Cape Peninsula
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THE VALUE OF ENERGY STORAGE FOR AN INDUSTRIAL CUSTOMER ON A UTILITY DISTRIBUTION NETWORK

by

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DECLARATION

I, Xolisa Koni, declare that the contents of this dissertation represent my own unaided work, and that the dissertation 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.

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Signed **Date**

ABSTRACT

Energy crises experienced by the electricity utility in South Africa has a huge impact to the country's functioning sectors particularly the industrial sector. Henceforth, adoption of renewable energy sources by these sectors is critical and is of paramount importance.

The research in this dissertation is about a proposed hybrid energy storage system for an industrial customer on a utility distribution network. The hybrid energy storage system considered are the Battery Energy Storage System (BESS) and Fuel Cell (FC) connected in parallel to each other and inverted in Alternating Current (AC) using the bi-directional Power Conversion System (PCS).

This research used two engineering software namely, Digsilent PowerFactory and Hybrid Optimisation Multiple Energy Resources (HOMER). The Digsilent PowerFactory was specifically used for the technical analysis of the network while the HOMER software was solely used for economic analysis of ESS to be incorporated into the distribution network.

The study used the Digsilent functionality called Quasi-Dynamic Simulation Language (QDSL) to model the network. QDSL is a program used in the model definitions to give existing network models logic, which is dependent on the manner in which one requires the model to operate. The programmable logic enabled the user to define how the energy storage system operates, including setting limits and measurements that get calculated autonomously. Quasi-Dynamic Simulation was coded to determine when the BESS and FC should charge and discharge. QDS plots/graphs showing Peak Shaving of the load, improvement of the voltage magnitude, and reduced electrical losses were achieved.

Furthermore, in this research project, another objective was to analyse economic feasibility of the energy storage system interconnected with utility distribution network using National Renewable Energy Laboratory (NREL) HOMER software. The optimisation results revealed the Net Present Cost (NPC) to be R36, 936, 360.00(US$2,234million), the Levelised Cost of Energy (LCOE) was R0.1055 (US$0.0064), and the Operating cost was R1, 789, 352.00 (US$108,233) respectively. The study found the energy storage system interconnection to be cost effective. A breakdown cost analyses of the configuration is presented in a Pie Chart format.

Keywords: Energy Storage System, Quasi-Dynamic Simulation Language (QDSL), Battery Energy Storage System (BESS), Fuel Cell, Industrial Customer, Distribution Network.

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Firstly, let me take this opportunity to thank my creator, the great Elohai, EL Shaddai, Elohim, Tzevaot. To God is the glory, without him this work could not have been a success.

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DEDICATION

This dissertation is dedicated to those special individuals who were part and parcel of my upbringing.

Nonkosiyethu Koni (Her Soul R.I.P)

Daughter of

Vatala koni & Nofenishala Koni

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ABBREVIATIONS AND ACRONYMS

APU	Auxiliary Power Units
BESS	Battery Energy Storage System
BESF	Battery Energy Storage Facilities
BB	BusBar
CDPES	Centre for Distributed Power and Electrical System
CPUT	Cape peninsula University of Technology
CHP	Combined Heat Power
CAES	Compressed Air Energy Storage
DC	Direct Current
DLFC	Direct Liquid Fuel Cell
DMFC	Direct Methane Fuel Cell
DoD	Depth of Discharge
EESS	Electric Energy Storage System
ESS	Energy Storage System
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
EPS	Electric Power System
EMT	Electromagnetic Transient Tool
FC	Fuel Cell
FES	Flywheel Energy Storage
GHG	Green-House Gas
GE	General Electronics
HOMER	Hybrid Optimization of Multiple Energy Resources
HYSA	Hydrogen South Africa
HESS	Hybrid Energy Storage System
HV	High Voltage

ICE	Internal Combustion Engine
IEC	International Electrotechnical Commission
LCOE	Levelised Cost of Energy
MG	Micro Grid
MCFC	Molten Carbonated Fuel Cell
MIC	Monitoring, Information Exchange and Control
MV	Medium Voltage
MW	Mega Watts
MVAR	Mega Volt-Amps Reactive
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
PEMFC	Proton Exchange Membrane Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
PHS	Pumped Hydro Storage
PCC	Point of Common Coupling
PCS	Power Conditioning/Conversion System
POC	Point of Connection
PVC	Polyvinyl Chloride
QDSL	Quasi Dynamic Simulation Language
QDS	Quasi Dynamic Simulation
RVC	Rapid Voltage Change
SOFC	Solid Oxide Fuel Cell
SMES	Superconducting Magnetic Energy Storage
SCADA	Supervisory Control and Acquisition data
SoC	Sate of Charge
UTC	United Technologies Cooperation
UPS	Uninterrupted Power Supply
V_{DG}	Distributed Generation Voltage

V_{GRID}	Grid Voltage
YSZ	Yttria-Stabilised Zirconia

GLOSSARY

Duty Circle	Representation of an ESS using the charge or discharge profile for demands associated with it.
Depth of discharge	is a measure of the removed capacity in percentage after a deep discharge of a fully charged battery.
DigSilent	Engineering software specially designed to analyze power system applications such as in Generation, Transmission, Distribution and Industrial Systems.
Embedded Gen.	Small scale production of power connected within the electricity distribution network, located close to the place of consumption.
Energy Storage	A chemical to electrical conversion device that has an ability to store energy when not in use and only dissipated when needed.
Energy Density	The amount of energy that can be stored for a given area, volume, or mass of the storage system
Energy efficiency	the input energy subtracting energy losses divided by the input energy to the ESS expressed as a percentage.
Hybrid	Combinations between different technologies to produce power
Peak Shaving	An energy storage application that requires duration of discharge of the ESS during on-peak demand and recharge during off-peak period.
Power Quality	Parameters (Voltage, Frequency) that are at steady state condition and stay within the prescribed range, or close to the rated value
Power Density	Indicates the amount of power that can be delivered for a given amount of area, volume, or mass of the storage system
Response Time	the amount of time required for a storage system to go from standby mode to full output
Round-Trip Efficiency	Indicates the amount of usable energy that can be

	discharged from a storage system relative to the amount of energy that was put in. This accounts for the energy lost during each charge and discharge cycle
State of Charge	indicates the level of charge of the ESS and gives awareness when the ESS should be charged

CHAPTER ONE
GENERAL INTRODUCTION

1.1 Introduction

Electrical Energy is amongst the main Global Growth drivers of the economy. According to the World Economic Outlook (WEO) projections, South Africa, in particular, is estimated to contribute 0.8 percent in 2019 to the world economic output of 3.5 percent (IMF, 2019). Since, energy infrastructure is a critical component that underpins economic activity and growth across the country; it needs to be robust and extensive enough to meet industrial, commercial and household needs (Notice, 2018).

Crisis faced by the electricity utility in South Africa (ESKOM) has a tremendous impact to various functioning sectors such as mining sector, agricultural sector, industrial sector, etc. Therefore, Adoption of renewable energy sources by these sectors is very crucial and is of paramount importance. Lately, research exhibits that there has been an increase in the use of renewable energy sources mainly due to the growing concern over the pollution caused by fossil fuel based energy. Renewable energy sources such photovoltaic (PV), wind, and fuel cell, can be comprehensively utilised to enhance the safety, reliability and sustainability of power system (Raji, 2008).

Specifically, Fuel cells are expected to play an important role in future power generation. The benefits of utilising a fuel cell to provide the chemical-to-electrical energy conversion is its high fuel-to-electrical energy efficiency of about 50% depending on the type of fuel cell technology employed including system losses (Raji, 2008). But despite that, fuel cell technology in terms of cost effectiveness is after all deemed too expensive compared to incumbent technologies such as internal combustion engines (ICE) and batteries. This is of course partly due to the early stage of development (Hardman, Chandan and Steinberger-Wilckens, 2015). And some interprets this as an indictment of the technology as it is often written off as another one of those technologies that is perpetually five years from commercialisation (Schneider, 2005).

Moreover, fuel cell has received less attention in the literature, but could potentially generate low-carbon electricity while avoiding some of the practical consume acceptance issues faced by other low-carbon technologies (Ekins *et al.*, 2015).

Efficiency and effectiveness operation of Fuel cells is best obtained when combined with other energy sources with fast dynamics, such as energy storage source, of which in the interest of this research is a Battery Energy Storage System (BESS) (Geidl, Martin, 2007).

Batteries have over the years gained public acceptance and they show almost no restrictions. Successful introduction and integration of fuel cell with battery energy storage interconnected to the distribution utility network will alleviate the burden experienced by the industrial customer by providing alternative and sustainable renewable energy source of supply that inherits reliability and security energy characteristics.

1.2 Background and awareness of the problem research

The Industrial sector, being highly dependent on electricity to maintain effective production, has to acquire reliable and sustainable electricity supply from the distribution utility network. However, due to unforeseen circumstances that affect the distribution utility such as load shedding, network over-load, apparatus vandalism and theft, it is therefore, very unlikely for the utility network to perform optimally as required. Therefore, an alternative and sustainable form of electrical energy is needed to offer the industrial consumer with reliable and sustainable electricity supply.

A hybrid electric energy storage system (HEESS) accompanied by new technology including inverter with real and reactive power control to provide a uniform standard interconnection with the distribution utility network, should be a suitable solution for the industrial consumer. Therefore, the application of a hybrid electric energy storage system will be fully investigated, different energy storage systems will be compared and evaluated to determine their benefits which they share together to improve the technical and economical performances of the combined systems. As a matter of interest, Fuel cells (FC) and batteries are the most promising energy systems in a wide power range, because of their potential as an alternative and sustainable energy sources for a wide variety of applications (Beheshti, Ghassemi and Shahsavan-Markadeh, 2016).

1.3 Statement of the research problem

Load shedding, electrical system over-loading, infrastructure vandalism and theft continue to be amongst other serious challenges facing the industrial customer interconnected to a distribution utility network.

Therefore, alternative and sustainable energy sources are required to address the aforementioned challenges. The possible solution includes incorporating large-scale Fuel cell (FC) with another large-scale energy storage system (i.e. Battery) that is ultimately technically and economically sound solution to serve the purpose.

1.4 Research aims and objectives

1.4.1 Aims

The aim of this research project is to investigate and provide full analysis of the value of energy storage systems for an industrial customer that is directly interconnected to a distribution utility network. This is In order to eventually meet the energy reliability and security requirements as acquired by the customer.

1.4.2 Objectives

The aim stated above will be achieved through the following objectives, which are:

- To review and analyze the existing literature on energy storage systems interconnected to a distribution network.
- To select the best combination (Hybrid) solution suitable for the industrial customer.
- To use simulation packages to study the optimization, reliability, cost effectiveness and efficiency of the hybrid solution.
- To maintain voltage levels at the permissible limits.
- To minimize running costs.
- To reduce greenhouse gas (GHG) emissions.
- To find the most desirable dispatch strategy to be used for the energy management of the hybrid system.

1.5 Delineation of the research

Fuel cells, as a preferred primary solution, due to their inability to respond to electrical load transients, this research project will also consider one specific energy storage unit that has an ability to supply for the electrical load transients whilst fuel cells provide the steady state part of the load. In addition, various energy storage systems will be partially discussed and compared with preferred solution.

