873% less than that of the LIB-SUPS system.

d) From the results in Table 7.6-1, the percentage spatial footprint of the LAB-RUPS system is [(47.32 ÷ 142.045) – 1] x 100 = 66.7% less than that of the LIB-SUPS system. From the results in Table 7.6-2, the percentage floor loading capacity of the LAB-RUPS system is [(59 516 ÷ 210 274) – 1] x 100 = 71.7% less than that of the LIB-SUPS system. A significant decrease in weight and size is the most far-reaching benefit a SUPS system offers to a facility implementing or planning to implement the technology. Substantial reduction in the total footprint of SUPS technology has significantly impacted the overall development of the facility's power protection philosophy.

e) With the yearly facility energy cost seating at R28 millions for the annual energy consumption of 21753MWh based on losses calculation in Section 7.4, the RUPS energy loss contribution is 27.5% and 21.22% of the total annual cost and energy consumed, respectively. Similarly, based on losses calculation in Section 7.5, the SUPS energy loss contribution is 18.4% and 11.54% of the total annual cost and energy consumed, respectively. The annual TCO savings represents 9.2% of the total yearly energy cost of the facility.
f) From losses calculation in Section 7.4 and 7.5, the new LIB-UPS offers up to 56% (2649.4MWh ÷ 4761.3MWh = 0.5565 x 100 = 55.65%) less heat dissipated when compared to the existing LAB-RUPS system on an annual basis.

CHAPTER EIGHT
SMART USE OF LITHIUM-ION-BASED SUPS SYSTEM

8.1 Scope and introduction

South Africa faces a major electricity crisis, which is why many industries are looking for systems that reduce their reliance on the national grid. There is a need to draw attention to other key applications of storage which include shifting the use of energy out of peak times (Longe et al., 2017:55-63; Merem et al., 2017: 1-27). Energy is essential to business growth. With pressure on profits due to continued tariff escalations, smart battery energy storage is increasingly becoming a viable option. The smart storage of energy will aid in stabilising facilities' supply during load shedding and power outages by balancing intermittency between demand and supply (Ahmet, 2021:150-154). South Africa is under pressure to cut emissions of greenhouse gases and other pollutants. The power utility sector accounts for about two-fifths of the country's emissions. South Africa is the world's 12th-biggest emitter of climate-warming gases. Sadly, this emission is nowhere close to what is necessary to limit global warming to less than 1.5°C, as countries agreed to in the Paris Agreement (Micheal et al., 2018:40-51). The utility sector has, therefore, an important role to play in the low-carbon transformation. But implementation of such a scale of transition will also require an increased interdependency between utility and business sectors (Clement, 2020:11-19; Guwaeder & Ramakumar, 2017:41-49). The transition is likely to be extremely challenging and will require high-level technical approaches. Efficient use of energy and smart battery storage systems are some of the approaches expected to witness considerable growth owing to this climate change needs (Merem et al., 2018:16-34; Sharif et al., 2018:1-6). The enhancement of digital technologies has created innovative software platforms that advance the technical capabilities of battery energy storage.

While the development of the lithium-ion battery chemistries gains paces every day intending to enhance their performances and prices, the evaluation of different storage capacity models load-profiled to the facility consumption behaviour is needed. The determination of the financial impact these storage capacity models have on the facility forms a significant aspect of their market sustainability and appraisal. This chapter uses a facility-based approach to evaluate the impact utility tariffs and various storage capacity models have on the TCO. The chapter also discusses how the LIB-SUPS system can economically impact the facility's energy costs when smartly used. These data are crucial in fully informed decision-making, capital expenditure budget, determination of their economic competitiveness, and how quickly they repay the capital investment injected into them (Kimutai et al., 2019:45-52).

This evaluation will conclude in three stages. The first stage will evaluate the impact of tariff structures on the facility energy cost for LI-BESS sized to take up the annual peak, standard, and peak + standard energies consumed by the facility, respectively. The second stage will evaluate the TCO and return on investment (ROI) of these storage capacity models based on the annual increase to the tariff structure of the power utility. The TCO and ROI analysis will be over the past 13 years in comparison to the average consumer price index (CPI) linked to equipment prices for the same period. The third stage is where the impact of three different time-of-use electricity tariffs on the economics of the UPS system at various storage capacity models is evaluated (Acquah et al., 2017:10-21; Nia & Niavand, 2017:32-38).

The three electricity tariffs structure considered are as follow: Nightsave Large is an electricity tariff for high load factor urban customers with a notified maximum demand (NMD) above 1MVA. Megaflex is a TOU electricity tariff for urban customers whose NMD is above 1MVA. Miniflex is a TOU electricity tariff for urban customers with an NMD from 25kVA up to 5MVA. TOU tariff means a tariff with energy charges that change during different TOU periods and seasons. It is commonly used in developed economy countries as it is structured to incentivise consumers who lower their consumption during peak periods. As shown in Figures 8.1-1 & 2 below, the TOU periods typically are peak (red), standard (yellow), and off-peak (green) periods and differ during high and low demand seasons.

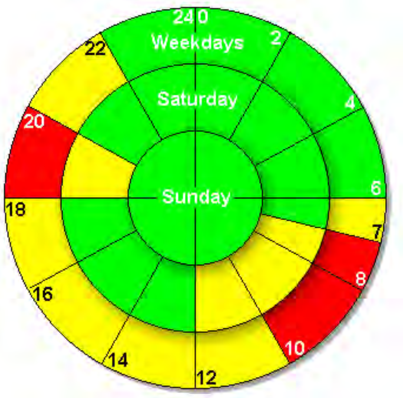


Figure 8.1-1: Megaflex and Miniflex periods

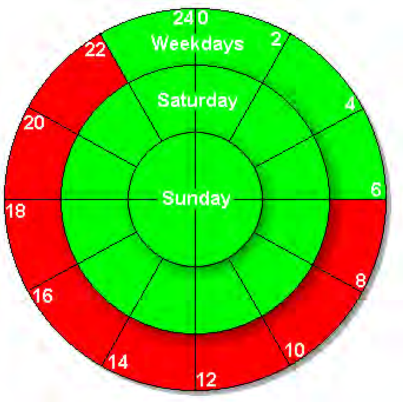


Figure 8.1-2: Nightsave Large periods

8.2 Assumptions

All calculations will base on the following assumptions. They are 365 days in a calendar year. From those, 303 days (weekdays and Saturdays) are when the facility consumes peak and standard energies, and 62 days (Sundays and public holidays) are when the facility consumes off-peak energy. In normal operation, based on data obtained from Eskom, the facility had 67 interruptions sustained above 5 minutes in the past ten years (Appendix I; Eskom, 2021b), giving an average of 7 interruptions per year. For that, we assume to have seven complete battery discharges and recharges a year. The discharge is made through a full 20 minutes design backup time to translate to a monthly discharge period of 0.2 hours (7 x 20 min/12 x 60). Each charging process takes 6 hours and translates to a monthly charge period of 3.5 hours (7 x 6 hours/12 = 3.5 hours). With the average number of hours per month taken to be 730 hours and based on monthly discharge and charge periods determined above, we can deduce that LI-BESS will be on standby operation for the rest of the time when not cycling; this is equivalent to 726.35 hours a month. The peak, standard, and peak + standard periods in our evaluation base on the periods detailed in Figure 8.1-1. Even though the Night-save Large tariff periods shown in Figure 8.1-2 do not correspond with Miniflex and Megaflex, its corresponding periods aligned with that of Miniflex and Megaflex will be considered. Based on the current price of electricity and LI-BESS, the determination of their costs in previous years will be by considering the percentage tariff adjustments and CPI throughout those years, respectively. Achievement of energy shift bases on the assumption that LIBs can withstand repeated cycles (discharge and recharge cycles) without performance degradation. And that they have a far shorter recharge time due to the use of advanced battery management systems. Like in Section 7.3, the determination of the TCO and ROI will base on energy costs from Eskom's TOU tariff structures (Eskom, 2021a). The designed LIB-SUPS can effectively be modified to achieve this cyclic shift of load using integrated static transfer switches. The SUPS system will automatically uncouple itself from the grid during the peak period and connect itself back to the grid during off-peak periods. Eaton Power Xpert 9395P SUPS inherently have similar application employed by both VMMS and ESS features.

8.3 Lithium-ion BESS (LI-BESS) rating

Based on calculations in Section 6.7, the following is determined:

<u>Normal storage capacity</u>

Initial storage capacity is as calculated in Section 6.7. The number of parallel battery racks or cabinets associated with each SUPS unit is 1134/61.5 = 18.44, rounded up to 20.

Peak storage capacity

In this case, the battery energy storage system is designed to take up peak energy consumed by the facility. Based on data in Appendix J, the yearly peak energy consumed by the facility is 3 153 798kWh. The daily average of that energy is equal to 3 153 798kWh / 365days = 8640kWh. With the total active power of the UPS system rated at 1100kW x 4 = 4400kW, the sustaining time required from the UPS system to cover this energy would be 8640kWh / 4400kW = 2 hours (120 minutes). For a backup time not exceeding 120 minutes, we can deduce that the number of parallel battery racks or cabinets associated with each SUPS unit is 1134/13 = 87.23, rounded up to 88.

Standard storage capacity

In this case, the battery energy storage system is designed to take up standard energy consumed by the facility. Based on data in Appendix J, the standard energy consumed by the facility per year is 8 072 705kWh. The daily average of that energy is equal to 8 072 705kWh / 365days = 22 117kWh. The sustaining time required from the UPS system to cover this energy would be 22 117kWh / 4400kW = 5 hours (300 minutes). For a backup time not exceeding 300 minutes, we can deduce that the number of parallel battery racks or cabinets associated with each SUPS unit is 1134/5.2 = 218.

Peak + standard storage capacity

In this case, the battery energy storage system is designed to take up the peak and standard energies consumed by the facility. The yearly peak and standard energies consumed by the facility is 3 153 798kWh + 8 072 705kWh = 11 226 503kWh (see Appendix J). The daily average of that energy is equal to 11 226 503kWh / 365days = 30 758kWh. The sustaining time required from the UPS system to cover this energy would be 8 640kWh / 4400kW = 7 hours (420 minutes). For a backup time not exceeding 420 minutes, we can deduce that the number of parallel battery racks or cabinets associated with each SUPS unit is 1134/3.7 = 306.

8.4 SUPS losses calculation and energy distribution

All energy losses calculated in Section 7.5 remains true except for 7.5(b): battery cabinets heat load. This difference is due to the change in the number of cabinets as elaborated above. The maximum heat dissipation of each battery cabinet is 567 BTU/hour. With 1BTU/hour equal to 0.2931W, the heat dissipation will then be 567 x 0.2931 = 166.131W = 0.166kW. With 60% of this heat representing electrical power consumed, the active power consumed is 0.166 x 0.6 = 0.0996kW. For an LI-BESS designed to take up the annual peak energy with all (88 x 4) cabinets running throughout 730 hours of the month, the monthly electrical energy is 0.0996 x 730 x 352 = 25.6MWh. Similarly, for LI-BESS designed to take up the annual standard and peak + standard energy, this electrical energy is, respectively, equal to 63.4MWh and 89MWh.

8.5 Impact of storage capacity and utility tariff on the total cost of ownership

Table 8.5-1 provides a comparison of the cost contribution of each energy backup option. The Table summarises the ROI versus the off-grid energy wheeling. It illustrates the financial analysis of backup models adopted and the determination of their economic competitiveness. Energy costs and ROI are attained from assumptions, losses calculation, and energy contribution of each battery storage model.

The analysis of ROI versus the off-grid energy wheeling and Tariff structures is in Table 8.5-2. The accompanying Figure 8.5-1 provides a graphical illustration of the tariff structure contribution to TCO for each battery energy storage model designed. The trend of the ROI versus the storage model, CPI, and tariff increase is illustrated where three tariffs structures, namely, Miniflex, Megaflex, and Nightsave-Large, are considered. The energy backup model seen in Figure 2-1 indicates that the cheapest option would be the wheeling of peak energy.

Table 8.5-3 analyses the annual total cost of ownership for the past ten years for various off-grid energy wheeling models vis-à-vis the tariff increases for the same period. Table 8.5-4 analyses the annual increase in the equipment price for the past ten years in comparison to the CPI for the same period.

Table 8.5-5 summarises the ROI versus the storage models, CPI, and tariff increase given calculations in tables above. The accompanying Figure 8.5-2 provide a graphical illustration of the analysis of ROI versus the off-grid energy wheeling and Tariff structures. It establishes the breakeven periods of the energy backup model. The ROI seen in Figure 8.5-2 indicates how quickly each energy wheeling model repays the capital investment injected into them. From this figure, the wheeling of peak energy will pay the cost invested in the project much quicker than the rest of the models. These data are crucial in fully informed decision-making and capital expenditure budget motivation (Eskom. 2021a & b; South Africa, 2020: 1-11).

Table 8.5-1: ROI versus off-grid energy wheeling

Miniflex Tariff 2021/22	Normal Operation	Peak Energy backup	Standard Energy backup	Peak + Standard Energy backup
Annual total facility energy cost	R32 197 132	R23 846 071	R20 297 119	R11 946 059
Annual cost of energy losses	R6 080 395	R6 408 183	R7 034 498	R7 458 670
Annual Off-grid energy wheeling	R2 450 748	R10 963 474	R14 395 264	R22 907 993
Annual TCO based on normal operation	-R3 629 647	R8 184 938	R10 990 413	R19 078 970
Backup runtime required (min)	20	120	300	420
Number of battery racks required per SUPS	20	88	218	306
Total number of battery racks required	80	352	872	1224
Stored Energy (kWh)	2608	11475	28427	39902
Nominal LI-BESS capacity (Ah)	5360	23584	58424	82008
LI-BESS purchasing price	R30 463 920	R134 041 248	R332 056 728	R466 097 976
LI-BESS + SUPS purchasing price	R40 592 048	R144 169 376	R342 184 856	R476 226 104
ROI (LI-BESS only) - Years		16.4	30.2	24.4

Table 8.5-2: ROI versus Off-grid energy wheeling and Tariff structures

Power Utility Tariff structures 2021/22		Normal Operation	Peak Energy backup	Standard Energy backup	Peak + Standard Energy backup
Miniflex	Annual total facility energy cost	R32 197 132	R23 846 071	R20 297 119	R11 946 059
	Annual cost of energy losses	R6 080 395	R6 408 183	R7 034 498	R7 458 670
	Annual Off-grid energy wheeling	R2 450 748	R10 963 474	R14 395 264	R22 907 993
	Annual TCO based on normal operation	-R3 629 647	R8 184 938	R10 990 413	R19 078 970
	LI-BESS purchasing price	R30 463 920	R134 041 248	R332 056 728	R466 097 976
	ROI (LI-BESS) - Years		16.4	30.2	24.4
Megaflex	Annual total facility energy cost	R33 190 224	R25 174 286	R22 148 017	R14 132 079
	Annual cost of energy losses	R8 500 688	R8 815 452	R9 416 880	R9 824 196
	Annual Off-grid energy wheeling	R5 015 952	R13 193 554	R16 102 663	R24 280 268
	Annual TCO based on normal operation	-R3 484 736	R7 862 839	R10 170 520	R17 940 808
	LI-BESS purchasing price	R30 463 920	R134 041 248	R332 056 728	R466 097 976
	ROI (LI-BESS) - Years		17.0	32.6	26.0
Nightsave large	Annual total facility energy cost	R35 511 637	R31 860 511	R26 163 469	R22 512 342
	Annual cost of energy losses	R14 967 622	R15 243 406	R15 770 353	R16 127 228
	Annual Off-grid energy wheeling	R11 905 458	R15 569 236	R21 283 524	R24 947 302
	Annual TCO based on normal operation	-R3 062 165	R3 387 995	R8 575 336	R11 882 239
	LI-BESS purchasing price	R30 463 920	R134 041 248	R332 056 728	R466 097 976
	ROI (LI-BESS) - Years		39.6	38.7	39.2

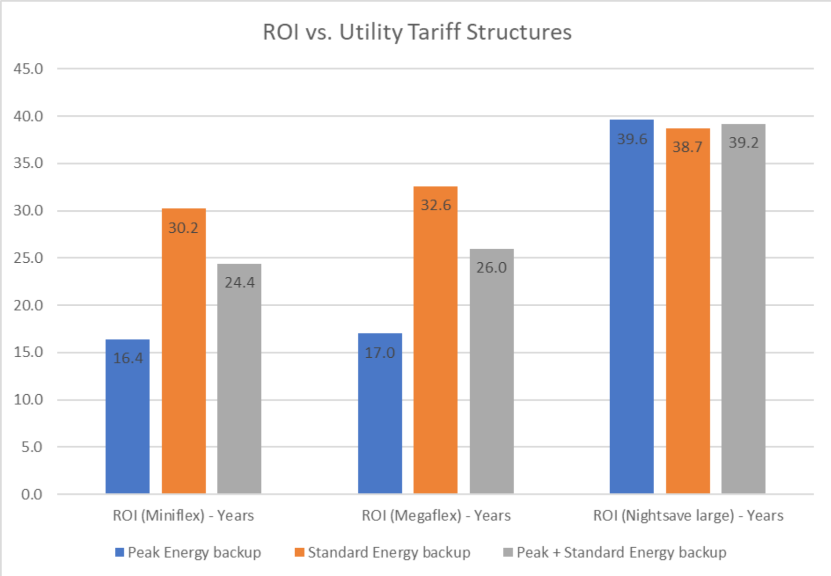


Figure 8.5-1: ROI versus Off-grid energy wheeling and Tariff structures trend

Table 8.5-3: TCO versus Off-grid energy wheeling and tariff increases

Year	Tariff price adjustment (%)	Peak TCO	Standard TCO	Peak + Standard TCO
2009/2010	31.3	R2 039 466	R2 738 515	R4 753 965
2010/2011	24.8	R2 545 254	R3 417 667	R5 932 948
2011/2012	25.8	R3 201 929	R4 299 425	R7 463 649
2012/2013	16	R3 714 238	R4 987 333	R8 657 833
2013/2014	8	R4 011 377	R5 386 319	R9 350 459
2014/2015	8	R4 332 287	R5 817 225	R10 098 496
2015/2016	12.69	R4 882 054	R6 555 431	R11 379 995
2016/2017	9.4	R5 340 967	R7 171 641	R12 449 715
2017/2018	2.2	R5 458 468	R7 329 417	R12 723 609
2018/2019	5.23	R5 743 946	R7 712 746	R13 389 053
2019/2020	13.87	R6 540 632	R8 782 504	R15 246 115
2020/2021	8.77	R7 114 245	R9 552 729	R16 583 199
2021/2022	15.05	**R8 184 939**	**R10 990 415**	**R19 078 971**

Table 8.5-4: Equipment price increases

Year	CPI (%)	LI-BESS	SUPS
2009/2010	6.16	R210 956	R1 402 699
2010/2011	5.4	R222 348	R1 478 445
2011/2012	4.5	R232 353	R1 544 975
2012/2013	5.2	R244 436	R1 625 313
2013/2014	6	R259 102	R1 722 832
2014/2015	6	R274 648	R1 826 202
2015/2016	5.7	R290 303	R1 930 296
2016/2017	6.59	R309 434	R2 057 502
2017/2018	5.3	R325 834	R2 166 550
2018/2019	4.5	R340 496	R2 264 045
2019/2020	4.1	R354 457	R2 356 870
2020/2021	3.3	R366 154	R2 434 647
2021/2022	4	**R380 800**	**R2 532 033**

Table 8.5-5: ROI versus Storage model, CPI, and tariff increase

Year	Tariff price adjustment (%)	CPI (%)	ROI Peak (years)	ROI Standard (years)	ROI Peak + Standard (years)
2009/2010	31.30	6.16	39.16	69.22	55.49
2010/2011	24.80	5.40	33.07	58.46	46.87
2011/2012	25.80	4.50	27.47	48.56	38.93
2012/2013	16.00	5.20	24.92	44.04	35.31
2013/2014	8.00	6.00	24.45	43.23	34.65
2014/2015	8.00	6.00	24.00	42.43	34.01
2015/2016	12.69	5.70	22.51	39.79	31.90
2016/2017	9.40	6.59	21.93	38.77	31.08
2017/2018	2.20	5.30	22.60	39.95	32.03
2018/2019	5.23	4.50	22.44	39.67	31.80
2019/2020	13.87	4.10	20.52	36.27	29.08
2020/2021	8.77	3.30	19.49	34.44	27.61
2021/2022	15.05	4.00	17.61	31.13	24.96

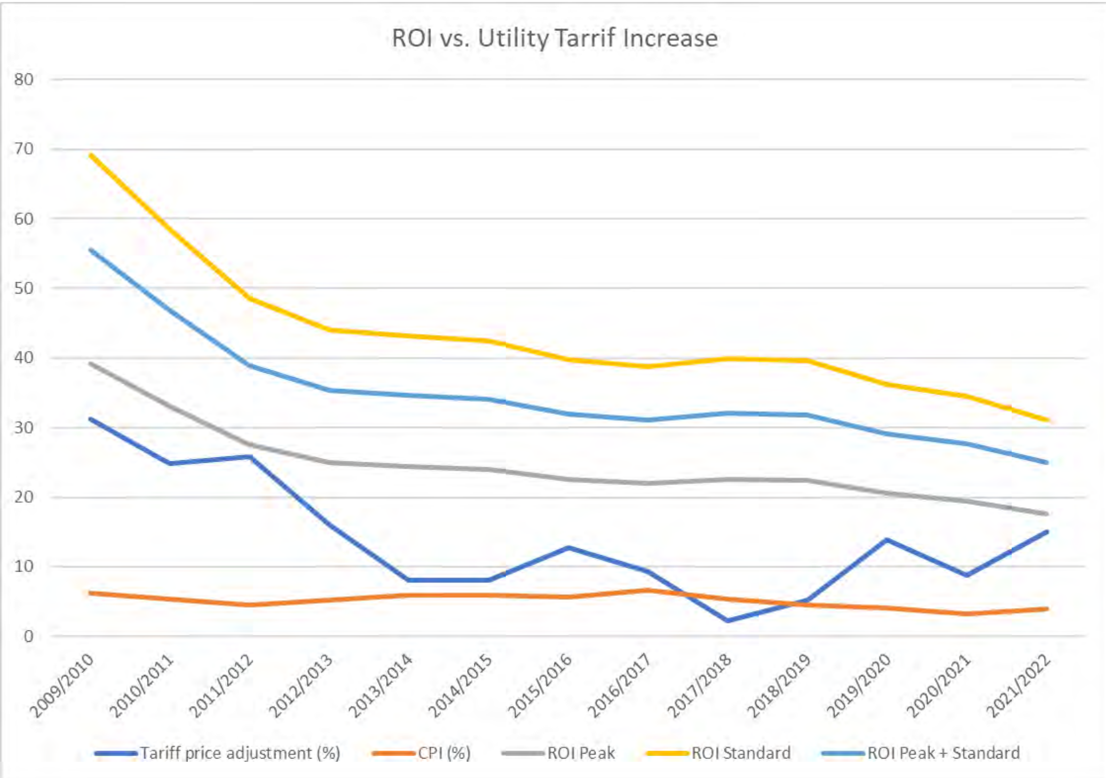


Figure 8.5-2: ROI versus Storage model, CPI, and tariff increase trend

To reduce the TCO of any UPS technology, it is imperative, amongst other requirements, to select an effective tariff structure for the facility. Based on Figure 8.5-1, out of the three tariffs structures considered, Miniflex offers a higher TCO than all others. Based on Figure 8.5-2, the breakeven periods established on LI-BESS are all over 15 years. With the LI-BESS providing a life expectancy that extends to 15 years (some manufacture pushes the lifespan to 20 years), this breakeven will occur at the replacement period. For market competitiveness, it is imperative to extend life expectancy and drop the cost of LIBs to reduce the TCO. The maturation and cheapening of lithium-ion technology is a key enabler of this strategy.

It will shorten the ROI period and increase the financial impact on the overall facility budgets. With the research to merge diverse cathode materials to reduce the quantity of cobalt (cobalt being the most expensive material), enhance battery cell performance, and drop price underway, the pricy lithium-ion cell will soon be the thing of the past. Lithium-ion battery deployment has not yet reached its peak and will be on an upward trajectory for the next 5-10 years (Nicolette, 2020:38-39). The cost has also dropped considerably in the past decade. So, facility-scale storage is very viable. Investment into LI BESSs will offset the need for the facility's distribution upgrade. The unpredictability of the tariff price adjustment and the reduction in lithium-ion battery prices expected to come will make the use of LIB-SUPS in normal operation mode more undesirable.

CONCLUSION AND RECOMMENDATIONS

The new LIB-SUPS system offers competitive energy-management specifications and an energy-saving technology that improves the overall facility's performance and effectiveness. It uses smart power software with advanced energy performance indicators for operational and maintenance control that provides monitoring, management, protection, and physical and virtual control capabilities of the entire LIB-SUPS system. This digitization or the use of these intelligent control systems and software has optimized the efficiency of the LIB-SUPS system.

The new lithium-ion-based, energy-efficient SUPS system has numerous benefits. The system provides conditioned power to critical loads and operates at a reduced noise level. The system increases the reliability of the facility's operation while securing its power supply, achieves lower maintenance and operational cost of up to 50%, offers a reduction in consequential exposure to ever-escalating energy tariffs and lessens environmental impact by reducing the carbon footprint. Inside the wide range of UPS technologies available in the market, LIB-SUPS topology has proven to be the better-suited system to replace the traditional LAB-RUPS system. Their power rating, modularity, redundancy, efficiency, and compactness have been improved due to the use of high-frequency and high-power IGBT semiconductors. All these characteristics are obtained without surrendering on footprint, weight, the total cost of ownership, and capital cost compared to traditional LAB-RUPS systems. Regarding associated BESS, although LAB, by tradition, has more popularity in energy storage systems, they necessitate a larger battery room with higher floor space to achieve the energy storage capacity required by the facility. On the contrary, LIB cells possess a higher energy density and a form factor that permits them to occupy only a fraction of floor space than required by LAB and still achieve the same energy storage capacity.

The LIB-SUPS system has a prominent fiscal return that offers a lesser total cost of ownership as compared to the existing LAB-RUPS system. With the sharp rise in energy price during the 2021/2022 financial year in South Africa, the TCO on lost energy is becoming a value not to ignore. The cost of energy losses, therefore, indicates the vulnerability of the facility toward electricity tariff increase. As a price response mechanism, the facility must now be more stimulated and motivated to reduce the cost of energy losses through effective consumption management and investment in energy-efficient technologies. The increase in TCO and reduction in the return on investment during the 2021/2022 financial year compared to the 2020/2021 financial year seem to have been driven by this sharp escalating electricity price.

A significant decrease in weight, footprint, cooling costs, and operating expenses are the most far-reaching benefits a LIB-SUPS technology offers to a facility implementing this technology. Due to electromechanics units utilized (motor-generator set), the LAB-RUPS system generates more heat than the LIB-SUPS system. Unlike conventional converter technology used by the exiting LAB-RUPS system that uses SCRs, the new Eaton Power Xpert 9395P High-Performance SUPS unit uses a three-level converter technology. This three-level converter uses IGBTs to lessen components stresses and energy losses while achieving higher efficiency even at a low load rate. This technology offers competitive energy management or saving and improves the overall facility's effectiveness. This technology also contributes to the reduction of consequential exposure to the ever-escalating energy tariff.

Scalability in the LAB-RUPS system is achieved only by supplementing RUPS units, thus limiting its flexibility to adapt to future variations in load demand. On the contrary, the LIB-SUPS system is scalable given its FI-UPM option. LABs inherently have a limited lifetime. It is essential to keep the battery room at around 20–25°C to optimize this lifetime. While all batteries will age faster at higher temperatures, the LIB's nominal lifetime and ageing characteristics are such that they will tolerate higher operating temperatures and still retain a much longer battery life than LAB. This temperature resilience, in summer seasons, allows significant downsizing of the cooling solution needed to remove the heat due to imperfect battery room insulation, thus contributing to financial savings. The development of LIB chemistry has introduced greater energy density boosting. This energy density boost caused the quantity of service power collected at the given state of its maximum stored energy charge to nearly double compared to the amount of energy charge sourced from the LAB technology maximum stored energy charge. This statement comes from the fact that LIBs have a depth of discharge of up to 100% (DOD ≤ 100%) compared to only up to 80% (DOD ≤ 80%) for BAE LABs.

South Africa faces a major electricity crisis. For a declared system emergency or critical peak day, customers are called on to reduce electricity usage. Critical peak days are times when the national electricity network is severely constrained. During such constraints, power utilities and consumers are forced to take emergency measures to avoid a blackout. A well-designed storage capacity model to offset the Eskom tariff during peak hours could be financially attractive. As more and more facilities move towards LIB-SUPS systems, their usage as energy storage systems will increase. The facility will then need to adopt this LIB-SUPS supply model as part of its broader power protection and management strategy to reduce future energy costs and achieve partial power independence. While the facility still uses the main power supply as a primary power source, it can benefit from feed-in energy exported from its LI-BESS to take up high-value demands, thus reducing overall electricity bills. The move to new battery energy storage approaches not only presents ideal economic opportunities for facilities to reduce energy costs, but facilities become active participants in demand response to the national grid. This research would signal to other big emitters of climate-warming gases to prepare for various internal strategies, which provide certainty to kick-start energy innovation and adaptation. This strategy would signify strong leadership in upholding facilities' commitment and legal obligation to look after the health and wellbeing of employees while making the country more resilient in the face of world climate change and meeting environmental standards. It would also send a strong global signal of commitment to decarbonise and attract real interest in significant transition and climate funding packages for South Africa.

Although this explorative study design draws some similarities from previous research, as demonstrated above, it provides repudiation to past approaches on how the costs are determined. The current work introduces this exciting approach to the technical audience. It highlights how various factors of the studied UPS systems and LIB-SUPS used as storage systems play out in a specific application where the facility-based energy profile behaviour assists in determining their losses costs and costs analysis more accurately. Given the narrow focus on a facility, one can get a contextualized understanding of how the UPS system can be analyzed, evaluated, and selected based on fully informed decision-making and related application. Concept understanding of how storage systems associated with UPS systems are smartly employed and evaluated based on a fully informed decision-making and related application.

In this thesis, the 3-phase modular double-conversion LIB-SUPS system is designed to provide 4.4MVA of maximum power to the facility's critical loads and processes. The system is configured in harmony with power requirements specific to the envisioned facility. Enumerated below are some of the identified areas, deriving from this thesis, where recommended future works could further be examined or investigated:

1) In this thesis, the 3-phase modular double-conversion LIB-SUPS system is designed to replace the facility's old LAB-RUPS system. Other research must extend this work in large facilities to address all key factors on how the new LIB-SUPS system improves the facility energy efficiency. This study will compare the newly developed LIB-RUPS type with the newly selected LIB-SUPS technology in terms of efficiency, power usage effectiveness, TCO, spatial footprint, usable energy density, and floor loading capacity. The result will provide facilities with all key data and considerations involved in selecting the right UPS system for the site.
2) Other tiers, with redundant capacity components and multiple paths simultaneously serving the facility's critical equipment, must be designed even though the facility has the responsibility to determine what UPS system tier configuration is required for the facility. Currently, critical loads, information technology (IT) and other non-IT systems are all supplied together from the same and single path. A tier where the distribution path to IT systems and complementary critical systems is separated and isolated to prevent any single event from affecting both systems still needs to be investigated and designed.
3) The current LA-BESS was commissioned in 2015, and cells have an operational life span of up to 20 years. The way these 1056 LAB cells will be utilized or gotten rid of should be investigated. An investigation into maintenance costs requirements of the LIB-SUPS system in comparison with the

overall cost of keeping the LAB-RUPS system up and running for the next five years needs to be carried out.