It is assumed that the documentation from this research will be used to source funding to upgrade and implement the proposed hybrid renewable energy storage system to the existing industrial customer network interlinked to the distribution utility network.

1.6 Research methodology

As mentioned in number 1.4.1, the aim of this research project is to investigate and provide full analysis of the value energy storage systems for an industrial customer that is directly interconnected to a utility distribution grid. Therefore, the methodology applied to achieve the aim includes the following:

1.6.1 Literature review

This is mainly gathering relevant theory and concepts about fuel cells and energy storage devices. Since there are several energy storage systems available, a detailed literature review will focus only to one specific energy storage unit and briefly discuss the other energy storage units. The information will be gathered through reading relevant books, recent published journals, conference proceedings papers, and through internet.

1.6.2 Simulation

This research work will adopt a creative approach of using Homer Pro (Hybrid Optimization of Multiple Energy Resources) to simulate an optimal solution. Furthermore, the research will use mathematical modelling to calculate the size of the hybrid energy storage units. The research will also utilise Digsilent package to model and simulate the involved electrical distribution network.

1.7 Motivation of the research

High cost, technology immaturity and operational transients are obstacles that need to be removed with regards to ESS [13]. Therefore, newly commercialized technologies such as Fuel cell (FC) specifically need to gain public acceptance as a safe and dependable technology [8]. Furthermore, everyone seeks to diminish CO_2, cut cost and increase efficiency. Therefore, these are the advantages this research paper will produce, consequently, having a significant improvement in the energy spectrum.

1.8 Organisation of the Dissertation

This dissertation is made up of six chapters, references, and appendices page and is outlined as follows:

Chapter One: Introduction – This chapter deals with the general aspects of this research project. This chapter further provides the background and awareness of the problem under study, presents the statement of the research, clearly outlines the aims and objectives of this research, the approach used in the study, and lastly, the motivation behind this research.

Chapter Two: Literature Review – The second chapter of this dissertation is focused on the literature review related to the research and consists of three sections. The first section deals with the fuel Cell component, the second section discusses the energy storage systems focusing mainly on the battery energy storage, and the third section is dedicated to the MV electrical distribution network.

Chapter Three: General Description of the Energy Storage System – This chapter discusses the type of the customer under study and provides full description of the various components that form part of the system under study and the system operating modes.

Chapter Four: Energy Storage System Modelling – This chapter provides full details on the modelling of each component of the proposed system under study and the simulation procedures followed in this study.

Chapter Five: Results and Discussion – This chapter presents and discusses the results obtained while modelling the proposed system mentioned in chapters three and four consecutively. The modelling includes the behaviour and the constraints of the industrial customer network

Chapter Six: Conclusion And Recommendations – In this chapter, the dissertation makes conclusion and gives recommendations for future research.

References – As per the requirements of this dissertation, all work collected from other sources are paraphrased accordingly and in-text referencing is applied, and reference list is provided in this chapter.

Appendices – This chapter provides appendix of all other key diagrams, graphs, etc. obtained from the modelling of the system under study.

CHAPTER TWO
LITERATURE REVIEW

This chapter tackles a review of the literature related to the topic under study and is divided into three sections. The first section immensely focuses on the Fuel Cell storage used as part of the solution to this project research. In this section, firstly, a historical background and brief operation description is presented, and thereafter, major different types of fuel cell are presented, discussing their unique properties and characteristics.

The next section of this chapter digests and indulges the literature of Energy Storage Systems. Herein, this study presents different kinds of energy storage systems, discussing their fundamental operation principle and suitable application of each. In addition, apart from other energy storage systems, the battery energy storage is extensively explored. In this last part of the section, the battery energy storage functions are discussed as well as the different kinds of battery technologies.

Lastly, the third section is devoted to the MV electrical distribution network. This section discusses the issues that arise when distributed alternative sources are interconnected to the electric power system, and how the network parameters are affected.

SECTION 1
FUEL CELLS

2.1 Introduction

The basic law, “Law of conservation of energy” clearly states that energy cannot be created nor destroyed; rather, it can only be transformed or transferred from one form to another. Therefore, Fuel cells (FC), by their unique reaction of converting chemical energy into electrical energy approve the law to be scientifically viable. Unlike the battery that is an energy storage device, the fuel cell is an energy conversion device that has the ability of generating electrical energy provided that the reducing agent (fuel) and oxidizer are supplied to the electrodes.

Mankind has over the years found it difficult to develop and design systems that will enable the storing of generated and excess energy. This has led to a huge loss in the energy sector. However, the new and rapidly growing technology of energy storage systems such as fuel cells (FC) has shown promising abilities to address the challenge. Furthermore, fuel cells are one of the key enabling technologies for future hydrogen economy. For the previous two decades, applications of the fuel cells are mostly replacing internal combustions engines, and providing power in stationary and portable power applications (Andújar and Segura, 2009).

2.1.1 History

There is a lot of uncertainty as to who discovered the principle of fuel cells. In reference (Andújar and Segura, 2009), the author stipulates that according to the Department of Energy (DoE) of the United States, it was the German chemist Christian Friedrich Schonbein, who in 1838 conducted the first scientific research on the phenomenon of a fuel cell. In contrary, authors (Bagotsky, 2011) and (Raji, 2008), believed that it was the British chemist Sir William Grove, who in the 1830s invented the fuel cell technology by conducting a series of experiments on water electrolysis. But, in spite of that all, through the set of letters that was sent to faradays by Schonbein, it was commented out explicitly that they could not conceive how Sir Grove was able to generate power through oxidation of a positive electrode (Faraday, 1899). So, this suggests that the original fuel cell comes from Grove and not from Schonbein.

His device (Grove) consisted of two platinum electrodes dipping into water acidified with sulfuric acid as shown below in Figure 1. However, the decomposition of water into hydrogen and oxygen using electricity was discovered years before the fuel cell, to be more precise, in 1800 by British scientists Sir Anthony Carlisle and William Nicholson. Both scientists are considered to be the first ones to produce a chemical reaction using electricity.

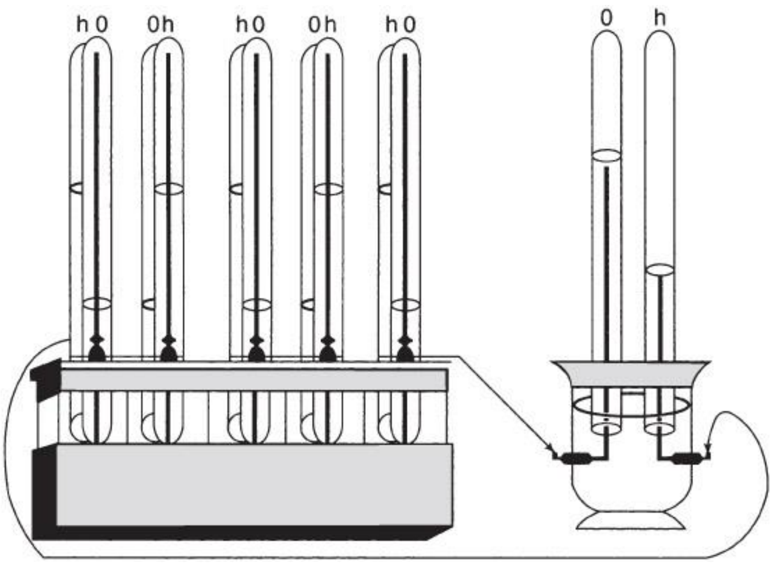


Figure 1: Grove's first prototype of a fuel cell (Bagotsky, 2011)

Sir Grove became aware that when the current flows, the water level rose in both tubes. He further realised that by combining pairs of electrodes connected in series a higher voltage was being produced, in essence, creating what he called a gas battery. This in which is regarded as the first prototype of a fuel cell.

2.1.2 Operation of the Fuel Cell

A fuel cell is an electrochemical energy conversion device much the same as the battery, but a fuel cell produces electricity from an external supply of fuel and oxygen as in contrast with the limited internal energy storage capacity of a battery cell. Moreover, electrodes within the latter react and change during an internal charge, or discharge activity, whereas in fuel cell electrodes are catalytic and relatively robust (Raji, 2008).

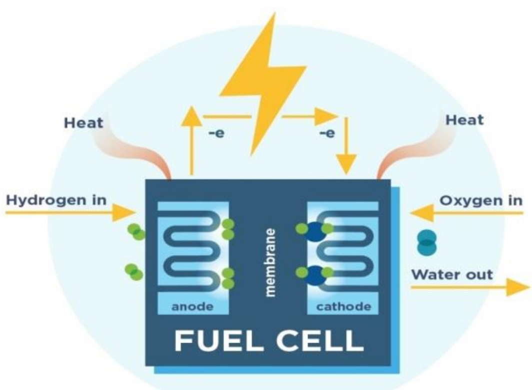


Figure 2: Fuel Cell basic operation (Association, 2013)

A fuel cell is composed of an Anode (+), a cathode (-), and an electrolyte membrane. A fuel cell operates by passing hydrogen (H_2) through the anode of a fuel cell and oxygen is fed into the cathode. At the anode, the hydrogen molecules are split into electrons and protons. The protons pass through the electrolyte membrane, while the electrons form current that can be useful before proceeding to the cathode, generating an electric current and excess heat. At the cathode, the protons, electrons, and oxygen combine to produce water atoms (H_2O). Figure 2, exhibits a basic operation principle of a fuel cell.

2.1.3 Characteristics of Fuel Cells Technology

The main part of a fuel cell system, described as the fuel cell stack, is made up of separate fuel cells assembled in a serial manner. Therefore, these fuel cell stacks can be constructed to cater for different wattage sizes ranging from small watts to high megawatts values(Ortiz-Rivera, Reyes-Hernandez and Febo, 2007). Furthermore, fuel cells are a versatile modular technology that can easily be scaled up from providing power for domestic use to large office blocks and industrial buildings. Because of their ability to produce highest proportion of electricity for any Combined Heat Power (CHP) technology, up to 95%, thus in most cases, CHP is their most common stationary application(Ekins *et al.*, 2015). Moreover, because of their remarkable electrical efficiency advantage, they are the most protuberant.

Fuel cell systems offer attractive electrical conversion efficiencies. Hence, are regarded as an ideal conversion system for an interconnected utility distribution network. But, the opposite is true, that fuel cell system remains efficient even to off-grid networks. Their efficiency for various fuel cell systems ranges from 40%-50%, when applied for less complicated systems in different size scales. However, the work of (Ortiz-Rivera, Reyes-Hernandez and Febo, 2007), further argues that more complicated fuel systems have a potential for even higher efficiencies. As has been pointed out, fuel cells can operate at high efficiency even in relatively small sizes, which consequently make them much attractive in small-scale cogeneration applications such as buildings(Ortiz-Rivera, Reyes-Hernandez and Febo, 2007). Fuel cells can offer cogeneration efficiency as high as 80% by generating electricity and thermal energy for various applications.

Due to their environmental friendly character, fuel cells have received much attention as compared to their counterparts such as conventional systems. Furthermore, fuel cells reduce emissions of regulated pollutants. As an environmentally abiding technology, fuel cells emissions which are of recently regulated pollutants such as carbon monoxide, nitrous oxides, sulfur oxides, and particulates are far below current air quality regulations and typically nearly non-existent (A. Williams, no date). Moreover, fuel cells systems are also relatively quiet; hence, minimal overall impact on the environmental is achievable.

However, like any other energy source, fuel cells possess some drawbacks and challenges. For instance, in grid independent application, FC are attributed to challenges like load transients, voltage unbalance and unregulated frequency at PCC (Roy, Biswal and Padhy, 2016). (Pravin, Bhartiya and Gudi, 2019), further emphasised that FC response to varying load power demand is comparatively sluggish than other power sources due to its complex dynamics. As the most abundant chemical substance in universe, hydrogen is the fuel used in the majority of FC. Hydrogen, when exposed to air can easily catch fire and can further lead to explosion (Pravin, Bhartiya and Gudi, 2019).

2.1.4 Major Types of Fuel Cells

Fuel cells come in different forms and designs. Fuel cells require unique conducting solution such as an electrolyte. This consequently determines the type of chemical that undergoes reaction in a cell, and further determines the operating temperature range of that involved cell, the type of fuel required and as well as the type of catalysts needed to speed up the reaction process. These defining properties, as a consequence, regulate the most suitable application of these cells. Currently, there are various types of fuel cells under development, solely possessing their own advantages, delineations and possible applications (Raji, 2008). The following are the most conspicuous types of fuel cells; Proton-Exchange Membrane Fuel cells (PEMFC), Direct Methane and Liquid Fuel cells (DM, DLFC), Phosphoric Acid (PAFC), Alkaline Fuel Cells (AFC), Molten Carbonate Fuel Cells (MCFC), and Solid Oxide Fuel Cells (SOFC). PEMFC is of interest in this research.

2.1.4.1 Proton-Exchange Membrane Fuel Cells (PEMFC)

Polymer Electrolyte Membrane (PEM) fuel cells also known as Proton Exchange Membrane fuel cell, at its inception was invented at General Electric (GE) Company in the early sixties, through the work of Thomas Grubb and Leonard Niedrach. GE announced its initial favourable outcome in mid-sixties when the company developed a small fuel cell for a program with the Electronics Division of the U.S Navy’s Bureau of Ships (Andújar and Segura, 2009),(Ortiz-Rivera, Reyes-Hernandez and Febo, 2007).

PEM fuel cells use a robust polymer membrane for its electrolyte and a precious metal, typically platinum, for its catalyst. Due to technical hydrogen carbon monoxide (CO) containment and other various impurities, the platinum catalyst becomes a good adsorbent thereof and thereby increasing polarization within and consequently the Catalyst is poisoned by the catalyst poison CO. The most reliable way of fighting this poisoning of the platinum catalyst by CO impurities in the hydrogen is by modifying the catalyst itself (e.g. by adding alloying elements) (Raji, 2008),(Bagotsky, 2011). This unfortunately escalates the system cost.

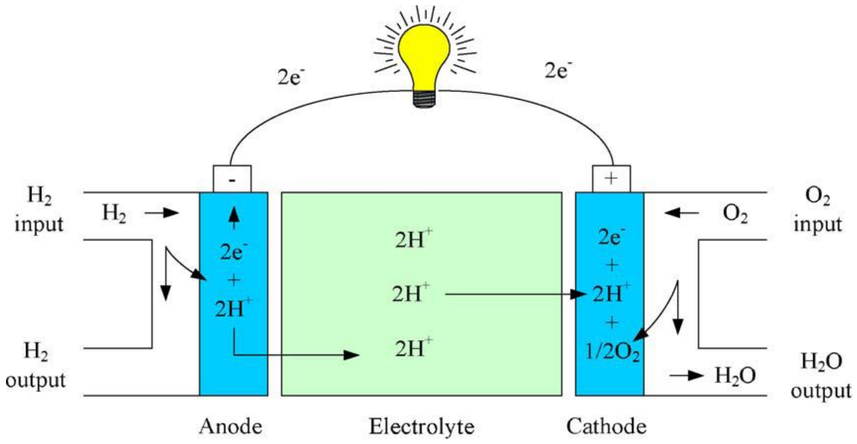


Figure 3: Proton exchange membrane fuel cell basic principle of operation

PEM fuel cells operate at relatively low temperatures, at about 80°C (176°F), this is to allow faster booting as compared to high temperatures. This will result in minimal wear on system components, attaining much desirable increased lifespan. Furthermore, these fuels cells have high power density, and because of their ability to varying output, can quickly respond to shifts in power demand. Figure 3, exhibits the basic operating principle of a PEM fuel cell type. PEM fuel cell appears to be the most promising for small scale distributed generation systems to be used in residents, industries etc. (Sabaripandiyan and Arul Daniel, 2010).

2.1.4.2 Phosphoric Acid (PAFC)

In many instances, acidic substances have been used as electrolytes. However, as early as in 1842, phosphoric acid was found as being a poor conductor of electricity and was not as attractive as other types of fuel cells and that led to slower development. In 1961, in the paper called “Intermediate Temperature Fuel Cells” G.V. Elmore and H. A. Tanner exposed new hope in phosphoric acid electrolytes by describing their experiments using an electrolyte that was 35% phosphoric acid and 65% silica powder pasted into a Teflon gasket (Ortiz-Rivera, Reyes-Hernandez and Febo, 2007). PAFCs cannot operate at temperatures below 100°C because leaching phosphoric acid with liquid water produced by cell operation leads to decrease in proton conductivity and thus to degradation of the cell. Hence, phosphoric acid operates at temperatures as high as 250°C, but that result them in taking longer to starting working.

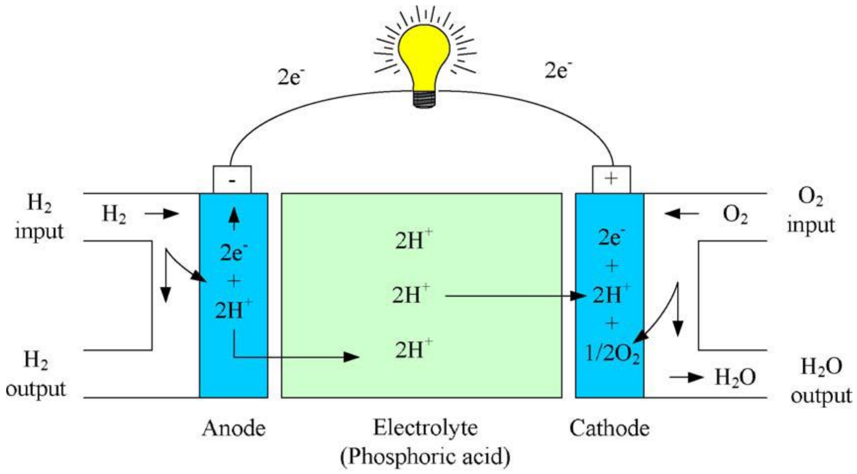


Figure 4: Phosphoric acid fuel cell principle of operation

Phosphoric acid fuel cells also run on hydrogen and oxygen. The efficiency of this type of fuel cell reaches 40% in electricity production and close to 85% if the steam produced by this fuel cell is used for cogeneration. And presently is amongst the few fuel cells that are commercially available. This fuel cells has been installed for different applications such as Office buildings, hospital, schools, waste water treatment plans and utility power plants (Andújar and Segura, 2009). Figure 4, represents the fundamental operation of a phosphoric acid fuel cell.

2.1.4.3 Alkaline Fuel Cells (AFC)

Unlike preceding aforementioned fuel cells, alkaline fuel cells use an alkaline electrolyte instead of the acidic electrolyte. This type of an electrolyte provides much wider range of materials to be selected as catalysts, and some of them are relatively less costly. In AFCs, solutions of potassium hydroxide (KOH) prepared in different concentrations are commonly utilised. The use of alkaline electrolyte offer less severe corrosion conditions, thus allows nickel and alloys of iron to be used as structural materials in AFCs. However, AFCs are extremely intolerant to CO_2, any carbon dioxide getting into the KOH solution binds (neutralises) alkali, yielding potassium carbonate, $CO_2 + 2KOH \longrightarrow K_2CO_3 + H_2O$.

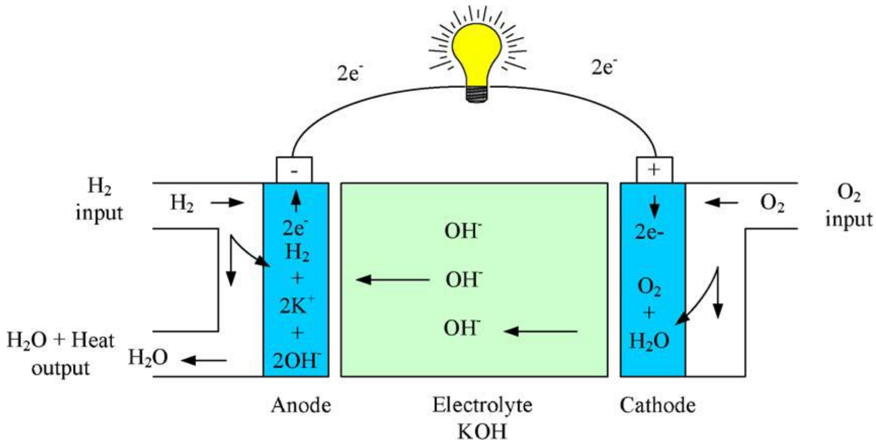


Figure 5: Alkaline fuel cell basic principle of operation

In contrast to PEM fuel cells, alkaline fuel cells, the electrolyte conducts hydroxide ions (OH^-) from the cathode to the anode, see Figure 5. The operating temperature ranges from 65° and 220°C. These fuel cells can achieve power generating efficiencies of up to 70%. The use of AFC in spatial applications is widely known. However, in earthly applications, there are certain complications as far as AFCs are concerned (Andújar and Segura, 2009).

2.1.4.4 Molten Carbonate fuel Cells (MCFC)

Molten carbonate fuel cells use an electrolyte composed of a molten carbonate salt mixture containing (Li_2CO_3 and K_2CO_3) suspended in a porous, chemically inert matrix. At its development inception, MCFC drew interests to researchers by the fact that not only hydrogen but also carbon monoxide (CO) could be used as a reducing agent. To date, MCFCs have been operated on hydrogen, carbon monoxide, natural gas, propane, landfill gas, marine diesel, and simulated coal gasification products. Due to their ability to operate at significantly high temperatures, fuel reforming is thus performed internally within the fuel cell. There are two types of internal-reforming fuel cells (IRFCs) that were established, the direct internal-reforming fuel cells (DIRFCs), in which the reform process takes place within the fuel cell at its anode catalyst, and the indirect internal-reforming fuel cell (IIRFCs), in which plates with special reforming catalysts are included within the stacks (Bagotsky, 2011). Thus, no external reformer is of necessity in order to be able to convert energy-dense fuels to hydrogen, resulting in cost reduction.