4) A simple generic formula considering the purchasing and operational costs is proposed in the profitability analysis of the LIB-SUPS system to estimate a project's return on investment (ROI) and total cost of ownership (TCO). Future research should consider the system's maintenance, material depreciation, fatigue, and ageing costs to account for the LIB-SUPS technology lifetime.
5) South Africa is the 12th biggest emitter of climate-warming gases in the world. The country is under pressure to cut emissions of these greenhouse gases and other pollutants. Most of the country's greenhouse gas emissions are from the electricity sector. This sector accounts for about two-fifths of the total emissions. Facilities goals are to increase the penetration of renewable energies to show their contribution to climate change and reduce the country's reliance on coal. These renewable energies include PV, wind, and battery storage.
6) Because many UPS units supply the same output paralleling bus, the parallel redundant scheme is limited to around 5MVA at low voltages. The fault-level currents, which can be dangerously high at low voltages, drive this limitation. For powers above 5MVA, the LV reticulation would have to be upgraded from cables, switch gears to a busbar distribution system to withstand the high fault currents. To accommodate the future facility expansion, research elaborating key design considerations between the medium voltage (11kV) UPS topology and the low voltage (400V/600V) topology is, therefore, needed. The modelling, simulation, and analysis of topology are to be studied and confirmed. The later study includes load flow, harmonic, arc flash, system dynamics, transients, and protection coordination.
7) The current oil switch gears are 30 years old and should be replaced to correspond with the new installation requirements. They now pose a safety risk to the maintenance personnel and the facility power protection. Research to design a new intake MV switch gears accommodating the new SUPS system configuration is required.

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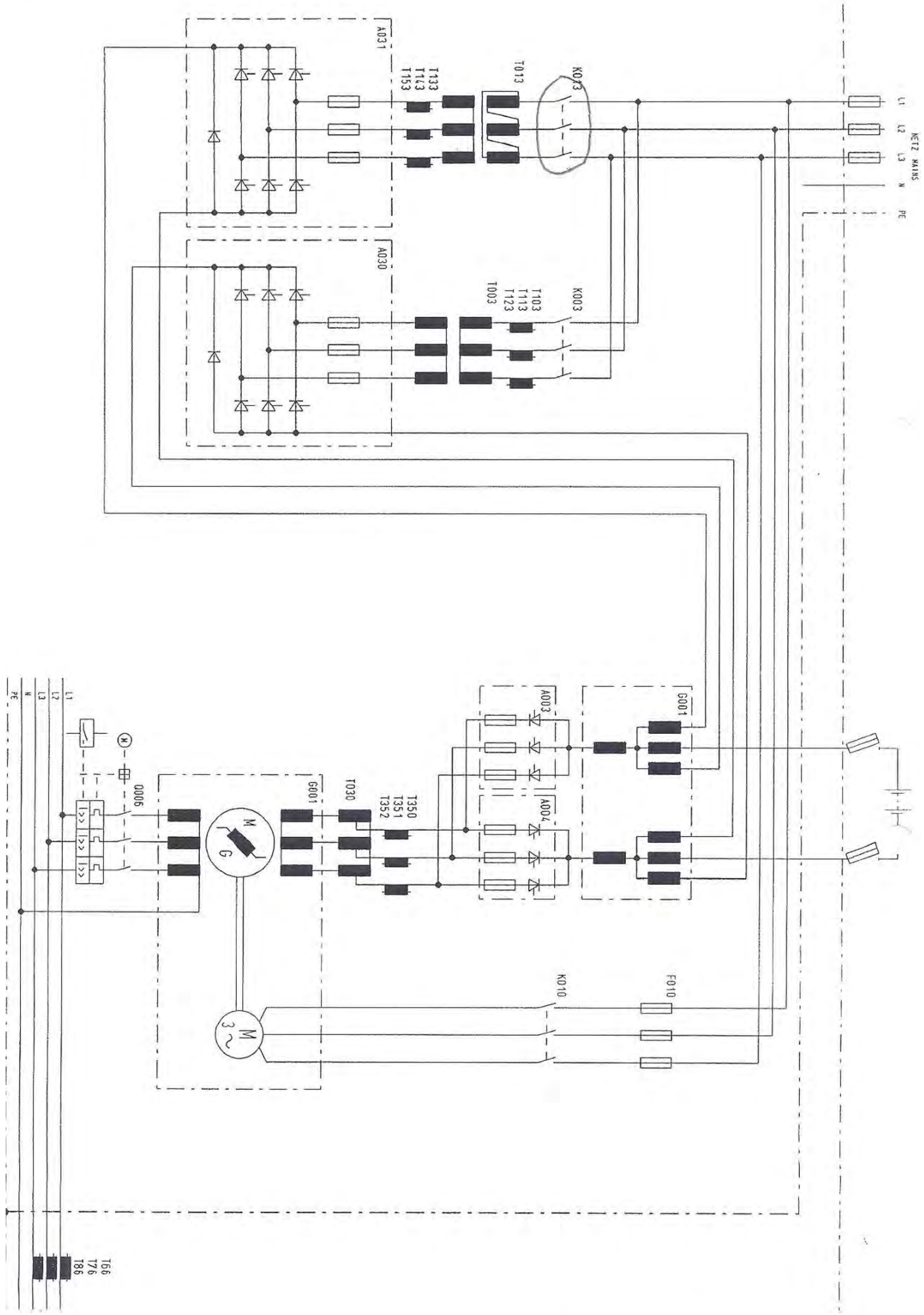
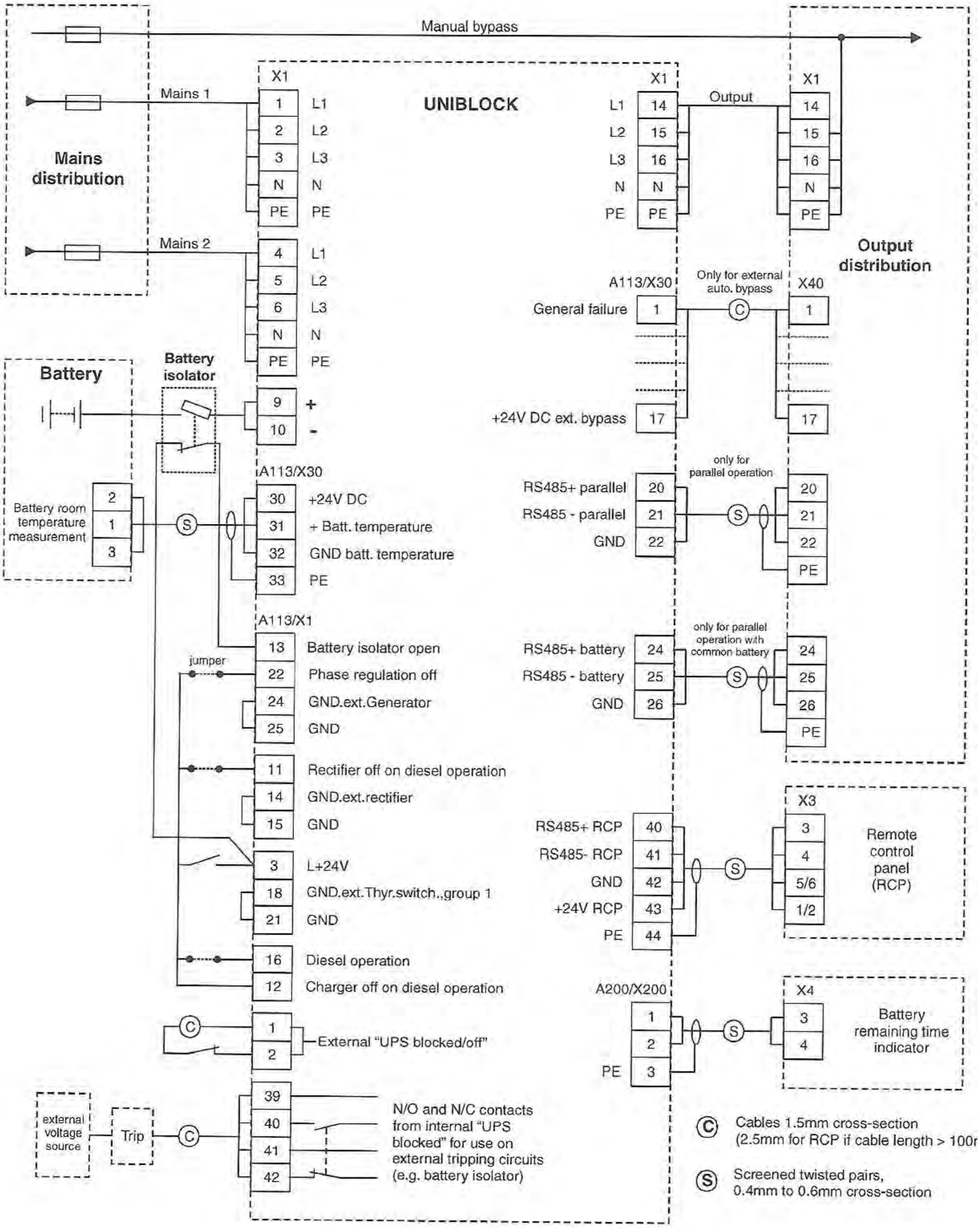
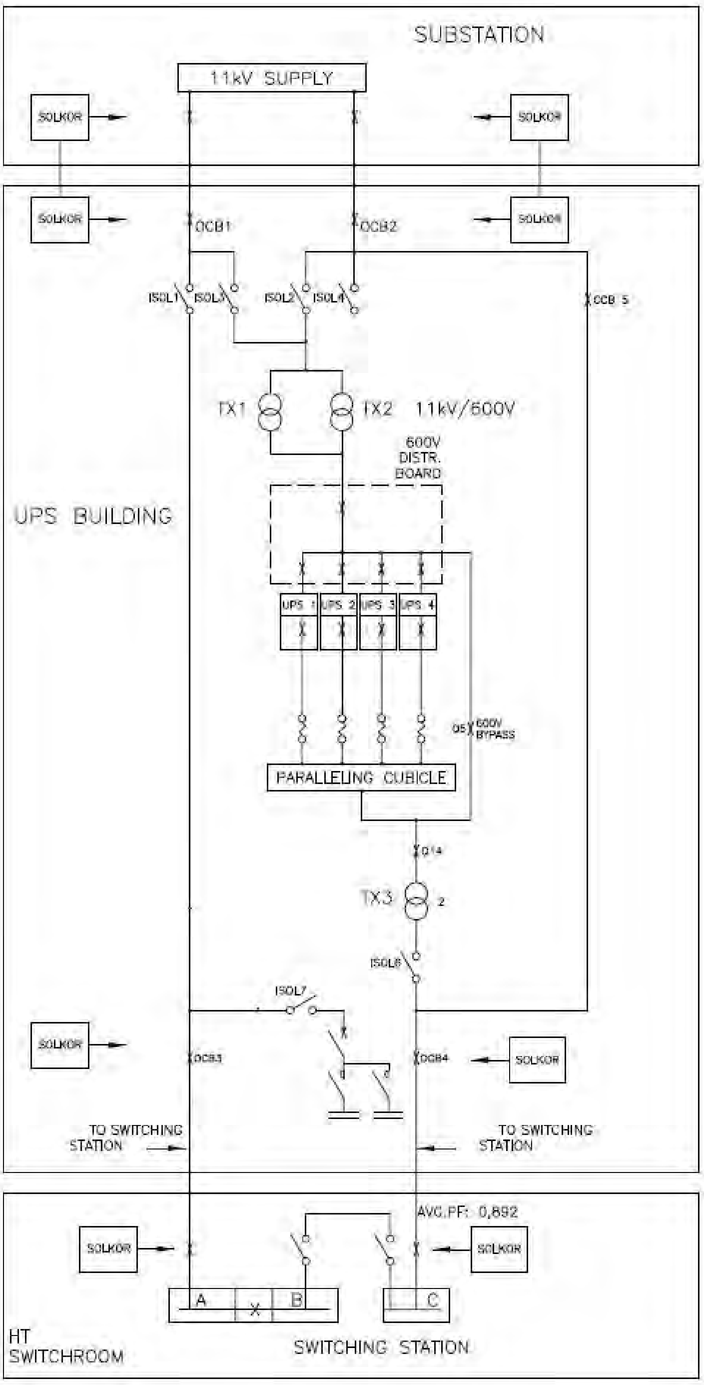
APPENDIX A: Uniblock main electrical layout

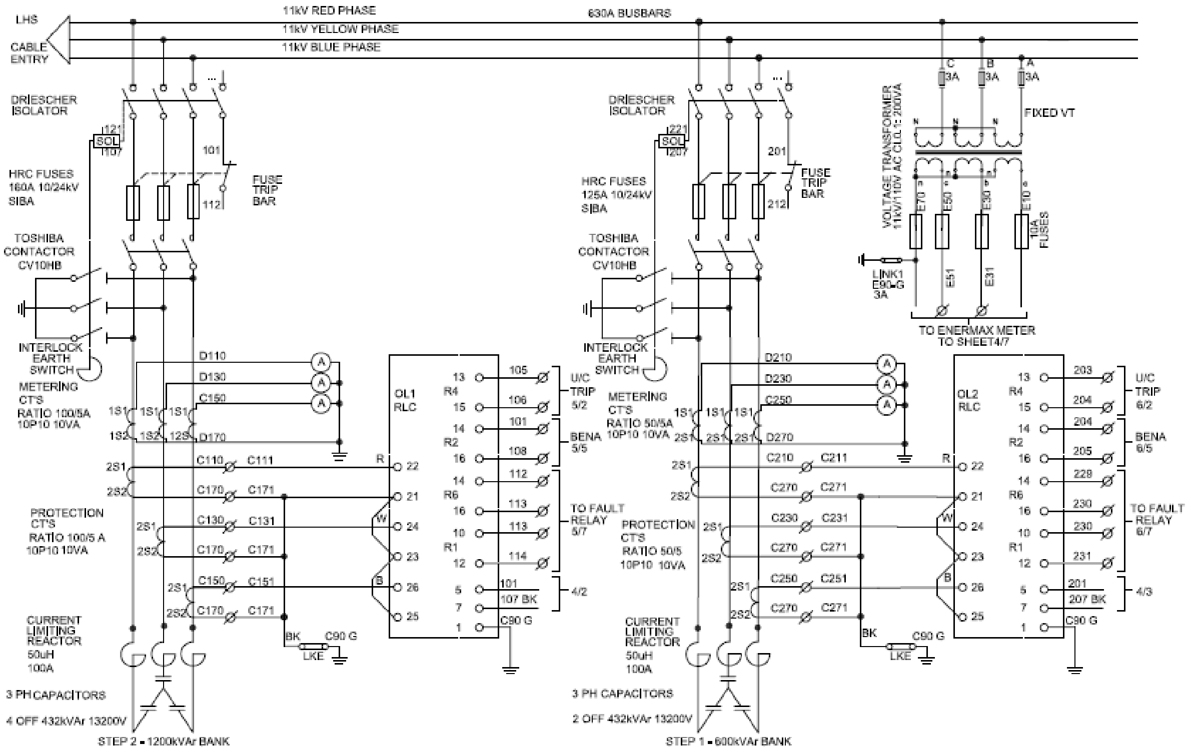



Manual bypass
Mains distribution
Mains 1
Mains 2
X1
UNIBLOCK
1 L1
2 L2
3 L3
N N
PE PE
4 L1
5 L2
6 L3
N N
PE PE
Battery
Battery isolator
9 +
10 -
A113/X30
30 +24V DC
31 + Batt. temperature
32 GND batt. temperature
33 PE
Battery room temperature measurement
A113/X1
jumper
13 Battery isolator open
22 Phase regulation off
24 GND.ext.Generator
25 GND
11 Rectifier off on diesel operation
14 GND.ext.rectifier
15 GND
3 L+24V
18 GND.ext.Thyr.switch.,group 1
21 GND
16 Diesel operation
12 Charger off on diesel operation
1
2
External "UPS blocked/off"
external voltage source
Trip
39
40
41
42
N/O and N/C contacts from internal "UPS blocked" for use on external tripping circuits (e.g. battery isolator)
Output
L1 14
L2 15
L3 16
N N
PE PE
Output distribution
A113/X30
Only for external auto. bypass
X40
General failure 1
+24V DC ext. bypass 17
only for parallel operation
RS485+ parallel 20
RS485 - parallel 21
GND 22
PE
only for parallel operation with common battery
RS485+ battery 24
RS485 - battery 25
GND 26
PE
X3
RS485+ RCP 40
RS485- RCP 41
GND 42
+24V RCP 43
PE 44
3
4
5/6
1/2
Remote control panel (RCP)
A200/X200
1
2
PE 3
X4
3
4
Battery remaining time indicator
Ⓒ Cables 1.5mm cross-section (2.5mm for RCP if cable length > 100r
Ⓢ Screened twisted pairs, 0.4mm to 0.6mm cross-section