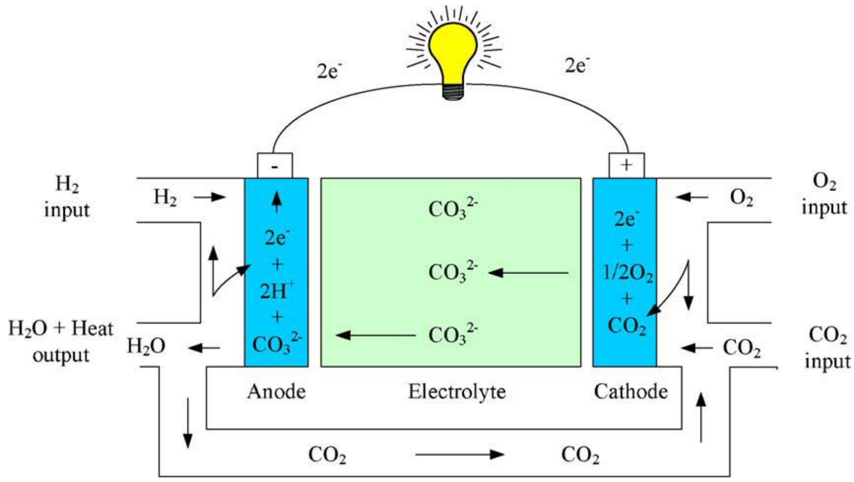


Figure 6: Molten carbonate fuel cell basic operation

Molten carbonate fuel cells qualify in the category of high-temperature fuel cells. Their operating temperature is approximately 650ºC (1.200ºF). Therefore, non-precious metals are utilised to speed up the reaction (catalysts) at the anode and cathode, thus, further minimising cost. As previously discussed, MCFCs use mixture lithium carbonate and potassium, by this electrolyte circulating carbonate ions (CO_3^{2-}) from the cathode to the anode, in which is the reverse operation of most fuel cells, Figure 6, (Andújar and Segura, 2009). MCFCs have an efficiency approaching 60%, and possible 85% if the waste heat is captured and re-used. However, their primary disadvantage is insufficient long period of trouble-free operation and secondly, corrosion of metal parts. Therefore, for future developments, materials resistant to corrosion without decreasing performance are needed. MCFCs have mostly gained attraction from the electric utility applications (Ortiz-Rivera, Reyes-Hernandez and Febo, 2007).

2.1.4.5 Solid Oxide Fuel Cells (SOFC)

Solid oxide fuel cells are constructed with a solid electrolyte, a typical solid electrolyte commonly known is the ceramic such as yttria-stabilised zirconia (YSZ). Porous Anode and cathode with interconnecting wires are components required to build such a cell, see Figure 7. SOFCs exist in several designs variants. The basic variants are tubular and planar cells.

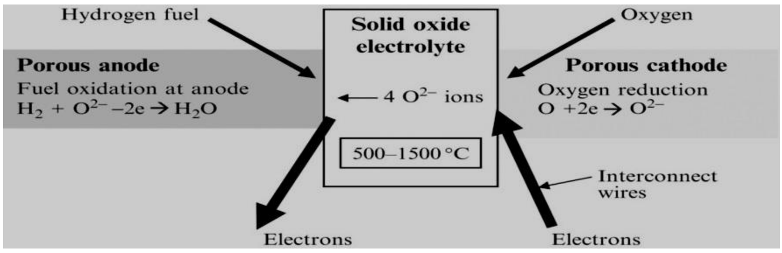


Figure 7 Sketch layout of Solid oxide fuel cell (SOFC)

Unlike other fuel cells, as exhibited in Figure 8, SOFC employ an electrolyte that conducts oxide ions (O^{2-}) from the cathode to the anode. SOFC operate at very high temperature conditions of close to 1000ºC. Because they have a very fast chemical reaction, they are flexible with regards to the use of catalyst. They are not sensitive to CO positioning, relatively high on efficiency and are cost effective.

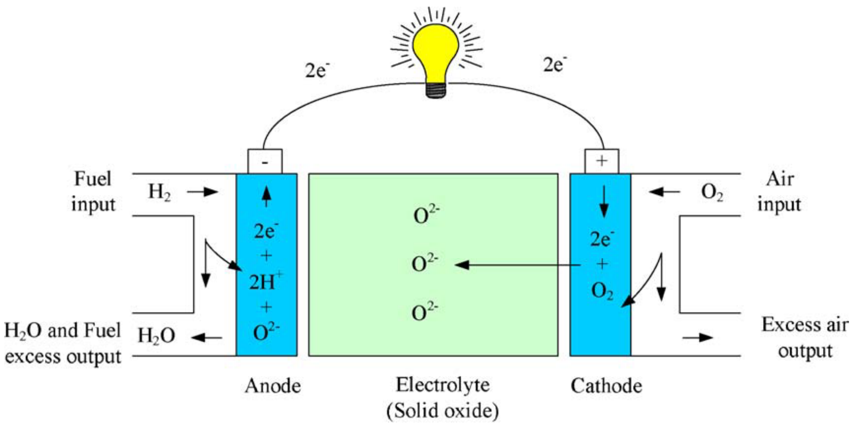


Figure 8 Solid oxide fuel cell basic principle of operation

This type of fuel cells is generally used in stationary applications or such as Auxiliary Power Units (APU) (Andújar and Segura, 2009),(Ortiz-Rivera, Reyes-Hernandez and Febo, 2007).

2.1.4.6 Direct Methane (DM) and direct liquid (DL) Fuel Cells

DMFC, use methanol as the fuel, it is regarded more convenient and much safer compared to gaseous hydrogen. Rather than using direct hydrogen fuel, DMFCs draw hydrogen from liquid methanol, thereby eliminating the need for a fuel reformer. DMFCs also run relatively at cool temperatures, between 50ºC and 120ºC.

In contrast to plants built up from other types of fuel cells such as PEMFC, PAFC and with MCFC and SOFC high –temperature systems, these type of fuel cells, on economic grounds there is reluctance in developing and producing for relatively large stationary plants having hundreds of kilowatts of power, or plants of a few megawatts for centralised or decentralised power supplies. Instead, their application ranges from small electronics to telecommunications backup.

2.1.5 Summary

In summary, at a glance, fuel cells offer pleasing benefits of low to zero emissions, high efficiency, reliability, fuel flexibility, energy security, durability, scalability and quiet operation. Despite the economic challenges faced with and technology immaturity, fuel cells are considered to be more convenient to provide power in stationary and portable power applications. Fuel cells are a versatile modular technology that can be scaled up and moreover, can be conveniently placed near consumer site, thus simultaneously reducing losses and cost.

SECTION 2
ENERGY STORAGE SYSTEMS

2.2 Introduction

An electric power system is designed in such a manner that the supply must always meet the demand. However, technical discrepancies do occur, therefore Energy Storage (ES) technologies become a popular solution to the imbalance between the supply and demand. Furthermore, in distributed generation (DG), Energy Storage Systems (ESS) does not only solve the imbalance but answers to the intermittency problems that exist and uncertainty of output and load shifting. Moreover, there are a number of useful functions that ESS offers such as aiding in black-start, power quality adjustment and control, and stability (Fusheng, Ruisheng and Fengquan, 2015).

Energy Storage is globally considered as the new wave in the energy sector. Energy storage systems are technologies that can provide flexibility and services in managing the electricity system in order to create a more resilient energy infrastructure (Manz and Miller, 2012). Exploitation of energy storage is possible from at least three options, Power-to-Power, Power-to-Heat, and Power-to Gas (Trade *et al.*, 2017).

- **Power-to-Power**

  A process of converting electrical energy from a power utility network into a form that can be stored and can be used for converting back to electrical energy when needed with as low as possible energy losses due to inefficiencies.

- **Power-to-Heat**

  A process of electricity energy used to generate heat for consumption at a later stage.

- **Power-to-Gas**

  A process of electricity energy used to produce a gas such as hydrogen. The gas (hydrogen) can then be utilised as a fuel or to produce electricity at a later stage.

A stored energy facility can operate in parallel with a generating unit to meet temporary peaks of demand higher than rated generating capacity. A storage system can also support voltage through mechanisms of reactive power control in a microgrid system (Farret and Simoes, 2006).

In this section, the Author, will briefly discuss different types of energy storage technologies, but, more focus will be given on the Battery Energy Storage System (BESS).

2.2.1 Brief description of energy storage systems

As stated above, several energy storage systems (ESSs) may be used to cover the electricity demand problems whether on interconnected or islanded modes (Kaldellis, Zafirakis and Kavadias, 2009). For application purposes, for every ESS, operational parameters must be clearly defined. This includes but not limited to, defining the corresponding service period, maximum permitted depth of discharge for long-term operation, total energy efficiency, the initial cost, the annual maintenance and operation cost and the power range in which every system can be utilised.

2.2.1.1 Pumped Hydro Energy Storage (PHS)

Pumped hydroelectric energy storage is one of the ancient large-scale energy storage. It has been in use since the beginning of the twentieth century. They are still in active operation and currently new units are being built. In a pumped hydro storage system, the energy surplus appearing in times of low demand and increased production is utilised to pump water into an elevated (upper) storage reservoir. Similarly, during peak demand periods, water is then released from the upper reservoir running through hydro turbines and consequently causes the electrical generators to turn to produce electricity. Thus, the system is able to cover the existing power deficit by using the appropriate amount of energy previously stored.

The typical overall efficiency of such systems mostly ranges from 65% and 77%, while their maximum depth of discharge is up to 95% without affecting their considerable service period of approximately 50 years (Farret and Simoes, 2006). Due to the lack of suitable sites, the use of this system is limited and ridiculously expensive.

2.2.1.2 Flywheels Energy Storage (FES)

Flywheels store energy in kinetic Formby spinning a disk of a certain mass. Through a coupled electric machine, power is retrieved by slowing the rate of rotation through driving a device similar to a turbine. Recharging of flywheels is achieved by increasing the rotation speed of the motor. The stored energy is dependent on the following scientific factors, the rotor's momentum of inertia, I, mass density around the rotating axis, $\rho(x)$, and geometrical radius of the rotor, r,. The energy stored is expressed as follows.

$$E = \frac{1}{2} I \omega^2 \tag{2.1}$$

$$I = \int \rho(x)\, r^2 \tag{2.2}$$

To minimise air drag and bearing losses, the flywheel along with the motor/generator must be placed inside a vacuum chamber so as to avoid deceleration effects caused by air. Their overall efficiency value is approximately 85%. Since flywheels are unable to store energy for prolonged duration, they are most suitable for small applications such as uninterrupted power supply and electric vehicles. However, if the inertia is increased by rotating velocities up to a couple of thousand revolutions per minute by utilising a large radius steel mass, that would result in relatively large and robust flywheel system. To maintain stable electrical frequencies required by the grid, the inclusion of rectified and inverted power electronics devices is necessary. Recently developed flywheel storage systems require less maintenance, they are much lighter in weight, with zero emissions, and promise compact size. Above all, flywheels have long life span, and do not suffer from multiple discharges and are not subject to sensitivity in terms of operating temperature (Farret and Simoes, 2006).