APPENDIX B: High-level MV reticulation schematic of the system



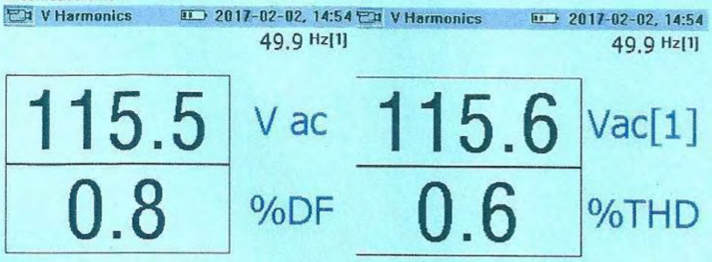
APPENDIX C: 11kV indoor PFC equipment main circuit step 1 & 2

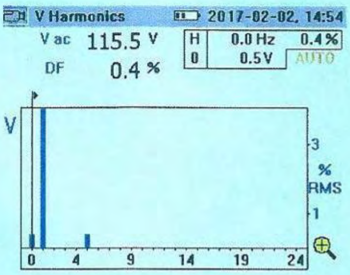


APPENDIX D: PCC harmonic readings

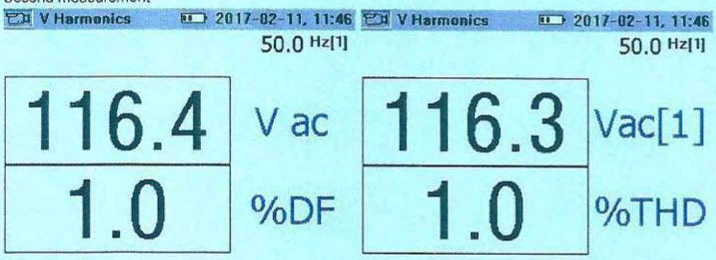
ESKOM SUBSTATION, MAIN 11kV BUS, V_{RY}

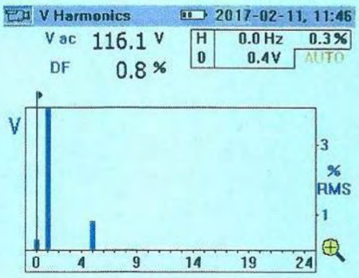
First measurement





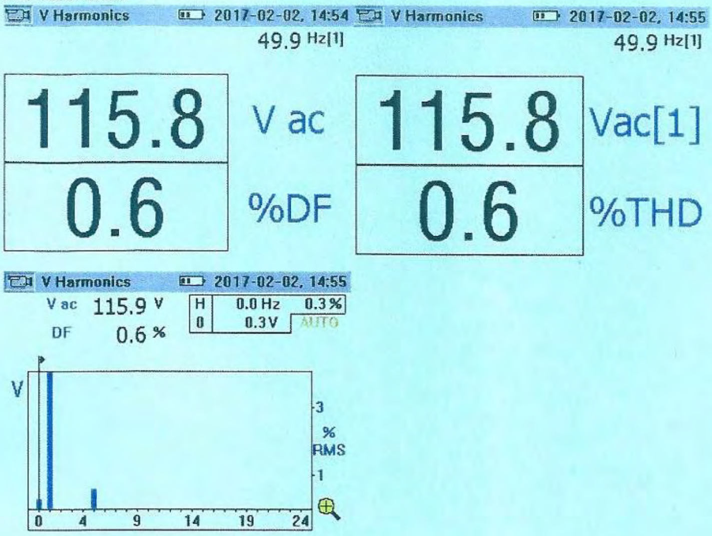
Second measurement



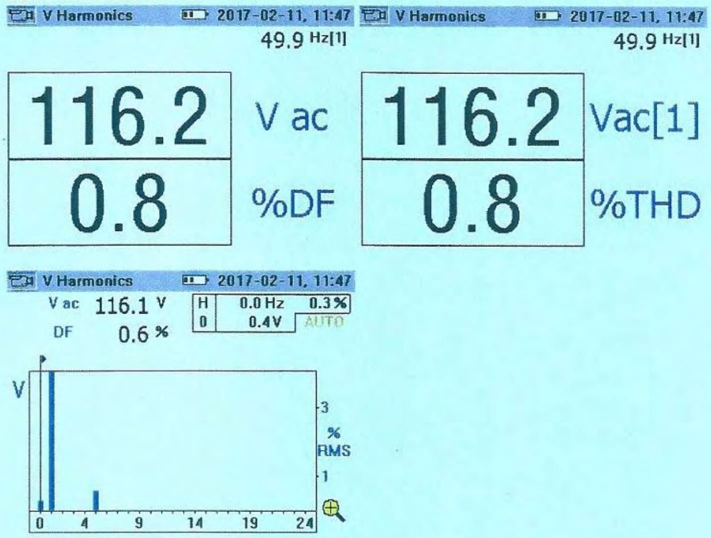


ESKOM SUBSTATION, MAIN 11kV BUS, V_{YB}

First measurement



Second measurement



APPENDIX E: BAE 25-OGi-2000, VLA battery cell - Technical specification

BAE SECURA OGi

Technical Specification for Stationary VLA - Cells

1. Application

BAE OGi - cells are suitable for backup power applications where operational safety and long service-life is a top priority. The OGi performs extremely well where discharge currents are required for short duration discharge times. It also works very well when these short discharge demands are coupled with continuous loads over longer duration discharge times.

BAE uses a round-grid flat-plate design for its OGi cells. Due to its excellent lead-mass and grid plate a long operational life and a very good high-current performance is realized. The sleek straight-walled containers and bridge-supported plates provide a high power-density in a compact foot-print. The transparent container allows visibility and control for easier maintenance and service.

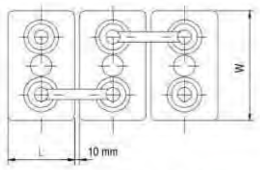
They are used as a stand-by energy source in transmission and/or distribution substations, as well as in data centers for UPS; for emergency lighting equipment and other applications requiring higher short duration rates.

2. Types, capacities, dimensions, weights

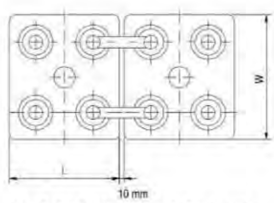
Type	1 min 25°C	C_1 25°C	C_4 25°C	C_8 25°C	C_{12} 25°C	R_i 1)	I_k 2)	Length (L)	Width (W)	Height (H)	Weight dry	Weight filled	Lead mass
U_e V/cell	Amps 1.75	Ah 1.75	Ah 1.75	Ah 1.75	Ah 1.75	mΩ	kA	inch	inch	inch	lbs	lbs	lbs
5 OGi 400	511	229	351	415	433	0.450	4.5	5.71	8.11	27.44	60.7	90.5	51.5
6 OGi 480	589	273	420	498	504	0.375	5.4	5.71	8.11	27.44	68.9	98.2	60.1
7 OGi 560	697	317	492	582	574	0.321	6.3	5.71	8.11	27.44	77.0	105.4	68.8
8 OGi 640	773	361	560	664	643	0.281	7.2	5.71	8.11	27.44	85.1	113.1	77.5
9 OGi 720	848	393	600	702	707	0.250	8.1	5.71	8.11	27.44	93.2	120.4	86.1
10 OGi 800	1130	464	700	824	855	0.225	9.0	8.27	7.52	27.44	112.3	149.3	99.2
11 OGi 880	1111	499	756	896	937	0.205	9.9	8.27	7.52	27.44	120.3	156.9	107.8
12 OGi 960	1292	537	792	928	1010	0.188	10.8	8.27	7.52	27.44	128.4	164.3	116.5
13 OGi 1040	1314	595	912	1080	1085	0.173	11.7	8.27	9.17	27.44	138.2	184.2	125.2
14 OGi 1120	1500	635	956	1128	1158	0.161	12.6	8.27	9.17	27.44	146.7	192.3	133.8
15 OGi 1200	1524	663	992	1160	1227	0.150	13.5	8.27	9.17	27.44	154.8	199.6	142.5
16 OGi 1280	1659	729	1116	1320	1281	0.141	14.4	8.27	10.83	27.44	165.6	220.4	151.2
17 OGi 1360	1683	760	1156	1360	1353	0.132	15.3	8.27	10.83	27.44	173.6	228.1	159.8
18 OGi 1440	1811	794	1192	1392	1424	0.125	16.2	8.27	10.83	27.44	181.7	235.5	168.5
19 OGi 1520	2016	873	1324	1568	1629	0.118	17.1	8.27	14.17	26.34	195.6	269.2	178.8
20 OGi 1600	2173	917	1392	1648	1701	0.113	18.0	8.27	14.17	26.34	203.6	276.6	187.4
21 OGi 1680	2259	961	1460	1728	1775	0.107	18.9	8.27	14.17	26.34	211.4	283.6	196.0
22 OGi 1760	2338	995	1504	1768	1856	0.102	19.8	8.27	14.17	26.34	219.7	291.1	204.6
23 OGi 1840	2421	1026	1536	1792	1923	0.098	20.7	8.27	14.17	26.34	228.2	298.3	213.3
24 OGi 1920	2499	1059	1572	1832	1990	0.094	21.6	8.27	14.17	26.34	235.7	305.8	222.0
25 OGi 2000	2580	1135	1740	2048	2042	0.090	22.5	8.27	17.32	26.34	248.8	339.7	230.6
26 OGi 2080	2655	1179	1808	2128	2114	0.087	23.4	8.27	17.32	26.34	256.8	347.2	239.3
27 OGi 2160	2734	1218	1864	2192	2175	0.083	24.3	8.27	17.32	26.34	265.0	354.6	248.0
28 OGi 2240	2808	1250	1896	2224	2247	0.080	25.2	8.27	17.32	26.34	273.2	361.8	256.6
29 OGi 2320	2884	1290	1932	2264	2317	0.078	26.1	8.27	17.32	26.34	281.4	369.6	265.3
30 OGi 2400	2956	1321	1964	2288	2376	0.075	27.0	8.27	17.32	26.34	289.4	376.9	274.0

1) Internal resistance from IEC 60896-11; 2) Short circuit current from IEC 60896-11; All data is subject to change.
Height (H) is the maximum distance between container bottom and top of bolts in assembled condition.

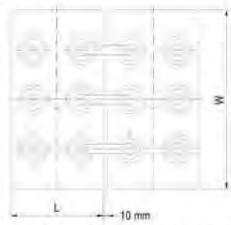
3. Terminal positions



5 OGi 400 to 9 OGi 720



10 OGi 800 to 18 OGi 1440



19 OGi 1520 to 30 OGi 2400

BAE | USA Energy from Batteries

Technical Specification for BAE *SECURA OGi*

4. Design

Positive electrode	Round-grid flat plate with low antimony alloy, circular bars, high lead weight solid grids in a corrosion-resistant PbSbSnSe - alloy
Negative electrode	Round-grid flat plate in low antimony alloy with long-life expander material
Separation	Microporous separator
Electrolyte	Sulphuric acid with a density of 1.24 kg/l
Lid	High impact, transparent SAN (Styrol-Acrylic-Nitrile), UL-94 rating: HB
Container	High impact SAN in dark grey color, UL-94 rating: HB
Flame arrestors	Includes standard ceramic arrestors with optional ceramic flip-top funnel arrestors acc. DIN 40740 available
Pole bushing	100% gas and electrolyte tight, sliding, injection moulded "Panzerpol"
Kind of pole	M10 copper insertion
Intercell connectors	Insulated solid copper connectors with cross-sections of 90, 150 or 300 mm² depending upon application
Inter-tier connectors	Flexible insulated copper cables
Connector screw	M10 stainless steel with insulated cap
Kind of protection	IP 25 regarding DIN 40050, touch protected according VBG 4

5. Charging

IU - characteristic	I_{max} without limitation U = 2.23 V/cell +/- 1%, between 10°C and 30°C (50°F and 86°F) $\Delta U/\Delta T$ = +/- 0.003 V/K below 10°C in the monthly average
Float current	15mA/100Ah, increasing to 45mA/100Ah at the end of life
Equalize charge	U = 2.33 to 2.40V/cell, time limited
Charging time up to 90%	6h with 1.5*I_{10} initial current, 2.23 V/cell, 80% C3 discharged

6. Discharge characteristics

Reference temperature	25°C (77°F)
Initial capacity	95% or better at time of delivery
Depth of discharge (DOD)	Normally up to 80%
Deep discharges	More than 80% DOD or discharges beyond final discharge voltages (dependent on discharge current) have to be avoided

7. Maintenance

Every 6 months	Check battery voltage, pilot cell voltage and temperature
Every 12 months	Record battery voltage, cell voltages and temperatures

8. Operational data

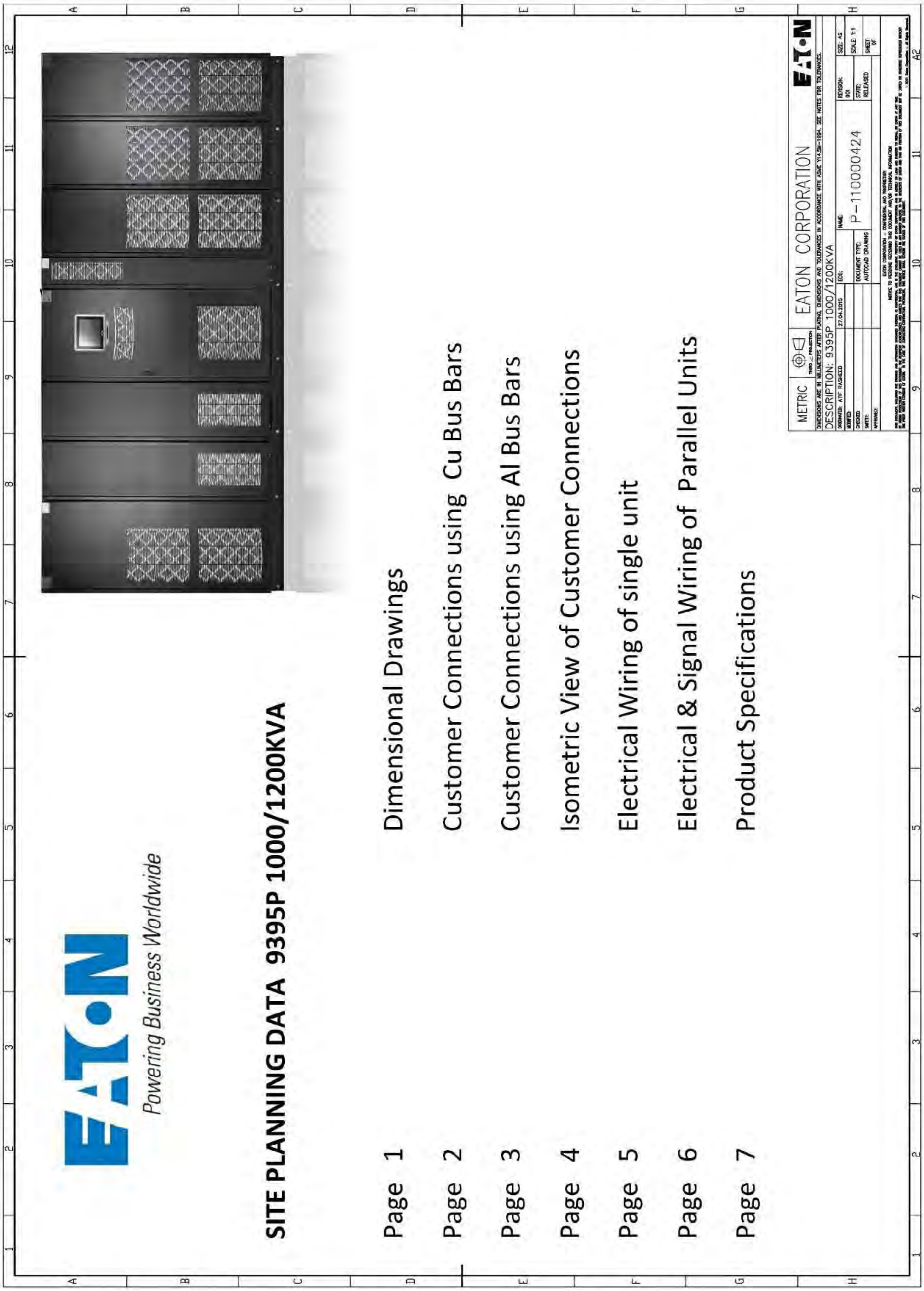
Operational life	20 years in stand-by operation, float at 20°C to 25°C (68°F to 77°F)
Water - refilling - interval	Up to 3 years, float at 20°C to 25°C (68°F to 77°F)
IEC 60 896-1 cycles	> 1200
Self-discharge	app. 3% per month at 20°C (68°C)
Operational temperature	-20°C to 55°C (-4°F to 131°F); recommended 10°C to 30°C (50°F to 86°F)
Standard	DIN 40736 part 1
Tests according	IEC 60896-11
Safety standard, ventilation	DIN EN 50272-2
Transport	Subject to DOT Regulations – See SDS for details

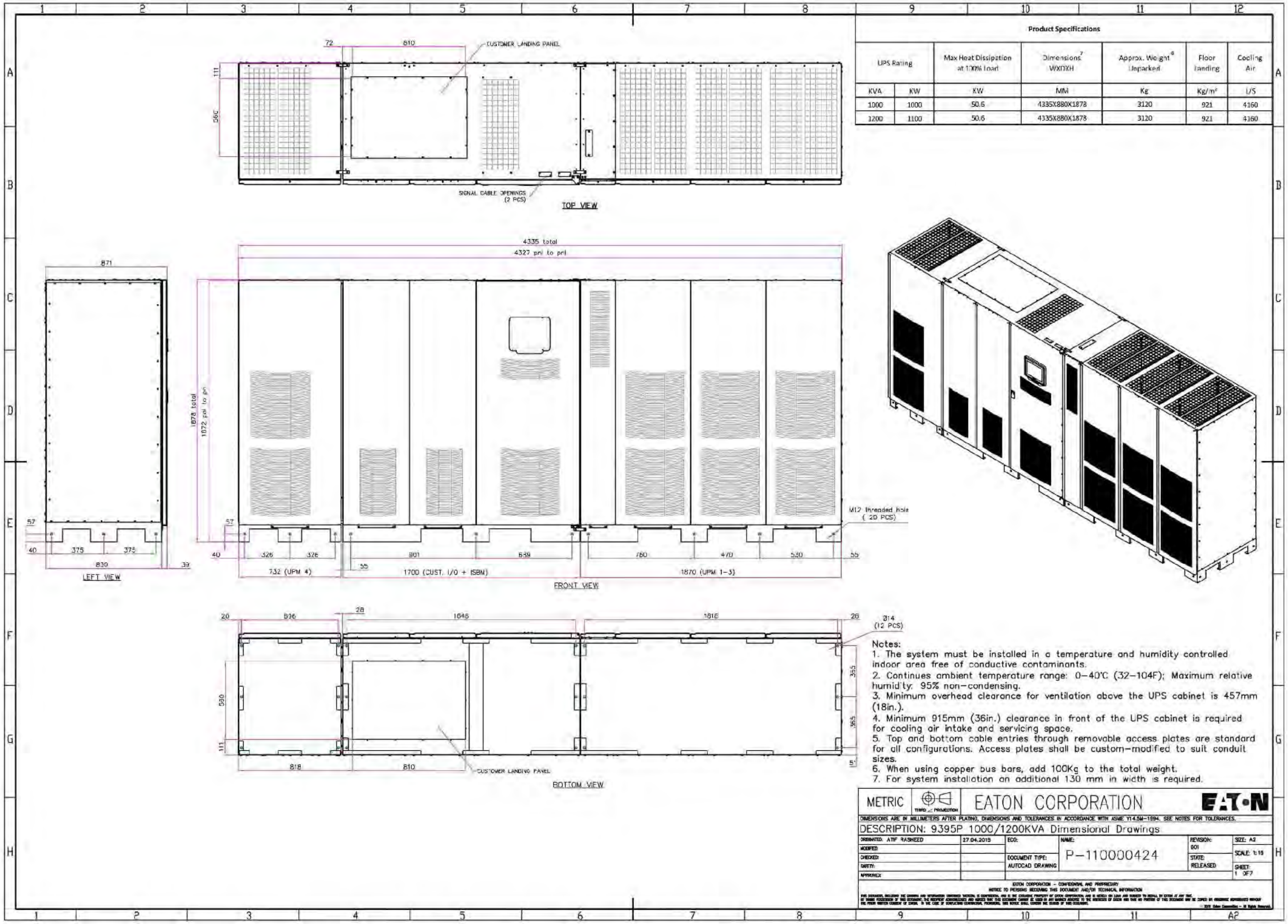
BAE Batteries USA ▪ 484 County Road V V ▪ Somerset WI 54025
TEL (715) 247-2262 FAX (715) 247-5741
www.baebatteriesusa.com

BAE | USA Energy from Batteries

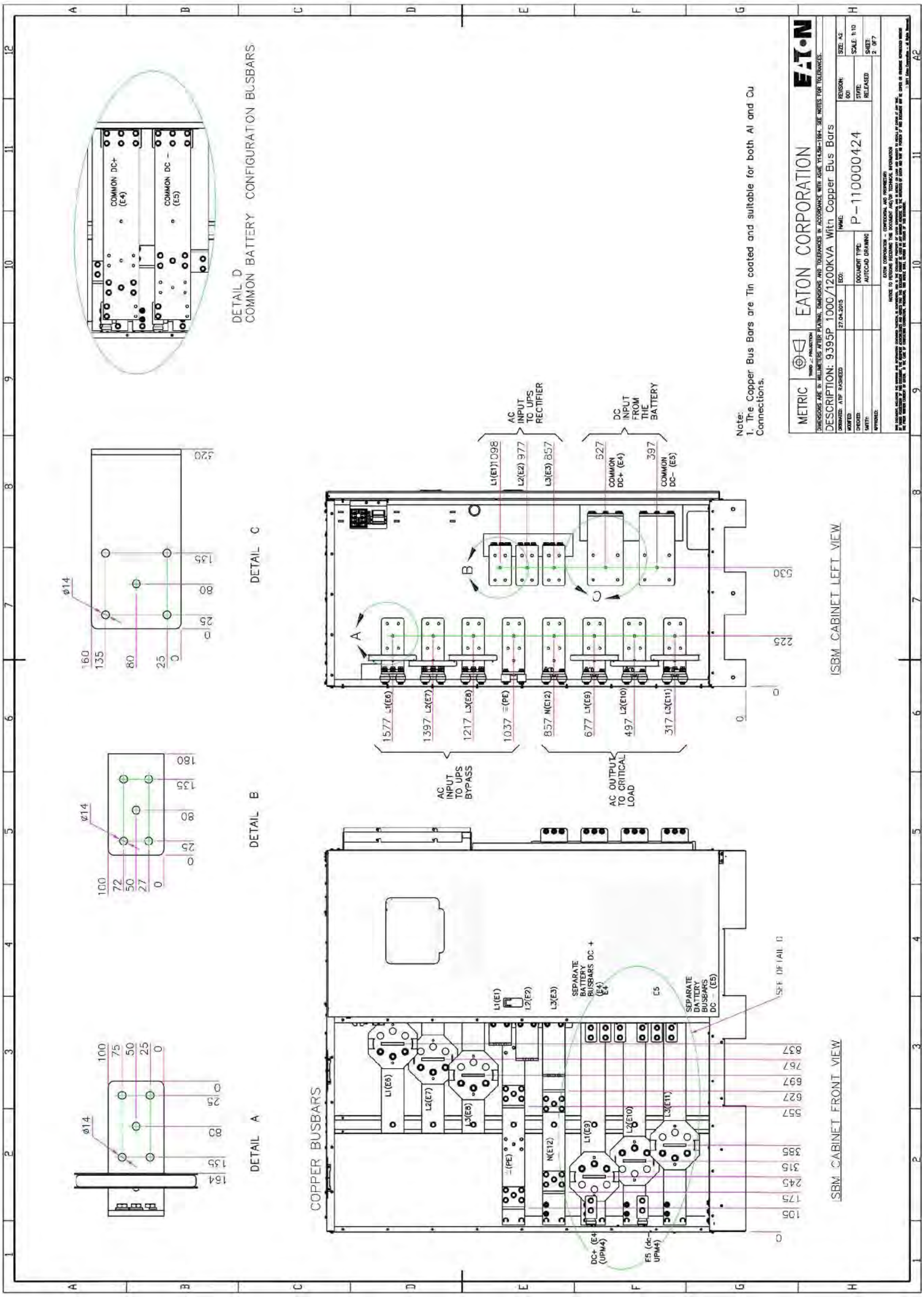
US-0518

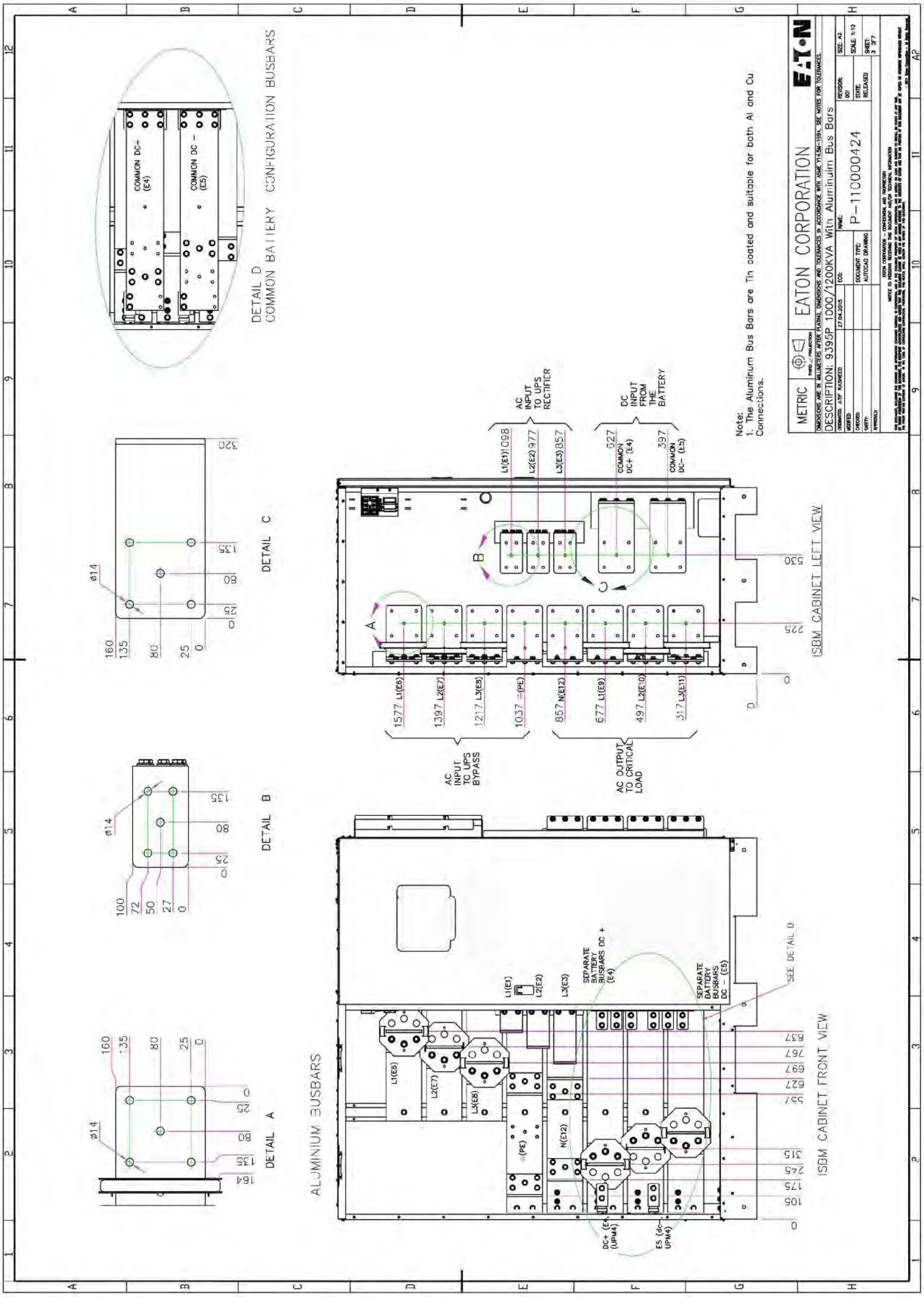
APPENDIX F: Eaton Xpert 9395P 1000/1200kVA SUPS site planning data