2.2.1.3 Compressed Air Energy Storage (CAES)

Compressed air energy storage (CAES) manifest by the compression of air to be utilised at a later stage, preferable as an energy source. At large scale purposes, it can be stored during periods of low energy demand (off-peak), and then can be used in meeting periods of higher demand (peak load). In other cases, compressed air energy storage system can be used to power tools, or even vehicles ('Energy Storage Systems.pdf', no date).

2.2.1.4 Superconducting magnetic energy storage (SMES)

SMES is a large super conducting coil that stores enormous amount of electric energy in the form of magnetic field with negligible resistive losses and discharge the energy in short period of time. SMES has wide range of applications such as compensating load fluctuations, power swings, generation fluctuations, frequency control and daily load levelling. But, most importantly, due to their fast response and capability it is more feasible for daily load scheduling (Saranya and Saravanan, 2018).

2.2.1.5 Battery Energy Storage Systems (BESS)

Batteries transform electrical energy into chemical energy and vice versa through redox reaction. Similarly to a fuel cell, a battery consists of five essential components namely, the Anode, Cathode, electrolyte, separator and cell connector, see Figure 9.

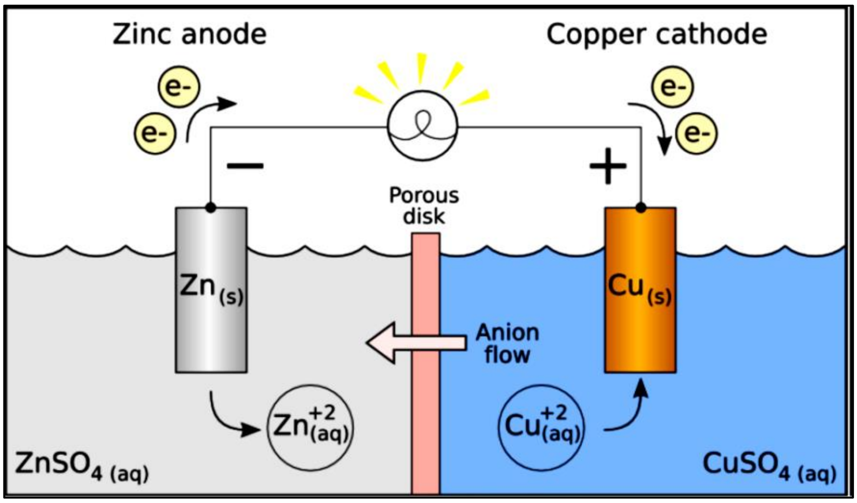


Figure 9: Basic Battery components

In the charging mode, the Negative material (Anode) is reduced, consuming electrons and the Positive Active material (Cathode) is oxidised, producing electrons. In the discharging mode, the reverse is true, the Anode is oxidised and Cathode is reduced.

Batteries are the most prominent storage system. As far as their application range is concerned, battery energy storage systems show almost no restrictions (Kaldellis, Zafirakis and Kavadias, 2009). Battery energy storage systems (BESS) technology can bring numerous benefits to the existing power system if properly sized and optimally located in the distribution network. Storage may also improve the quality of supply, decrease electrical losses, provide network reliability and in addition mitigate voltage related concerns on the connecting networks (Pillay, Heerden and Ramdhin, 2019).

Battery technologies come in different designs with unique performance criteria, maturity, risk/barriers, advantages/disadvantages and best use case applications, Appendix 1 (Trade *et al.*, 2017).

2.2.1.5.1 Functions of battery energy storage systems (BESS)

While many technologies have been developed for large-scale energy storage purposes as discussed previously, the fact of the matter is that many of them are restricted in their site dependence, capacity, or response capabilities (Lawder *et al.*, 2014). Nevertheless, electrochemical energy storage devices such as BESS provide flexibility in capacity, siting, and rapid response required meeting consumer demands over a much variety of functions than other types of storage.

Herein under, but not limited to are basic and advanced battery energy storage system functions are briefly discussed; they include voltage regulation, emergency back-up, frequency regulation, electric energy time-shift, and power quality. These Applications are categorised according to their shared characteristics (Committee *et al.*, 2017).

2.2.1.5.1.1 Voltage Regulation

There are various ways in which BESS performs regulations, such as in cases when the BESS is connected to distribution or customer facilities and the point of common coupling (PCC) is at the consumption side. Therefore, when the EPS is unable to provide stable system voltage due to the failure of up-stream EPS, the BESS itself or SCADA will calculate the reactive power the BESS needs to supply based on the actual voltage and the reference voltage and therefore regulate the abnormal voltage indirectly, ultimately the EPS voltage will remain in a reasonable range.

In this function, BESS generally operates in the P/Q mode.

2.2.1.5.1.2 Frequency Regulation

During the regulation, The EPS frequency should be properly kept from abrupt changes and the frequency control accuracy shall not be less than that specified in relevant standards or grid code.

When BESS is connected to distribution or customer facilities, the PCC is at consumption side. Therefore, when the EPS is unable to provide stable system frequency due to the failure of an up-stream EPS, the BESS itself or SCADA will calculate the active power the BESS needs to output based on the actual frequency and the reference frequency and subsequently regulate abnormal frequency indirectly, ultimately the EPS frequency will remain in a reasonable range. In this function, BESS generally operates in the P/Q mode.

2.2.1.5.1.3 Emergency back-up

As discussed previously, grid connected customers may experience total loss of power due to unforeseen circumstances, therefore, BESS, as a reliable source of energy, may effectively provide support in such cases. If power availability is properly maintained, BESS can be used as the local island source. This would further assist in restoring grid power that was lost and resynchronised with the local islanded source (the BESS).

2.2.1.5.1.4 Power Quality

The loads at customer site and sensitive electrical machinery are sometimes exposed to harmful network disturbances that occur for short-duration of time due to the poor power quality events in the distribution network. When power quality problems such as these occur, BESS has the ability to absorb and eliminate these disturbances with appropriate methods. Through this concept improved power quality to the customer side can be achieved. Some examples of illustrating poor power quality includes variations in the primary frequency, flickering, low power factor, interruptions of service, voltage spikes or dips and harmonics.

2.2.1.5.1.5 Peak shaving

In many instances, industrial customers operate apparatus and devices that require large amount of electric power over relatively short periods of the day (Oudalov, Cherkaoui and Beguin, 2007). Therefore, accumulated cost in keeping up with the peak demand becomes a burden to the customer in the form of demand charges. Thus, Peak shaving reduces this extra cost and moreover increases the capacity of the existing grid infrastructure.

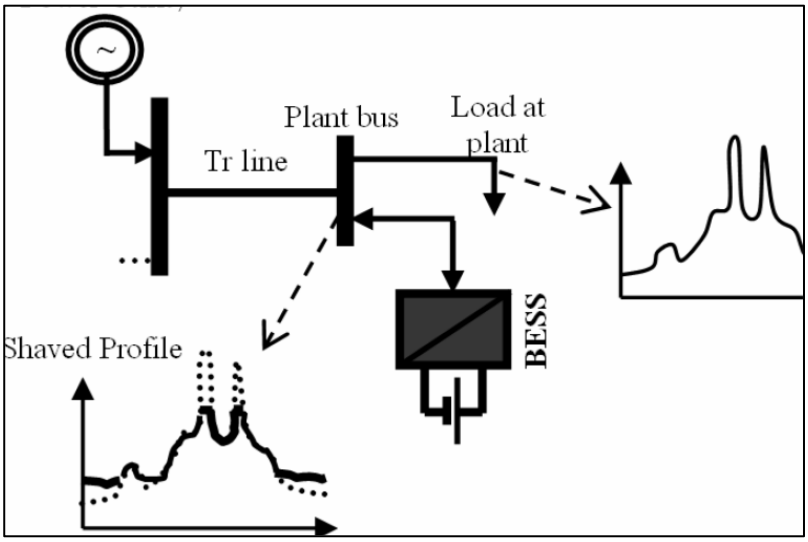


Figure 10: Principle of load peak shaving by BESS (Oudalov, Cherkaoui and Beguin, 2007)

As depicted in Figure 10, peak shaving is similar to load levelling but is primarily used for reducing peak demand by for instance installing BESS capable of discharging for short periods of time during the peak hours and charging during the low demand periods at night hours.

2.2.1.5.2 Different Types of Battery Technologies

Battery energy storage come in different types of technologies and their differences depend on various aspect including maturity, risks, barriers, disadvantages and advantages. The battery technology high level of comparison is found as Appendix 2 in the appendices page of this report. Significant advancement in battery chemistries has allowed for a wide range of battery options for new storage applications and has increased the robustness and functionality of batteries within the electrical grid (Lawder *et al.*, 2014). These new chemistries include but not limited to: Lithium (Li) ion, Nickel-cadmium, Sodium Sulfur, Vanadium redox flow battery, and Lead-acid (Fusheng, Ruisheng and Fengquan, 2015). Lithium-ion is of interest in this research.

2.2.1.5.2.1 Lithium-ion battery

Lithium-ion batteries have some interesting characteristics when compared to other type of batteries. Lithium-ion batteries possess high specific power and energy, minimal self-discharging capabilities, and do not contribute to pollution. However, the integration of high capacity is extremely challenging and not neglecting the exorbitant costs associated with manufacturing and maintenance required. Nevertheless, improvements in technology landscape and reduction of cost will see lithium-ion battery being widely used especially in Distributed Generation (DG).

2.2.1.5.2.2 Nickel-Cadmium battery

With respect to Nickel-Cadmium battery, there, is a capacity degradation issue as time passes, therefore the charge retention needs to be strengthened. In spite of that, Nickel-Cadmium battery has high efficiency and long life span. Unfortunately, the heavy metal pollution posed by the battery has resulted in the battery type being hardly utilised in electric power systems.

2.2.1.5.2.3 Sodium Sulfur battery

Sodium sulfur battery has an efficiency of about 80%. The size of the sodium sulfur battery is approximately 20 percent that of lead-acid battery, this is primarily due to the high energy density and secondly, it is also convenient for installation purposes, as well as transportation and modular design. Sodium sulfur offers appreciable electric power system solutions; it is much suitable for urban based substations. Furthermore, in the DG space, sodium sulfur battery is amongst the most promising Energy Storage technologies in the market and as far as microgrid is concerned it has the ability to improve the system stability, load shifting, and can act as back-up to maintain power supply in case of any emergency that could arise.

2.2.1.5.2.4 Vanadium redox flow battery

The vanadium flow battery also has some interesting features and qualities such as 100% discharge capability, lengthy life span, and the rated capacity has limited influence on the rated power. Furthermore, concerning vanadium flow battery, there are two ways in which the capacity can be increased, firstly, by adding more electrolyte and secondly, by increasing the concentration of the electrolyte. The storage form and pattern can be designed according to the location. Similarly to Sodium sulfur, Vanadium redox flow battery is amongst the most promising Energy Storage technologies in the market and as far as microgrid is concerned it has the ability to improve the system stability, load shifting, and can act as back-up to maintain power supply in case of any emergency that could arise.