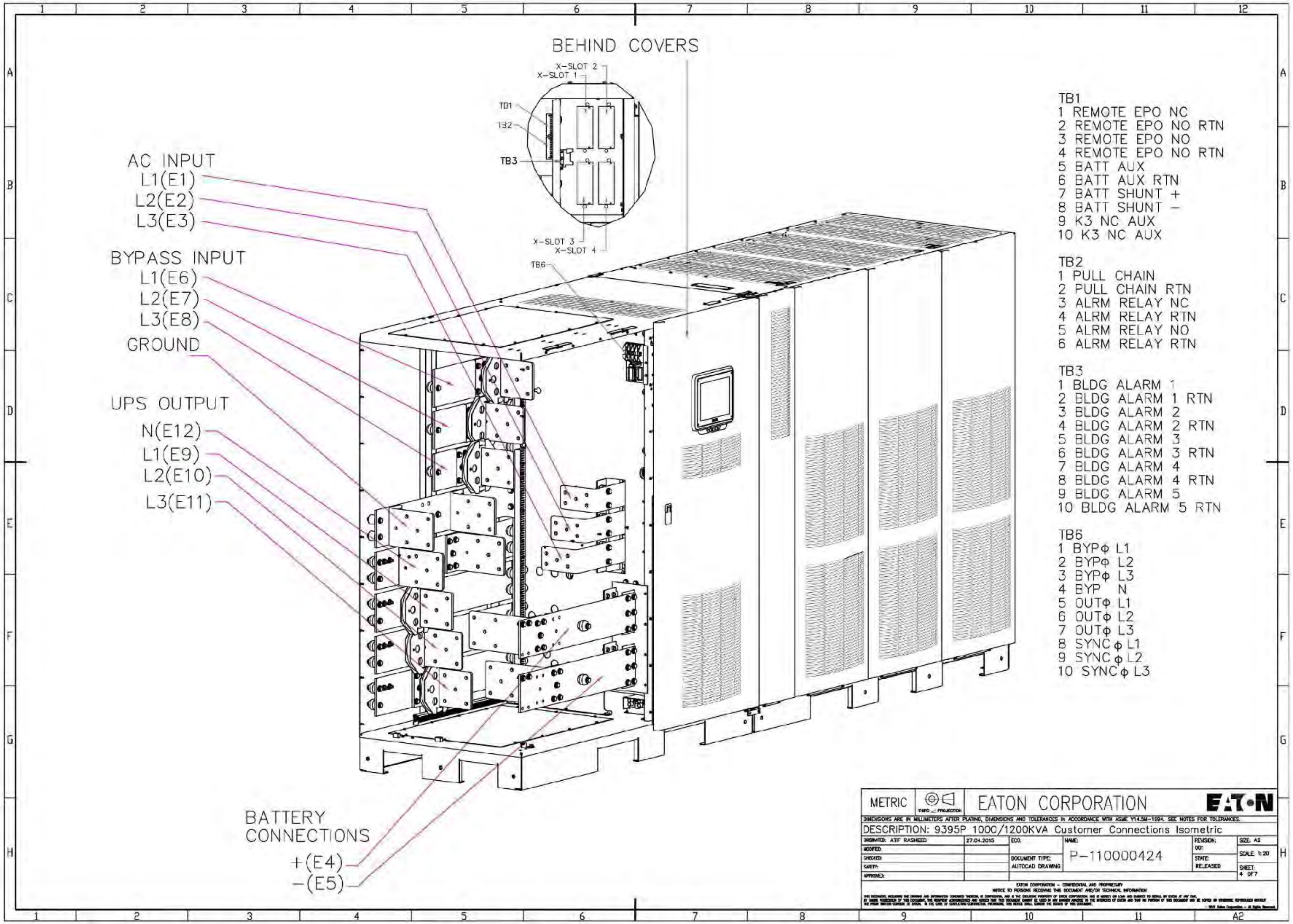


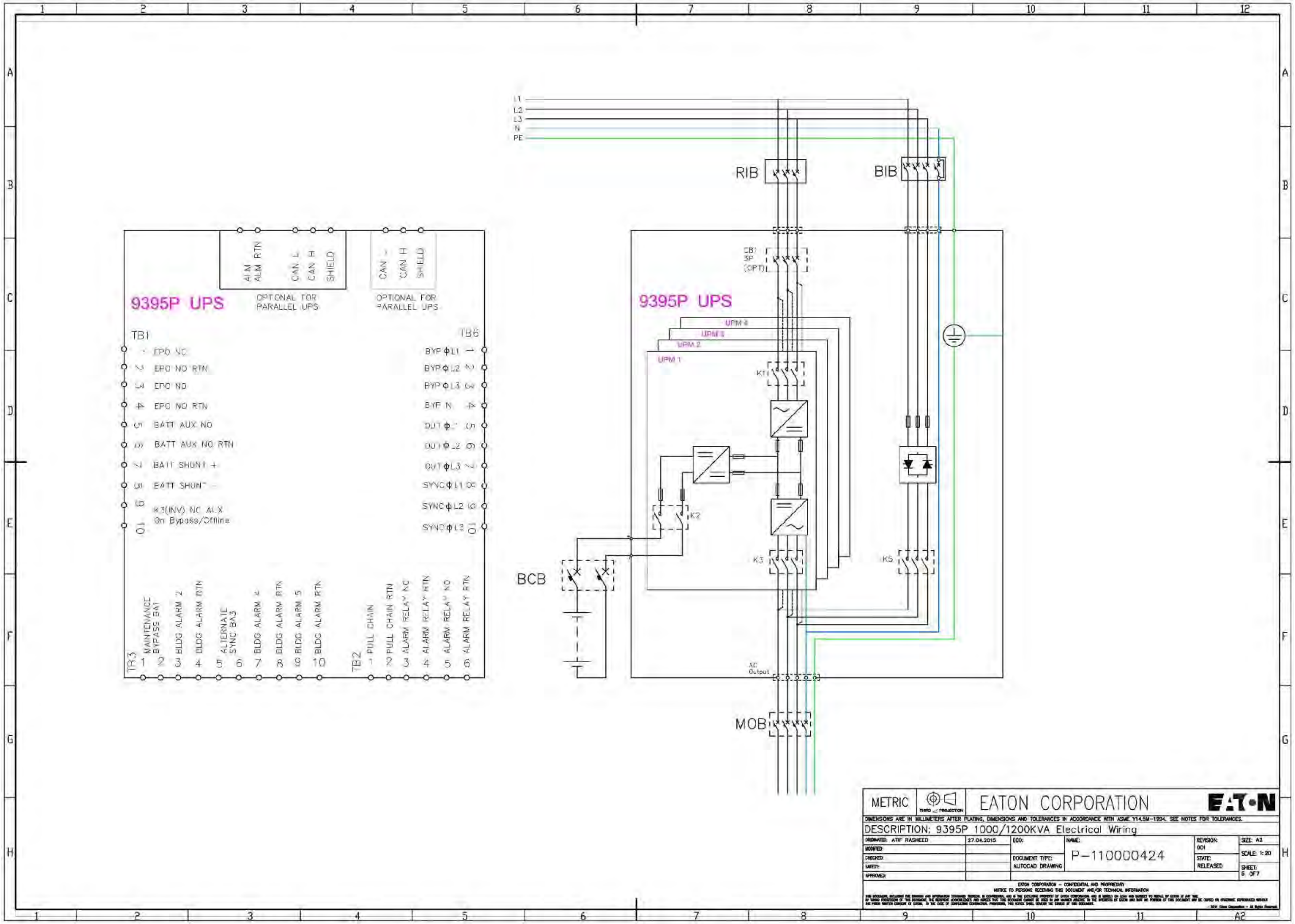


UPS Rating		Max Heat Dissipation at 100% load	Dimensions[7] WXDXH	Approx. Weight[6] Unpacked	Floor landing	Cooling Air
KVA	KW	KW	MM	Kg	Kg/m²	l/S
1000	1000	50.6	4335X880X1878	3120	921	4160
1200	1100	50.6	4335X880X1878	3120	921	4160

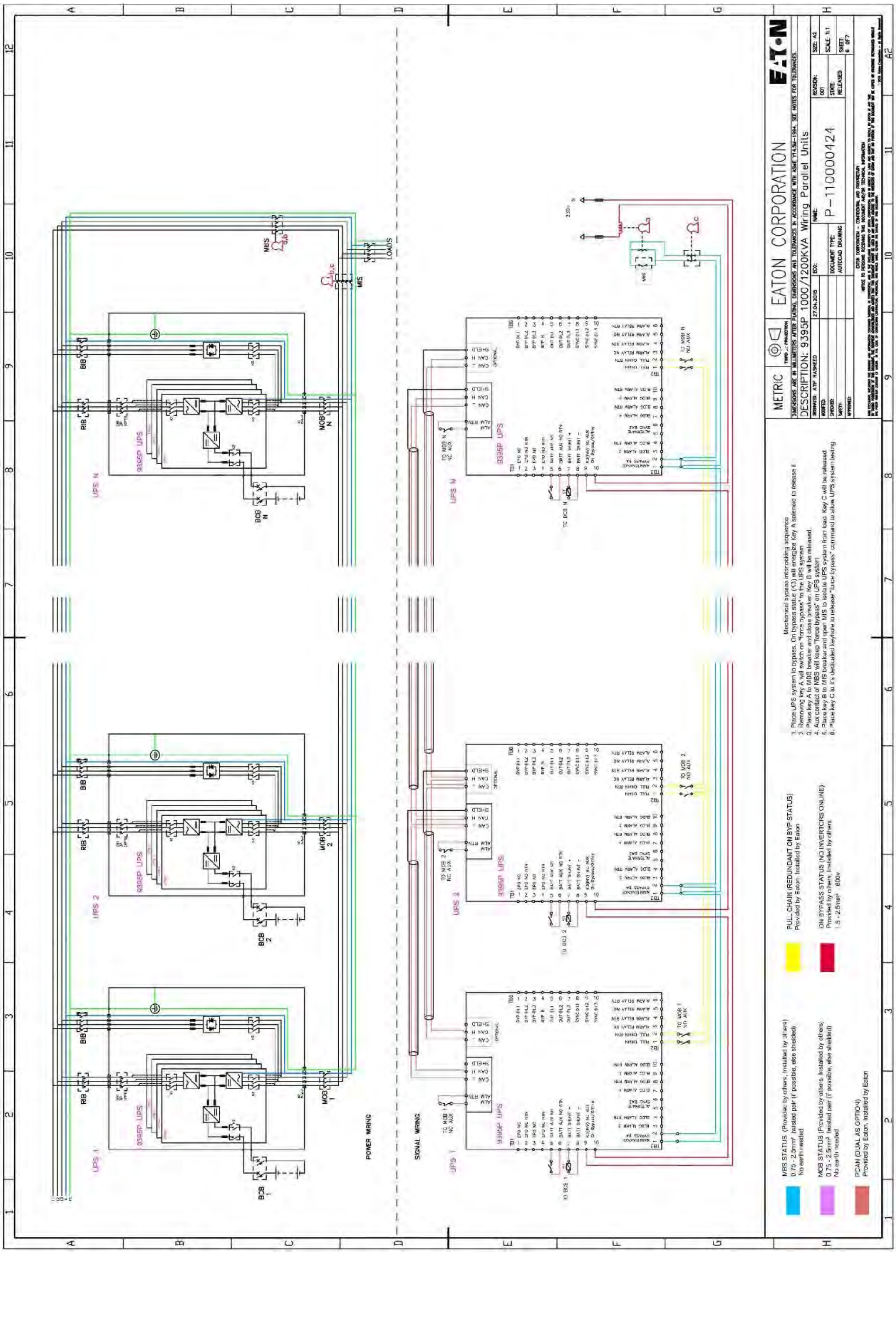

DETAIL D
COMMON BATTERY CONFIGURATON BUSBARS
COMMON DC+ (E4)
COMMON DC - (E5)
DETAIL A
DETAIL B
DETAIL C
COPPER BUSBARS
AC INPUT TO UPS RECTIFIER
DC INPUT FROM THE BATTERY
AC INPUT TO UPS BYPASS
AC OUTPUT TO CRITICAL LOAD
SEPARATE BATTERY BUSBARS DC +
SEPARATE BATTERY BUSBARS DC - (E5)
SEE DETAIL D
ISBM CABINET LEFT VIEW
ISBM CABINET FRONT VIEW
Note:
1. The Copper Bus Bars are Tin coated and suitable for both Al and Cu Connections.
METRIC
EATON CORPORATION
DESCRIPTION: 9395P 1000/1200KVA With Copper Bus Bars
P-110000424


EATON CORPORATION
DESCRIPTION: 9395P 1000/1200KVA With Aluminuim Bus Bars
P-110000424
METRIC
Note:
1. The Aluminum Bus Bars are Tin coated and suitable for both Al and Cu Connections.
ISBM CABINET FRONT VIEW
ISBM CABINET LEFT VIEW
ALUMINIUM BUSBARS
DETAIL A
DETAIL B
DETAIL C
DETAIL D
COMMON BATTERY CONFIGURATION BUSBARS
COMMON DC+ (E4)
COMMON DC − (E5)
AC INPUT TO UPS RECTIFIER
DC INPUT FROM THE BATTERY
AC INPUT TO UPS BYPASS
AC OUTPUT TO CRITICAL LOAD
SEPARATE BATTERY BUSBARS DC + (E4)
SEPARATE BATTERY BUSBARS DC − (E5)
SEE DETAIL D


BEHIND COVERS
X-SLOT 2
X-SLOT 1
TB1
TB2
TB3
X-SLOT 3
X-SLOT 4
TB6
AC INPUT
L1(E1)
L2(E2)
L3(E3)
BYPASS INPUT
L1(E6)
L2(E7)
L3(E8)
GROUND
UPS OUTPUT
N(E12)
L1(E9)
L2(E10)
L3(E11)
BATTERY
CONNECTIONS
+(E4)
−(E5)
TB1
1 REMOTE EPO NC
2 REMOTE EPO NO RTN
3 REMOTE EPO NO
4 REMOTE EPO NO RTN
5 BATT AUX
6 BATT AUX RTN
7 BATT SHUNT +
8 BATT SHUNT −
9 K3 NC AUX
10 K3 NC AUX
TB2
1 PULL CHAIN
2 PULL CHAIN RTN
3 ALRM RELAY NC
4 ALRM RELAY RTN
5 ALRM RELAY NO
6 ALRM RELAY RTN
TB3
1 BLDG ALARM 1
2 BLDG ALARM 1 RTN
3 BLDG ALARM 2
4 BLDG ALARM 2 RTN
5 BLDG ALARM 3
6 BLDG ALARM 3 RTN
7 BLDG ALARM 4
8 BLDG ALARM 4 RTN
9 BLDG ALARM 5
10 BLDG ALARM 5 RTN
TB6
1 BYPφ L1
2 BYPφ L2
3 BYPφ L3
4 BYP N
5 OUTφ L1
6 OUTφ L2
7 OUTφ L3
8 SYNC φ L1
9 SYNC φ L2
10 SYNC φ L3
METRIC
EATON CORPORATION
EATON
DESCRIPTION: 9395P 1000/1200KVA Customer Connections Isometric
ATIF RASHEED
27.04.2015
P-110000424
AUTOCAD DRAWING
RELEASED
SIZE: A2
SCALE: 1:20
SHEET: 4 OF 7
A2



9395P UPS
OPTIONAL FOR PARALLEL UPS
ALM
ALM RTN
CAN L
CAN H
SHIELD
TB1
1 EPO NC
2 EPO NO RTN
3 EPO NO
4 EPO NO RTN
5 BATT AUX NO
6 BATT AUX NO RTN
7 BATT SHUNT +
8 BATT SHUNT −
9 K3(INV) NC AUX On Bypass/Offline
10
TB6
BYP ϕL1 1
BYP ϕL2 2
BYP ϕL3 3
BYP N 4
OUT ϕL1 5
OUT ϕL2 6
OUT ϕL3 7
SYNC ϕL1 8
SYNC ϕL2 9
SYNC ϕL3 10
TB3
1 MAINTENANCE BYPASS BAT
2 BLDG ALARM 2
3 BLDG ALARM RTN
4
5 ALTERNATE SYNC BA3
6
7 BLDG ALARM 4
8 BLDG ALARM RTN
9 BLDG ALARM 5
10 BLDG ALARM RTN
TB2
1 PULL CHAIN
2 PULL CHAIN RTN
3 ALARM RELAY NC
4 ALARM RELAY RTN
5 ALARM RELAY NO
6 ALARM RELAY RTN
L1
L2
L3
N
PE
RIB
BIB
CB1 3P (OPT)
UPM 4
UPM 3
UPM 2
UPM 1
K1
K2
K3
K5
BCB
AC Output
MOB
METRIC
EATON CORPORATION
DIMENSIONS ARE IN MILLIMETERS AFTER PLATING. DIMENSIONS AND TOLERANCES IN ACCORDANCE WITH ASME Y14.5M-1994. SEE NOTES FOR TOLERANCES.
DESCRIPTION: 9395P 1000/1200KVA Electrical Wiring
ORIGINATED: ATIF RASHEED
27.04.2015
DOCUMENT TYPE: AUTOCAD DRAWING
P-110000424
REVISION: 001
STATE: RELEASED
SIZE: A2
SCALE: 1:20
SHEET: 6 OF 7
EATON CORPORATION – CONFIDENTIAL AND PROPRIETARY
A2


EATON CORPORATION
DESCRIPTION: 9395P 1000/1200KVA Wiring Parallel Units
P-110000424
METRIC
POWER WIRING
SIGNAL WIRING
UPS 1
UPS 2
UPS N
9395P UPS
LOADS
Mechanical bypass interlocking sequence

9395 P 1000/1200 KVA UPS Site Planning Data

Product Specifications																		
UPS Rating		AC Input	3P Rectifier Input Breaker (RIB)		3P+Bolted N Bypass Input Breaker (BIB)			AC Output	4P Inverter AC output Breaker MOB			Battery Breaker (BCB) (Ratings at the end of discharge, 1.67VPC)					For Parallel Units Common Maintenance Bypass Switch (MBS)	
			Nominal Current	Maximum Current	Nominal Current at 400v Input	Maximum Current at 10% under voltage	Integrated Bypass Fuse		Output Current	Inverter Short Circuit Current	Auxiliary Switches	Rating	Separate Battery Configration (UPM Bttery	Common Battery Configration (UPSBattery)	Trip Device (Shunt Trip)	Auxiliary Switches	Rating	Auxiliary Switches
KVA	KW	v	A	A	A	A	Type	v	A	A	Qty	VDC	A	A	VDC	Qty	A	Qty
1000	1000	400	1508	1819	1444	1589	170M7084 3000A	400	1444	3040	2	600	664	2654	48	1	1444 x N	1
1200	1100	400	1665	2000	1733	1907	170M7084 3000A	400	1733	3040	2	600	733	2920	48	1	1733 x N	1

Notes:
1. Rectifier AC input current calculations: Nominal – 100% load without charging; Maximum – 100% load with maximum charging (Rectifier current limit).
2. Inverter AC output current calculation: At 100% rated output load.
3. The system must be installed on a level floor suitable for computer or electronic equipment.
4. All wiring and installations must be in accordance with applicable National and Local Electric Regulations.
5. AC input to UPS: (3) phases, (1) neutral, (1) ground.
   AC output to load: (3) phases, (1) neutral, (1) ground.
   DC input from battery to UPS: (1) positive, (1) negative, (1) ground.
6. All breakers should be adjusted according to the specified Ampere values to protect the UPS and installation.
7. For UPS installations that utilizes single feed input, The input breaker should be configured according to the rated rectifier input current..
8. Specifications are subject to change.