2.2.1.5.2.5 Lead-acid battery

Lead-acid battery is manufactured into two forms, namely flooded or wet cell (periodic topping up of cells with de-ionised water required) and valve regulated or sealed cell (topping up of is not possible). Its lifetime is even more compromised when operating at high temperatures. Lead-acid battery has a low specific energy and specific power, however, its affordable low cost, high reliability, and high maturity level technology makes it to be the most advantageous compared to others.

Because of high maturity level, in the past and recent years, it has been widely used in electric power system. Lead-acid battery causes environmental pollution during manufacture. It is mainly used by power utilities for various functions including powering circuit breakers during system operation, and an independent power source for relay protection, driver motor, communication, and emergency lighting in the event of failure of power plants or substations.

2.2.2 Summary

Energy Storage technologies become a popular solution to technical discrepancies that occur in any electric power system and aid at solving the imbalance between the supply and demand. Energy storage systems offer important functions to the network such as black-start, power quality, control, and stability. Despite the limitations that exist for some of the energy storage technologies, they cause less harm to the environment. Energy Storage Technologies such as the battery bring many benefits into the electric power system by decreasing electrical losses, provides network reliability, and mitigates voltage related concerns.

SECTION 3
MV ELECTRICAL DISTRIBUTION NETWORK

2.3 Introduction

The ultimate objective of the medium voltage electric distribution network is to deliver the electric power to consumers in accordance to correct regulated voltage levels. In conformity with the electricity regulation act No. 4 of 2006, distribution is legally responsible for the distribution of electricity at all voltages less than and including One Hundred and Thirty-Two kilovolts (132kV) within its supply area. Originally, utility Electric Power Systems (EPSs) were not designed to accommodate active generation and storage at the distribution level (Farret and Simoes, 2006). Therefore, there are critical factors that require undivided attention that must be dealt with as far as interconnecting Alternative Energy Sources (AESs) with the utility distribution grid is concerned. In this section, the author seeks to identify and address the most critical elements of the distribution network in order to meet prescribed compatibility standards for the interconnection system.

2.3.1 Distributed Alternative Energy Sources (DAESs)

When interconnecting an Alternative Energy Sources (AESs) with an area Electric Power System (EPS), there are several issues that should be tested to give assurance that the distributed generator systems integrated with the EPS is done in a safe and reliable manner.

2.3.1.1 Voltage Stability

Amongst many essential factors that influence the operation of a power distribution system are the voltage regulation and stability. If a system is not properly regulated or stable, machines that are fed by this power system will not perform efficiently as required. This is evident when factors such as voltage flickering and voltage dips are present in the power system.

2.3.1.2 Synchronisation

For synchronisation between the utility network and the distributed generator system to be achieved, the output of the Alternative Energy Source and input of Electric Power System must possess identical voltage magnitudes, frequency, phase rotation, and phase angle.

2.3.1.3 Isolation

For best practice, it is of paramount importance to have isolation points between the EPS and the AES which are readily accessible, lockable, visible-break isolation. These switches provide isolation points to allow for safe work practices in cases of any abnormal conditions that may arise on either side. Switches must be strategically placed between the systems.

2.3.2 Impact of Embedded Generation on the Electrical Parameters of the Distribution Network

2.3.2.1 Impact on short circuit current

Unlike transmission networks, distribution networks can have magnitude of the line's resistance higher than the line's reactance ($X_{line}/R_{line}<0$), and therefore it must be taken into account when analysing power transfer in embedded generation systems interconnected to power distribution networks (Doumbia and Agbossou, 2005).

The integration of Embedded Generation in the grid network at distribution level alters the entire impedance of the network and because of inversely proportionality of the impedance to the current, therefore, the short-circuit current and short-circuit power are also affected respectively.

2.3.2.2 Harmonics

Harmonics are well known as distorted waveforms, in the representation of voltages and currents. In Embedded Generation, for conversion and inversion purposes, power electronics interfaces are most likely to form part of the network. It is these power electronics devices that are capable of inflicting more high frequency harmonics into the network shorting the lifespan of the materials. The fundamental frequency of a power system in South African distribution networks is typically 50Hz.

2.3.3 MV constrained networks

The state owned enterprise (Eskom) provides some guidelines on identifying constrained medium voltage (MV) networks. Each MV feeder or transformer is simulated on Digsilent PowerFactory to represent the current years' peak demand value and assigned a level of constrained based on its minimum voltage, maximum thermal loading and reliability indices. In Table 1, is the illustration of identifying MV constrained networks.

Table 1: Criteria for MV constrained networks

Criteria (x)	Severity	Red	Orange	Green
Min MV voltage at end of feeder (%)	Licence requirement	$x \leq 93\%$	$x > 93\%$ but $x < 96\%$	$x \geq 96\%$
Max thermal backbone loading (%)		$x \geq 95\%$	$x < 95\%$ but $x > 85\%$	$x \leq 85\%$
Max thermal transformer loading (%)	Reliability requirement	$x \geq 85\%$	$x < 85\%$ but $x > 80\%$	$x \leq 80\%$

Source: (Malapermal and Dedekind, 2014)

2.3.4 Summary

In summary, assumption made in the conventional distribution network, that power flow is in one direction from the transmission to distribution system can no longer be considered where Distributed Generators are concerned. Hence, critical factors must be confronted when dealing with the interconnection of DGs to the distribution system. Over and above, distribution networks can experience constraint cases and therefore, there must be methodologies in place to identify such constraints and propose possible solutions.

CHAPTER THREE

GENERAL DESCRIPTION OF THE ENERGY STORAGE SYSTEM

3.1 Introduction

This chapter discusses the type of the customer under study and it fully describes the various components that compound the system under study.

3.2 Description of the Customer

The type of customer under study is categorised as an industrial customer. The customer is responsible for manufacturing metal and steel products. These include reinforcing bar, steel billets, and all custom produce steel bars. As a mechanism to preserve the environment, the customer manufactures its entire product from completely recycled and scrap steel.

Furthermore, the customer uses energy conservative and less emission emitting electric induction furnaces. The steel scrap is melted and then refined, alloyed and stirred in an arc ladle furnace prior casting into billets continuously. Billets are then rolled into final products, all manufactured in accordance with international and South African National Standards (SANS) specifications.

3.3 Description of the system

3.3.1 System operation

The Block diagram shown in Fig.11 shows the proposed energy storage system that consists of battery energy storage system (BESS) and Fuel Cell storage system (FCSS), this energy storage system is connected to the medium voltage (MV) distribution utility network through the power conversion system (PCS).

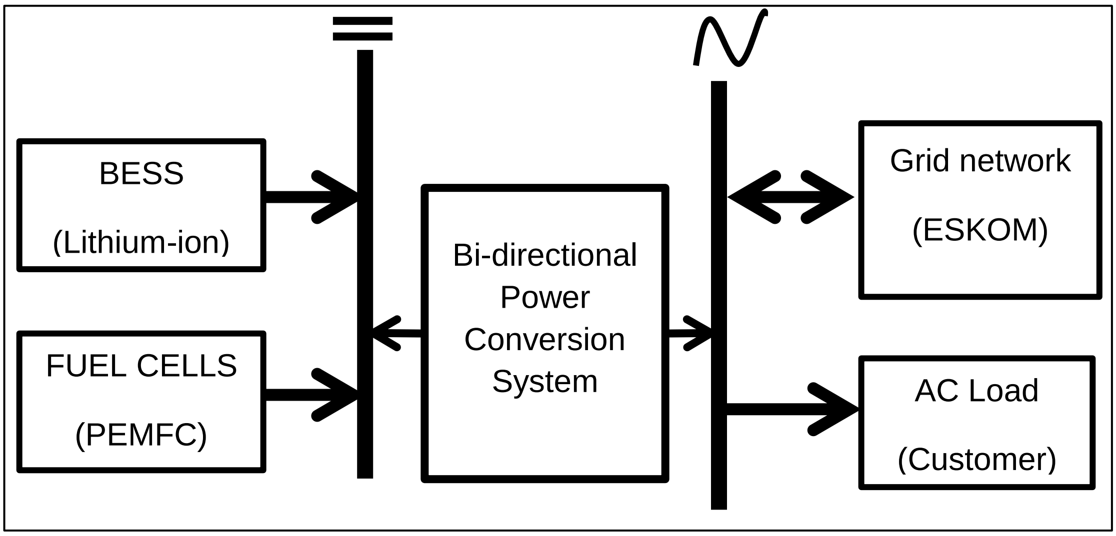


Figure 11: ESS interconnected with distribution MV network

This study considers that there are three modes of operation of the supply system; of course relying on the availability of the primary energy source which in this case is the Utility electrical distribution network. These operating modes are presented in the following sections of this chapter.

As seen in the system component architecture, for the management of power in these different operation modes there are monitors and control systems in place to monitor voltage and currents, these are sensors placed at inlets and outlets points of the power system. It is assumed that the system will have supervisory control and data acquisition (SCADA) system and control unit. Furthermore, the sensors will be able to monitor system temperatures, electrolyte levels, hydrogen level, etc.

3.3.2 System components

Exhibited below in Fig.12, are the major components of the proposed energy storage system and are composed of subsystem, namely, storage device (storage cells i.e. BESS and FCSS), the power conversion system (i.e. the AC/DC inverter system), the AC transformer (used to step up to the grid connection voltage), protection devices (switches and breakers) and the monitoring / control system (auxiliaries).

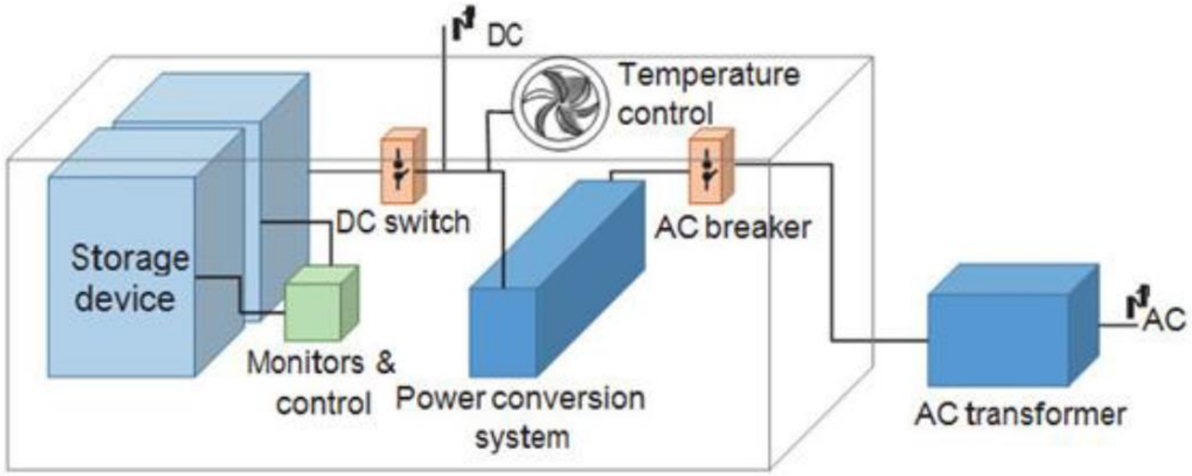


Figure 12: Energy Storage System

3.3.2.1 Subsystem description

3.3.2.1.1 Fuel Cell storage system

The fuel cell system consists of individual fuel cells assembled in repetition forming the fuel cell stack. As the fuel cell stack operates at a low DC voltage ranges, the power conversion system (PCS) must be introduced to boost and invert DC voltage to AC grid voltage as this study deals with grid-connected operation (Choi and Lee, 2009). The grid-interactive PCS also controls power flow and quality.

3.3.2.1.1.1 Behaviour of the fuel cell technology subsystem

Ultimately, when the produced hydrogen via the electrolysis process is stored and available, then the chemical reaction between hydrogen and an oxidant (Oxygen) is converted into electrical energy for consumption (Ortiz-Rivera, Reyes-Hernandez and Febo, 2007).

3.3.2.1.2 Battery energy storage subsystem

Similarly to Fuel cell in basic operating principle, a battery is formed by individual positive and negative cells connected together in series or parallel configurations (two electrodes separated by an electrolyte). Battery energy storage systems have three active states of operation, which is a charging state, a discharging state and an idle state. In the charging state, the BESS acts as a load, whilst in the discharging state, the BESS acts as a generator. Likewise, batteries produce DC voltage and therefore a power conditioning system is required to boost and invert the DC voltage to AC grid voltage.

3.3.2.1.2.1 BESS subsystem behaviour

Depending on the type of application, the battery energy storage device comes in different technologies, as discussed in Chapter 2, section 2.2.1.5.2. But in essence, a battery is a device that stores energy electrochemically (positive and negative plates separated by electrolyte) in a way that allows for direct conversion to electricity. There important technical features that must be considered when assessing the BESS system such as:

- Energy Density
- Power Density
- Discharge and Recharge Characteristics
- Footprint
- Response Time
- Roundtrip efficiency
- Lifetime
- Environmental impact
- Maintenance
- Temperature range
- Design Complexity
- Reliability
- Life cycle Cost

- Cycle Life
- State-of-Charge
- Useful Voltage Range
- Cost

3.3.2.1.3 Power Conditioning System (PCS) or Inverter

The power condition system (PCS) is the interface between the energy storage system (DC bus) and the utility grid system (AC bus) and also provides for charging and discharging of the battery energy storage system. The PCS functions as both an AC→DC power factor controlled rectifier and a DC→AC inverter and can smoothly transition between these operations while in the online state. The PCS consist of solid state electronic switches (IGBTs) along with associated control and protection, filtering, measuring instruments and data logging devices. For the purpose of this study, the PCS shall be a bi-directional inverter that can provide real and reactive AC power simultaneously with full four quadrant operation.

Detailed operation and technical characteristics of the power conditioning system (PCS) is intensively discussed in numerous literature articles (Choi and Lee, 2009),(Li, Iijima and Kawakami, 2013).

Typical PCS technical specifications are illustrated and summarised in Table 2. The illustrated sizes are 500KVA-PCS and 100KVA-PCS. More external views and internal circuit configurations are exhibited in the Appendices as Appendix 3-5.

Table 2: PCS Technical Specifications

Item	PCS Specifications	
	500kVA-PCS	***100kVA-PCS***
DC Voltage Range	450V~800V	320V~550v
Rated AC voltage	300V	210V
Rated Output Range	Active Power:±500kW Reactive Power:±360kvar	Active Power:±100kW Reactive Power:±100kvar
Frequency	50/60Hz	
Main Circuit	3-Level	2-Level
Isolation Transformer	External	Internal
Efficiency (Max)	98.5%	96.4%
Cooling Method	Forced-cooling	Self-cooling
Installation Location	Container or indoor	
Dimensions	1900W×700D×1950H	1400W×800D×1950H

Source: (Li, Iijima and Kawakami, 2013)

3.3.2.1.3.1 Behaviour of the Power Conditioning System

As mentioned above, the PCS is injected with the DC electrical power from the DC bus and thereafter internally converts it into AC. The PCS shall be capable to adjust the output voltage and frequency to suit the grid conditions. The PCS must be able to synchronise with the grid frequency and provide a stable output – appearing to the grid to be a synchronous generator. Suitable rated contactors or equivalent automated disconnecting devices shall be provided for the connection of the inverter input - and output terminals to the fuel cell and battery DC bus and to the three phase AC isolation power transformer, respectively. This will allow the inverter to disconnect automatically in cases of power cuts from the utility electrical distribution network.

3.3.2.1.4 Direct Current (DC) Bus-Bar

The DC bus is a common point where both the Fuel cell and Battery energy storage subsystems meet together. The DC bus-bar further facilitates and acts as interface between the energy storage system and the inverter. Moreover, the DC bus, its ultimate function is to pass the DC power generated by the combined energy storage system to the inverter or pcs.

3.3.2.1.5 Energy Management System (EMS) functionality

The energy storage system (ESS) management (alternatively known as the energy Management System) shall facilitate the real time monitoring, operation, control, reliable, efficient and safe operation and performance optimisation of the Energy Storage System (ESS).

a) The EMS shall be able to acquire real time data, status and alarm information from all critical subsystems necessary for the effective and safe operation of the ESS:
   - Energy and power meters
   - Transformers
   - Switchgear
   - Protection relays and schemes
   - Uninterrupted Power Supply (UPS)
   - Power Conversion System
   - Fire Protection System
   - Battery management System
   - Fuel Cell Management System
   - Any other equipment deemed necessary

b) The Energy Management System will further display the following system parameters:
   - Network Voltages
   - Network Currents
   - Power factor
   - Apparent Power
   - Active Power
   - Reactive Power
   - System status and alarms
   - All other data necessary for operation and fault finding, including diagnostics and self-check functions.

c) The EMS shall be powered from an UPS in order to remain operational in the event of an auxiliary power supply failure. This is necessary to ensure the safe shutdown of the

ESS and also to enable continued remote monitoring and control from the Network Management Centre.

d) The EMS shall log and store critical system parameters, alarms, events and trends required for the effective performance management of the ESS. This data shall be date and time stamped.

In this system it is assumed that the first option of an electrical energy supply is assigned to the utility grid through the MV electrical distribution network. Therefore, only when the utility grid network is experiencing peak demand situations, load shedding, power cuts due to vandalism or planned outages, then the system will prioritise the Energy Storage System.

Therefore, in this system, three operating modes are considered, which operate as follows:

1st operating mode

Initially, in this operating mode the study considers that there is enough available electrical power from the utility grid distribution network to meet the load demand of the industrial customer. Moreover, under normal circumstances, the overabundance of electrical power from the utility grid will be used to charge the Battery in the float or boost mode depending on the level of depth of discharge, and also to fill up the hydrogen tank through the electrolyser of the fuel cell system.

2nd operating mode

In this operating mode the study considers that there is enough available electrical power from the utility grid distribution power to satisfy the load demand of the industrial customer. In this period, the utility distribution electrical power continues to provide sufficient electrical power to cater for the total load demand. Nevertheless, in this operating mode, it is assumed that there is no overabundance of electricity from the utility distribution network.

The system continues to operate in these two modes until a certain point when the system begins to experience constrained conditions due to the total load reaching the maximum peak demand. Once this scenario occurs, the monitoring and control unit switches to the third operating mode which consist of bringing in the battery energy storage system together in parallel fuel cell energy storage system.

3rd operating mode

In this last operating mode the study considers that there is absence of utility grid distribution electrical power to meet the load demand. In this instance, the total load demand of the customer is fulfilled by the battery energy storage in parallel with fuel cell energy storage system.

Although the ESSs will be synchronised to share the load demand, it must be noted that both Energy Storage Subsystem are designed to meet the total load requirement even when operating in isolated modes.

3.4 Summary

This Chapter focused on outline of the under study system and has described the type of customer under study, giving description of the entire system by describing all the respective components individually. Furthermore, this chapter evaluated the respective components' behaviours and has discussed the operating modes considered in the study.

CHAPTER FOUR

ENERGY STORAGE SYSTEM MODELING

4.1 System Description

The system consists of Battery energy storage system (BESS), an electrolyser-fuel cell system, hydrogen tank, power conversion system, an inverter, interconnected to the utility distribution network and load as illustrated in Fig.13. The utility distribution network is the primary source that fulfils the load requirements. The BESS and electrolyser-fuel cell system are storage system that aims to cater for power cuts, and peak demands. As mentioned in the previous chapter, the utility distribution network, whilst supplying the load, it's also use its surplus power to charge the BESS and produces enough hydrogen through the electrolyser for the fuel cell stack.

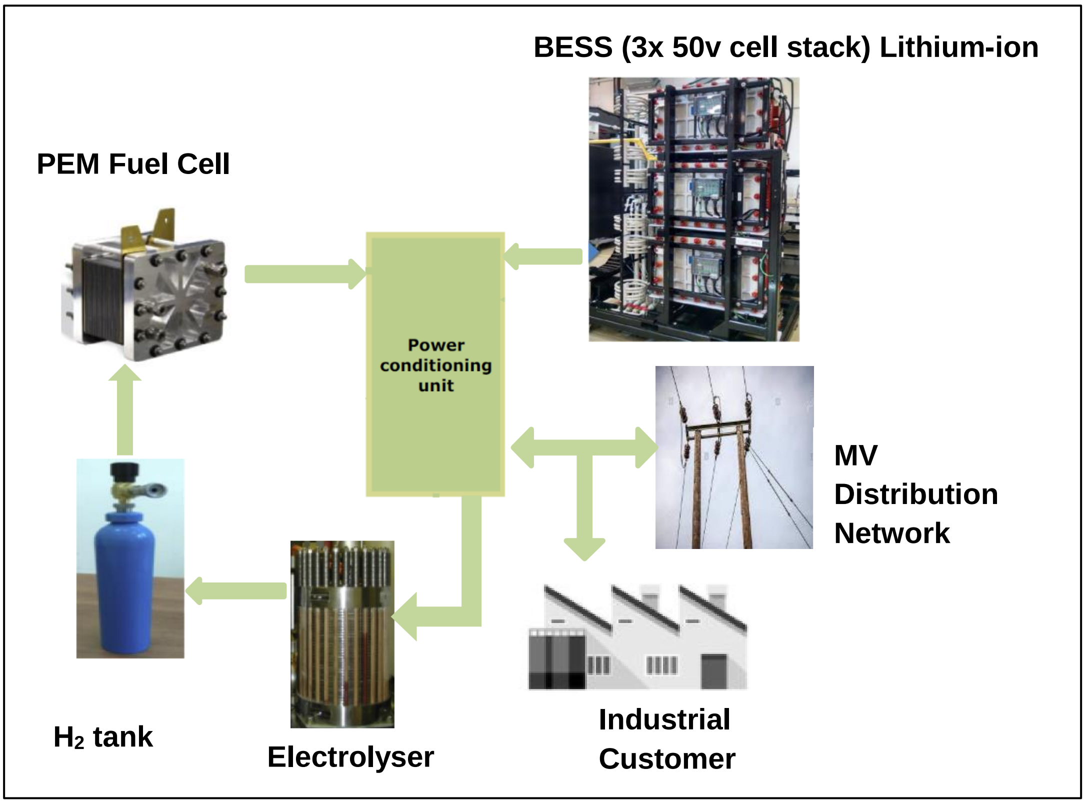


Figure 13: Full description of the BESS (cell stack) & FC (electrolysis) system

4.2 System Modelling

4.2.1 Fuel cell

The output voltage of a fuel cell stack is given below as in Ref. (Chong, Lee Wai & Wong, Yee Wan & Rajkumar, Rajprasad Kumar & Rajkumar, Rajpartiban Kumar & Isa, 2016):

$$V_{FC} = N_{Cell} E_{Cell} \quad (4.1)$$

But $E_{Cell} = E_o - V_{act} - V_{conc} - V_{ohmic}$

Where;

N_{Cell} = Number of cells per stack

E_{Cell} = Voltage per cell

E_o = open circuit voltage

V_{act} = Voltage activation

V_{conc} = Voltage Concentration

V_{ohmic} = Ohmic fuel cell overvoltage

4.2.2 Electrolyser

Amongst others, the preferred and most frequently used method of producing hydrogen is through the electrolysis of water using electricity. In this electrolysis process water is split into two substances, namely hydrogen and oxygen. Likewise to fuel cells, electrolysers are also distinguished according to the type of electrolytes used (Luta and Raji, 2019).