METRIC EATON CORPORATION

DESCRIPTION: 9395P 1000/1200KVA Specifications

ORIGINATED: ATIF RASHEED 27.04.2015

DOCUMENT TYPE: AUTOCAD DRAWING

P-110000424

REVISION: 001 STATE: RELEASED SIZE: A2 SCALE: 1:1 SHEET: 7 OF 7

APPENDIX J: Eaton Power Xpert 9395P SUPS technical specifications (Eaton, 2019b:11)

UPS rating (unity power factor 1.0)					
kVA/kW	200/200	250/250	275/275	300/300	400/400
	500/500	550/550	600/600	675/675	750/750
	825/825	900/900	1000/1000	1100/1100	1200/1200

General characteristics	
Efficiency	99% in Energy Saver System (ESS) (up to 97% (480V) and 96% (600V and 400V) in double-conversion)
Parallel capability	4 UPS units maximum for distributed bypass and 8 UPS units maximum with SBM
Max modules per size	Up to 2 modules, 300 kW Up to 3 modules, 600 kW Up to 4 modules, 900/1200 kW
Audible noise	75dBA @ 1 meter**
Altitude (max)	1000m at 40 degree C (104 degree F) 1000m at 35 degree C (95 degree F) when UPM capacity is above 275 kW Field upgrade module,
N+1 redundancy capable	Yes
Field upgradeable	Yes
System bypass module	Included

Input characteristics	
Voltage	480V standard; 600/575V and 400/415V optional
Voltage range	+10% / -15%
Frequency range	45–65 Hz
Power factor	0.99 (minimum)
Input current distortion	<3% (no input filter required)
Soft start capability	Yes
Internal backfeed protection	Yes

Output characteristics	
Voltage	480V standard; 600/575V and 400/415V optional
Regulation	±1%
Inverter	PWM with IGBT switching
Voltage THD	<2% (100% linear load), <5% (non-linear load)
Load power factor range	Up to a .9 power factor leading without derating
Overload	110% for 10 minutes, 125% for 2 minutes, 150% for 15 seconds

Battery	
Battery types	VRLA, AGM, wet cell, lithium-ion
Battery voltage	480V
Temperature compensation	Optional
Charging method	ABM technology or float, selectable

Dimensions and weights (480V and 400V* system)		480V	400V
200, 250, 275, 300 kW	52.5"w x 34.4"d x 74"h	2150 lb (975 kg)	1886 lb (857 kg)
200-300 kW redundant	73.8"w x 34.4"d x 74"h	3184 lb (1447 kg)	N/A
Field upgrade module, 300 kW	29"w x 34.4"d x 74"h	1037 lb (470 kg)	N/A
400, 500, 550, 600 kW	73.8"w x 34.4"d x 74"h	3184 lb (1447 kg)	3184 lb (1447 kg)
400-600 kW redundant	103"w x 34.4"d x 74"h	4221 lb (1918 kg)	N/A
675, 750, 825, 900 kW	141"w x 34.4d x 74"h	5236 lb (2375 kg)	5236 lb (2375 kg)
675, 750, 825, 900 kW +1 redundant	170.1w x 34.4d x 74"h	6523 lb (2959 kg)	N/A
1000, 1100, 1200 kW	170.1w x 34.4d x 74"h	6523 lb (2959 kg)	6620 lb (3003 kg)

Dimensions and weight (575V/600V* system)		
200, 225, 250, 275 kW/kVA	102.9"w x 34.4"d x 74"h	4354 lb (1975 kg)
200–300 kW/kVA +1 redundant	126.2"w x 34.4"d x 74"h	5683 lb (2578 kg)
400, 450, 500, 550 kW/kVA	126.2"w x 34.4"d x 74"h	5683 lb (2578 kg)
400–550 kW/kVA +1 redundant	155.2"w x 34.4"d x 74"h	6722 lb (3049 kg)
675, 750, 825 kW/kVA	195"w x 34.4"d x 74"h	10050 lb (4559 kg)
675, 750, 825 kW/kVA +1 redundant	224"w x 34.4"d x 74"h	11550 lb (5239 kg)
1000,1100 kW/kVA	224"w x 34.4"d x 74"h	11550 lb (5239 kg)
Field upgrade module, 275 kW	29"w x 34.4"d x 74"h	1037 lb (470 kg)

General characteristics	
Control panel (LCD)	Color touchscreen
Battery startup	Standard
Frequency conversion	Standard
Multi-language	Standard
Building alarm inputs	5 (galvanic isolated)

Options

- External maintenance bypass
- PDU, RPP and STS
- Maintenance bypass module, matching cabinet, 2/3/4 breaker
- DC disconnects
- Human Machine Interface (HMI) designs for monitoring of connected equipment
- 100 kAIC input breakers

Certifications	
Safety	UL1778, cUL
EMC	IEC 62040-2, C3 limits

PredictPulse™ remote monitoring and management service

PredictPulse is a monitoring and management subscription service that collects and analyzes data from connected power infrastructure devices, providing Eaton with the insight needed to make recommendations and take action on your behalf. PredictPulse is included with the 9395 high performance UPS for the first year at no-charge along with a PXGX-UPS card and Environmental Monitoring Probe (connectivity parts are required).

Communications

Software compatibility: Software and Power Xpert Reporting
Communications cards: Four communication bays standard. The following connectivity options can be installed at any time:
- PXGX-UPS card (included with PredictPulse activation)
- ModBus RTU card
- AS/400 Relay card
- Industrial Relay card
- Powerware HotSync CAN Bridge card
- Environmental Monitoring Probe (included)
- BACnet IP communication protocol supported

Remote inputs/outputs: Five building alarm inputs and one summary alarm contact (5A @ 120V) standard
Remote monitor panel: Eight backlit status indicator lamps plus an audible horn

***Assumes operation in nominal voltage, no battery charging and <60% load*
1. Due to continuing improvements, specifications are subject to change without notice.

Notes:
**600V and 400V are 275 kW UPM max capacity.*

EATON
Powering Business Worldwide

Eaton
1000 Eaton Boulevard
Cleveland, OH 44122
United States
Eaton.com

For more information on the 9395, visit **Eaton.com/9395**

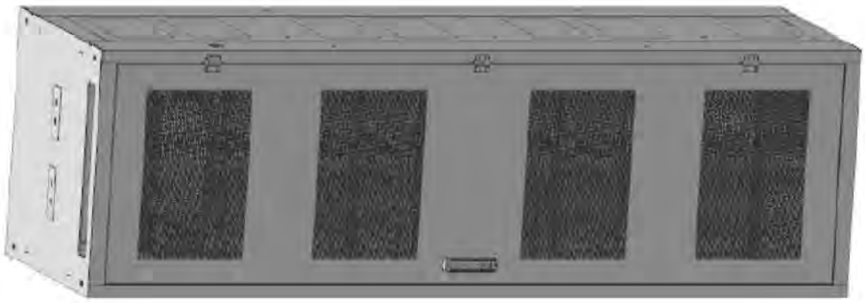
APPENDIX H: External LIB cabinet site planning data

Powering Business Worldwide

SITE PLANNING DATA - Eaton EBC-Li

External Battery Cabinet with Lithium-Ion batteries

Page 1	Detailed exterior dimensions
Page 2	Installation clearance
Page 3	Packing details
Page 4	Wiring and connection details
Page 5	System connection

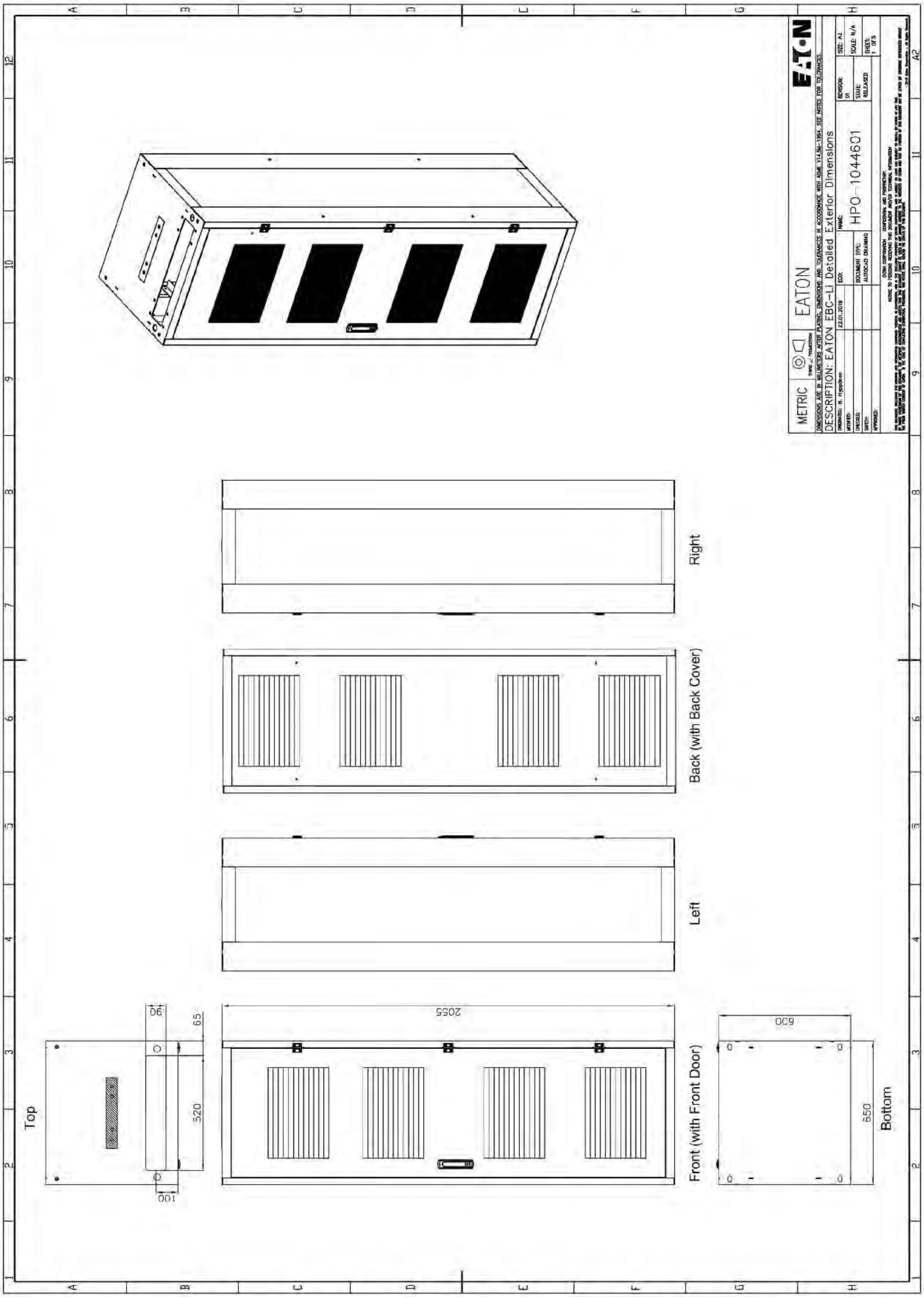


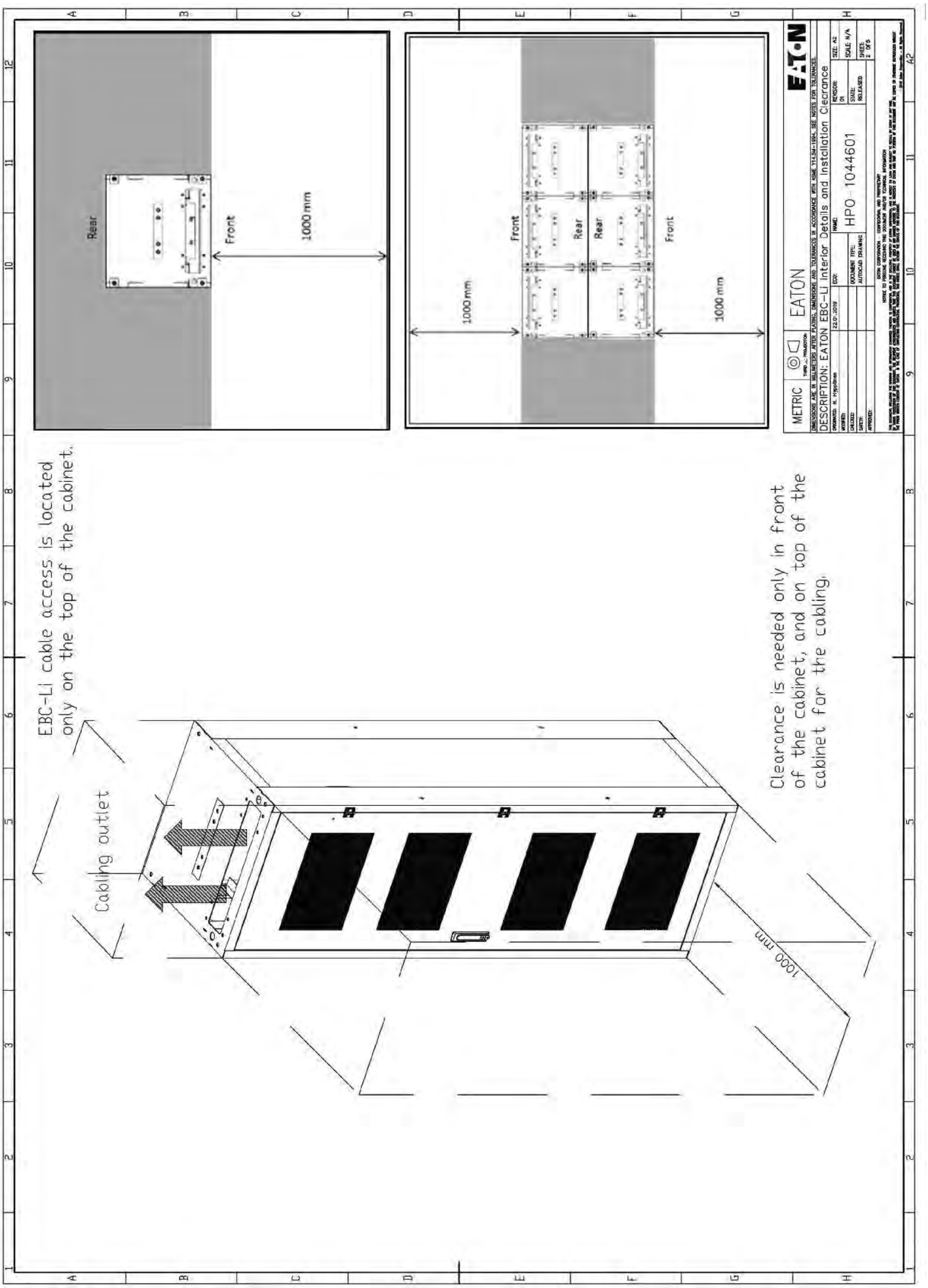
METRIC

EATON

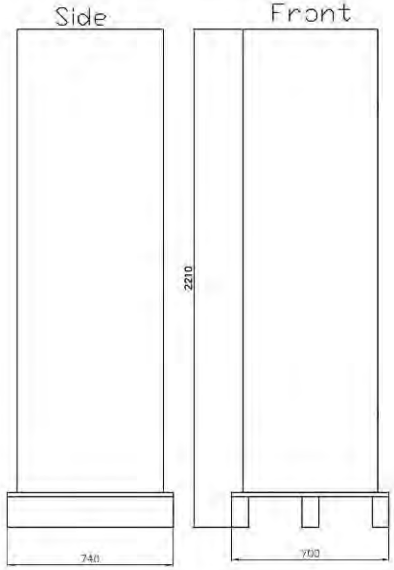
DESCRIPTION: EATON EBC-Li

HPO-1044601


Top
Front (with Front Door)
Left
Back (with Back Cover)
Right
Bottom
2055
520
65
90
100
600
550
METRIC
EATON
DESCRIPTION: EATON EBC-Li Detailed Exterior Dimensions
HPO-1044601
A2

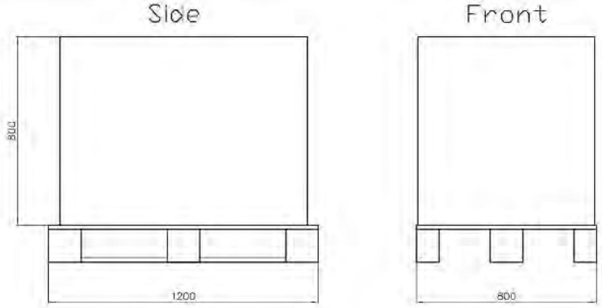

EBC-Li cable access is located
only on the top of the cabinet.
Cabling outlet
1000 mm
Clearance is needed only in front
of the cabinet, and on top of the
cabinet for the cabling.
Rear
Front
1000 mm
1000 mm
Front
Rear
Rear
Front
1000 mm
METRIC
EATON
DIMENSIONS ARE IN MILLIMETERS AFTER PLATING, DIMENSIONS AND TOLERANCES IN ACCORDANCE WITH ASME Y14.5M-1994, SEE NOTES FOR TOLERANCES.
DESCRIPTION: EATON EBC-Li Interior Details and Installation Clearance
ORIGINATED: N. Hyppönen
22.0.2019
NAME:
HPO-1044601
REVISION: 01
SIZE: A2
SCALE: N/A
STATE: RELEASED
SHEET: 2 OF 5
DOCUMENT TYPE: AUTOCAD DRAWING

Frame - 196 kg

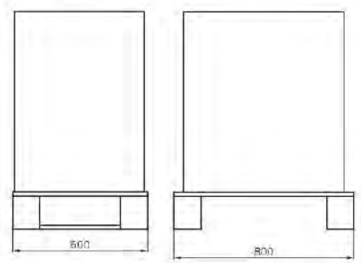


Battery modules - 260 kg

Note!
Consists of Hazardous material, refer to product Material Safety Data Sheet (MSDS) for details.



Accessories - 62 kg
(cables, switchgear, SMPS)



Factory provided cables:
Switchgear to Module #1 signal cable
Module to module signal cables
DC power cables (SMPS to Switchgear)
CAN cable - SMPS to Switchgear
Signal cable for multiple rack solutions, adjacent installation

Not factory-provided cables:	Connector type
TCP/IP Cable	VS-08-BU-RJ45/LP-1
AC input cables (SMPS)	

NOTE!
1. Final product is packed and delivered on 3 different pallets.
2. Storage temperature: 0 - 40°C
   2.1. To minimize capacity degradation, storage temperature of less than 10°C and 3.630V per cell is recommended
3. Storage humidity: Less than 90% RH (Recommended to be less than 60% RH)
4. Storage period: Less than 6 months
   4.1. The Capacity degradation will occur depending on storage time
5. Refer to Product specification for general handling guidance.

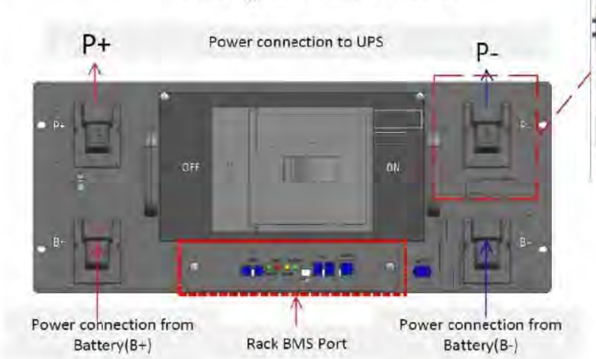
METRIC EATON

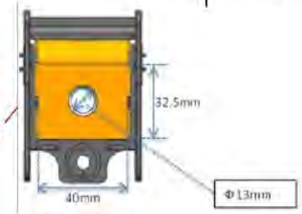
DESCRIPTION: EATON EBC-Li Shipping and packing details

HPO 1044601

DOCUMENT TYPE: AUTOCAD DRAWING
STATE: RELEASED
SIZE: A2
SCALE: N/A

Switchgear connections





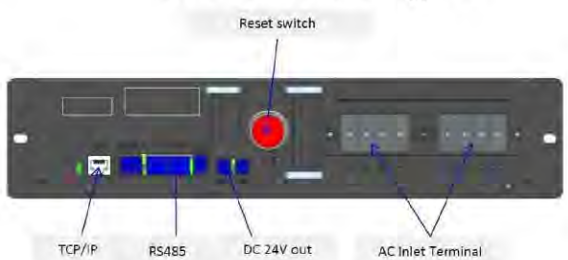
P+/P- connectors (Front, cover off)

	Size	Torque
Rack anchoring*	M16 bolt	140 Nm
Ground wire *	≥ 70 mm2	30 Nm
Ground wire fasteners *	M12x30	
Switchgear and SMPS to rack	M5x10	5.1 - 6.1 Nm
Switchgear and SMPS ground	M5x10	5.1-6.1 Nm
Battery to SG (busbar) (B+/B-)	M12 bolt (SG)	30 Nm
	M8 bolt (Batt)	8.16-11.94 Nm
Batt to batt (busbar)	M8 bolt	8.16-11.94 Nm
Power cable connection*	M12 cable lug	30 Nm

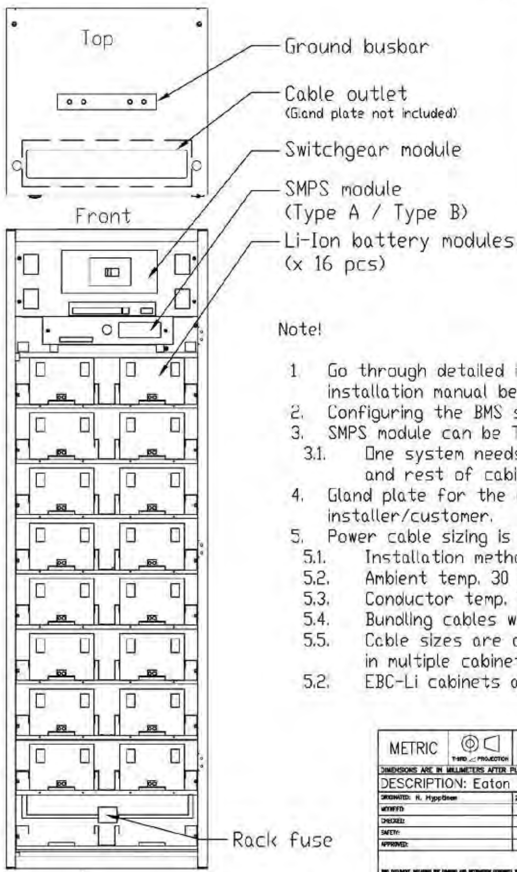
*Not factory-provided

UPS power	Suggested power cable sizes
50 kW / 50 kVA	35 mm^2, Cu
100 kW / 100 kVA	95 mm^2, Cu
150 kW / 150 kVA	150 mm^2, Cu
175 kW / 200 kVA	185 mm^2, Cu

SMPS connections (Type A)



SMPS connections (Type B)



Note!

1. Go through detailed installation guidance in manufacturer installation manual before installing the product.
2. Configuring the BMS system is made through ELP-MUN software.
3. SMPS module can be Type A (Master) or Type B (Secondary)
   - 3.1. One system needs only one Type A SMPS (the first one) and rest of cabinets are mounted with Type B SMPS's.
4. Gland plate for the cable outlet must be provided by installer/customer.
5. Power cable sizing is based on IEC 60364-5-52, table B.52.2
   - 5.1. Installation method C
   - 5.2. Ambient temp. 30 dgr C
   - 5.3. Conductor temp. 70 dgr C (PVC insulation)
   - 5.4. Bundling cables with other circuits not allowed
   - 5.5. Cable sizes are calculated for 1x EBC-Li - 1x UPS systems, in multiple cabinet systems, cable sizes varies
   - 5.2. EBC-Li cabinets are not possible to daisy chain

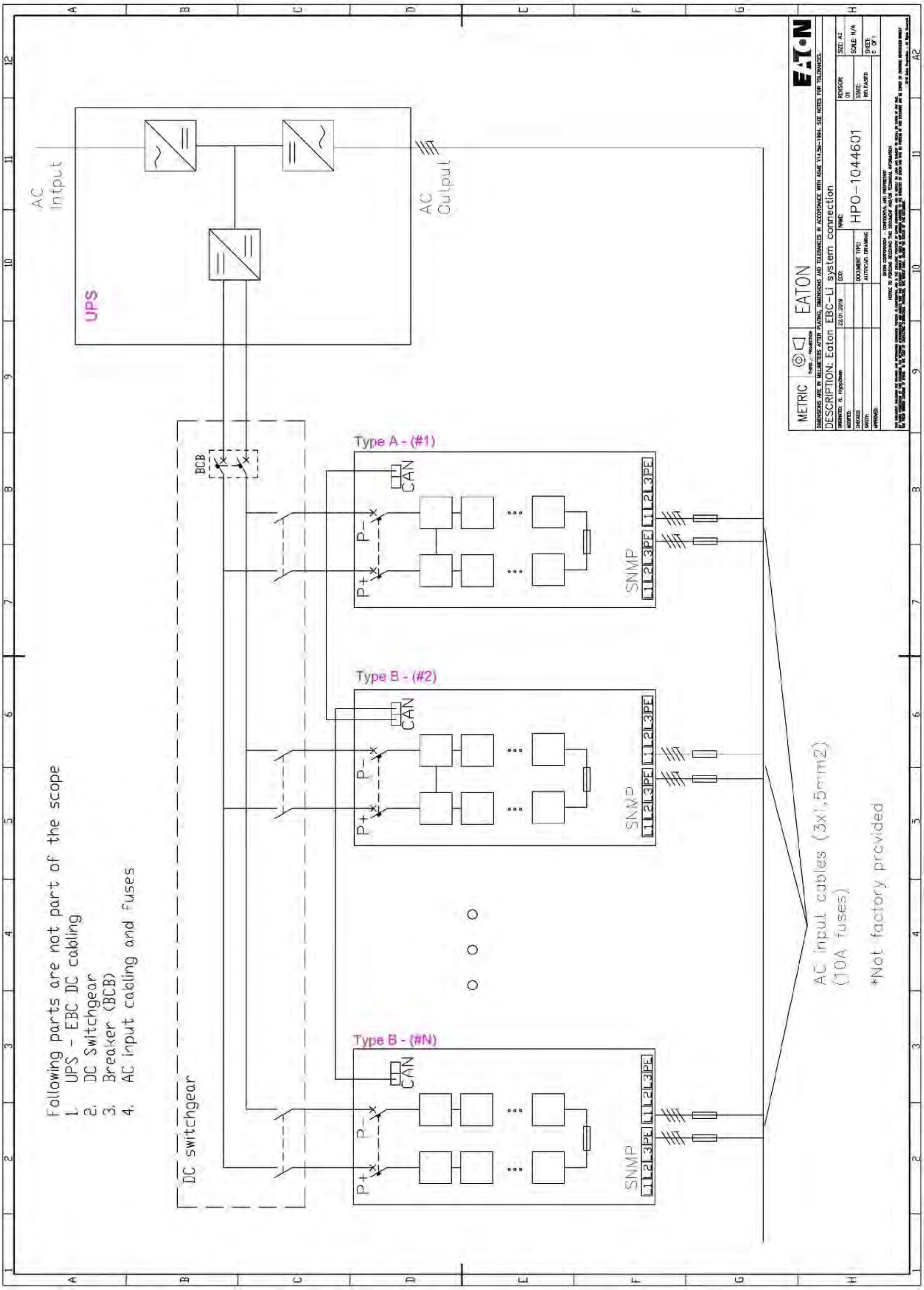
METRIC | EATON | EATON

DIMENSIONS ARE IN MILLIMETERS AFTER PLATING. DIMENSIONS AND TOLERANCES IN ACCORDANCE WITH ASME Y14.5M-1994. SEE NOTES FOR TOLERANCES.

DESCRIPTION: Eaton EBC-Li Wiring and connection details

ORIGINATOR: H. Hyppönen | 22.01.2019 | DOCUMENT TYPE: AUTOCAD DRAWING | NAME: HPO-1044601 | REVISION: 01 | STATE: RELEASED | SIZE: A2 | SCALE: N/A | SHEET: 4 OF -

A2


Following parts are not part of the scope
1. UPS - EBC DC cabling
2. DC Switchgear
3. Breaker (BCB)
4. AC input cabling and fuses
UPS
AC Intput
AC Output
DC switchgear
BCB
Type A - (#1)
Type B - (#2)
Type B - (#N)
CAN
P-
P+
SNMP
L1 L2 L3PE
AC input cables (3x1,5mm2)
(10A fuses)
*Not factory provided
METRIC
EATON
DESCRIPTION: Eaton EBC-Li system connection
HPO-1044601
A2

Appendix I: Network supply interruptions for the past 10 years (data obtained from Eskom)

STCH_NOFELCA	(All)											
LOSS_CATEGORY	L											
#Interruptions	**Interruption_type**	**YEAR**										
	Momentary(<=5min)	**Momentary(<=5min) Total**	**Sustained(>5min)**								**Sustained(>5min)**	**Grand Total**
Cause	**2018**		**2011**	**2012**	**2013**	**2014**	**2015**	**2017**	**2018**	**2019**	**2020**		
Animals/Birds					2							2	2
Cable/Hardware				2								2	2
Equipment_failure						2		2		2	2	8	8
Line/Hardware	2	2	2						2			4	6
Load_shedding							2			27	6	35	35
Maintenance/Construction						2	2	4		2		10	10
Trees											2	2	2
Weather			2									2	2
Grand Total	**2**	**2**	**4**	**2**	**2**	**4**	**4**	**6**	**2**	**31**	**10**	**65**	**67**
Average interruptions per year (sustained >5min)												**7**	
We assume that, for each of these interruptions, all UPSs run at full capcity for 15 minutes (0,25hrs)												**0,25 x 7 = 1,75hrs**	

APPENDIX J: Energy distribution coefficients table

Energy distribution coefficient calculation					
Total site		**Total kW·h**	**Peak energy**	**Standard energy**	**Off-peak energy**
April	Low demand season (LDS)	2079276	255364	678722	1145190
May		2358752	355050	904331	1099371
September		2166594	304977	806283	1055334
October		2325992	343511	853438	1129044
November		2260316	345077	867311	1047928
December		863849	103850	275286	484713
January		1617873	251233	643733	722908
February		1914059	295395	740120	878545
March		1131875	160177	401861	569837
LDS average energy		1857621	268293	685676	903652
Peak energy coefficient			0.297		
Standard energy coefficient				0.759	
Off-peak energy coefficient (reference)					1
Main dividing coefficient					2.056
June	High demand season (HDS)	2284114	334394	863368	1086352
July		1425119	201109	515139	708872
August		1325070	203662	523117	598292
HDS average energy		1678101	246388	633875	797838
Peak energy coefficient			0.309		
Standard energy coefficient				0.794	
Off-peak energy coefficient (reference)					1
Main dividing coefficient					2.103