The rate of hydrogen generated by the electrolyser is expressed as:

$$q_{H_2} = \eta_F \frac{N_C I}{2F} \quad (4.2)$$

Where;

η_F = Represents the faradays efficiency

N_C = Represents the number of cells in series

I = Represents the electrolyser current

F = Represents the faradays constant.

4.2.3 Hydrogen storage tank

The hydrogen generated from the electrolyser is compressed using a compressor and stored in a tank. The power required for the compression is given below as in Ref. (Torres, 2015):

$$P_{comp} = \frac{\gamma}{\gamma-1} R \frac{T}{\eta_C} \left[\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] q_{H_2} \quad (4.3)$$

Where;

γ represents the polytrophic coefficient, R is the denotation of gas constant, T stands fir the compressor inlet temperature, η_C denotes the efficiency of the compressor, P_1 and P_2 is the representation of inlet and outlet pressure respectively and q_{H_2} is the mass flow rate of hydrogen.
The pressure of hydrogen in the tank is also expressed below as in Ref. (Torres, 2015):

$$P_{tank} = \frac{RT}{V_{tank}} n_{tank} \quad (4.4)$$

Where;
V_{tank} = represents the volume of the tank
n_{tank} = represents the number of moles of gas in the tank.

4.2.4 Battery Energy Storage

In Hybrid Energy Storage Systems (HESS), power sharing is important. Hence, the need for adequate sizing of the battery storage is of paramount importance. As it has been reiterated in previous chapters, battery energy storage, acts both as backup system whenever there is a loss of power or, and to compensate in situations of peak demand.
Firstly, the voltage of the battery V_{batt} can be expressed as function of the state-of charge SOC_{batt} of the battery and the current I_{batt} of the battery as in Ref. (Torres, 2015):

$$\begin{aligned} V_{batt}(t) = {} & V_{0,batt} - K_{1,batt} \frac{C_{120,batt}}{C_{120,batt} - C_{batt}(t)} I_{batt,ch}(t) \\ & + K_{1,batt} \frac{C_{120,batt} \left(\delta_{batt,ch} - \delta_{bat,dis}\right)}{C_{120,batt} - C_{batt}(t)} C_{batt}(t) \\ & - K_{1,batt} \frac{C_{120,batt}}{C_{120,batt} + 0.1 C_{batt}(t)} I_{batt,dis}(t) \\ & - K_{2,batt} \cdot e^{\left(K_{3,batt} \cdot C_{batt}(t)\right)^{\cdot}} + R_{ohm,batt} \cdot I_{batt}(t) \end{aligned} \quad (4.5)$$

Where;
$V_{0,batt}$ = is the denotation of the battery internal voltage (V)
$C_{120,batt}$ = indicates the maximum battery capacity (Ah)
C_{batt} = represents the capacity of the battery (Ah)
$K_{i,batt}$ = are internal parameters of the battery and
$R_{ohm,batt}$ = is the internal ohmic resistor of the battery.
The model differs for the states-of-charge and discharge of the battery, so the binary variables of the state of the battery are introduced $\delta_{batt,ch}$ and$\delta_{bat,dis}$.
Secondly, the state-of-charge of the battery is related with the capacity as illustrated in the following equation:

$$SOC_{batt}(t) = \frac{C_{batt}(t)}{C_{120,batt}} \quad (4.6)$$

Lastly, the battery size and number of battery cells required can be determined using the following expression:

$$N_{batt} = \frac{E_{\frac{1}{day}} * n_d}{V_{batt} * C_{120,batt}} \quad (4.7)$$

Where;

$E_{\frac{1}{day}}$ = energy consumption per day

n_d = number of days of backup power required

V_{batt} = rated battery voltage

$C_{120,batt}$ = maximum capacity of the battery

DOD = depth of discharge of the battery

The capacity (Ah) of the battery can expressed with the following expression:

$$C_{batt}(t) = \int_0^t I_{batt}(t)\, dt \quad (4.8)$$

Where; I_{batt}, is the current flowing in the battery string.

4.3 Digsilent method

The simulation software that is used in this work is the Digsilent PowerFactory due to the fact that the author is mostly being accustomed to the tool, including the existing functionality offered by the tool to model Energy Storage System (BESS and Fuel Cell). Digsilent PowerFactory is also the approved network modelling and simulation tool by well-known South African monopoly utility company (Eskom), and Municipalities (City of Cape Town).

4.3.1 Digsilent Model

Digsilent PowerFactory offers Energy Storage System (ESS) models with differing capabilities which can be utilised for the various use cases described in Section 1 & 2 in the literature review.

4.3.1.1 Energy Storage Static Generator Model

The Energy Storage System (BESS and Fuel Cell) static generator model in Digsilent PowerFactory can be utilised for the steady-state ESS integration studies, as it is a simple model that represents any non-rotating generator.

This model can be directly connected onto the network without the need to individually model the various components of an energy storage system such as the inverter, transformation, management system etc. The energy storage system rating, inverter control mode/operational limits and short circuit parameters etc. can be populated within this model.

4.3.1.2 Energy Storage Quasi-Dynamic Simulation Language (QDSL)

The energy storage quasi-dynamic simulation language model is effectively a static generator model with programmable logic (an assigned model definition or QDSL type) and can therefore also be utilised for the majority of steady-state and time series ESS integration studies. Quasi-Dynamic Simulation language is the programming language used in the model definitions to give existing network models logic, which is dependent on the manner in which one requires the model to operate.

The programmable logic enables the user to define how the energy storage system operates, including setting limits and measurements that get calculated autonomously. A simple example can be the coding of how the state of charge of the battery is determined, including the charging and discharging operation status of the battery and how it should behave. Input signals and output signals can also be coded into the model.

Digsilent currently offers 3 pre-coded battery storage QDSL model definitions:

- Power Measurement
- Voltage measurement
- Current measurement

These definitions can be manipulated or re-programmed to operate as per user requirements, however due to the scope of this report, it will not be discussed further.

4.3.1.3 Energy Storage Dynamic Simulation

It must be noted that since the dynamic simulation model is available in Digsilent PowerFactory for dynamic studies, each component of an ESS, including the parametric functions for the ESS management system and inverter are required to be populated. However, this level of modelling is only possible (and reasonable) if precise manufacture specifications are obtained for a particular battery type, control system and inverter system. These details are normally not readily available during the planning stage which makes the usage of this specific model inappropriate unless the required information is available or populated generically.

4.4 Procedure Details

Battery energy storage systems operate over time and operate in different modes (Charge/Discharge), similarly to Fuels Cells as well (Discharge/Regenerate fuel and oxygen), hence it is important for the simulations and the network analysis to be time based.

It is therefore required that the network models be setup and that the analysis be done using the Quasi-Dynamic simulation functionality in Digsilent PowerFactory, which completes a series of static load-flow simulations spaced in time.

The following is the procedure followed in the simulation of energy storage system (BESS and FC) using the static generator models on the network.
Herein under, each step will be briefly discussed and thereafter a summary in the form of a flow chart will presented.

- **Step 1: Obtain the Network Casefile**

The initial step is to obtain the casefile for the network in which the ESS is to be integrated into.

- **Step 2: Obtain Network Load & generation Profiles**

The next step is to obtain the network load profiles (historic and forecast) and the profiles of embedded generators on the network. Load data can be obtained from Analogue Download System) which includes statistical metering. The historic load and generation data should be recent, and should align within the same time period and frequency. The span of the historic load and generation data should at minimum encompass a year to ensure that seasonality is taken into consideration and a season with highest peak demand shall be considered. Should any anomalies or gaps (zero value) arise in these datasets, corrective measures and investigation must be carried out as per normal planning practice to ensure the integrity of the data to be used.

- **Step 3: Prepare the casefile for Quasi-Dynamic Simulation**

The next step is to ensure that the casefile prepared (applying relevant historic and forecasted loading and generation characteristics to the feeder, loads, and embedded generators etc.) and is functional for quasi-dynamic simulation.

- **Step 4: Perform Quasi-Dynamic Network Simulation & Analysis**

Once the network model without any ESS integration is setup for quasi-dynamic simulation and analysis, the next step is to run a quasi-dynamic simulation for the base year and forecasted years of the study and then to analyse the network for any constraints (current and Future.

- **Step 5: determine ESS Use Cases and Integration Location**

Once the network constraints have been identified, the primary application for an energy storage system will need to be identified, including any potential secondary application. The integration location is depended on the use cases and stacked benefits that one wishes to achieve with the ESS.

At the end of this step, the primary use case and integration location of the ESS had been identified.

- **Step 6: Determine BESS SIZE**

In this step, the author will perform high level analysis to determine the BESS and Fuel cell size and capacity in order to fulfil the ESS's primary application. The analysis will be based on the load profile, forecasted load, available local distribution network transformer and line thermal capacities and the results from the preliminary power system analysis. The author will consult with the BESS and FCs sizing methodology guidelines to size the BESS and FC in their entirety, taking factors such as operational behaviour (duty cycles), degradation and efficiencies into consideration. The following steps offer supplemental guidance in terms of determining the size of the BESS and FC:

- The network requirements: i.e. what is required of the BESS and FC by the network to alleviate constraints?
- The discharge duration: i.e. the period of the local (Consumer) and system peaks, during which period the BESS and FC will need to discharge.
- Potential charge periods: i.e. Average charging potential of the BESS and FC periods in which the BESS and FC can potentially charge.
- Network power evacuation potential: i.e. the amount of power that the network can accommodate from and to the BESS and FC system.

Once the BESS and FC size has been determined, step 7 to 12 below will be performed. This may be an iterative process until the selected BESS size complies with the defined planning criteria and meets the requirements to alleviate the network constraint.

- **Step 7: Setup Static Generator (Battery and Fuel Cell) Storage Model**

Once the BESS and FC size has been determined, the next step is to select the static generator battery storage and fuel cell model in Digsilent PowerFactory and connect it onto the network integration point (PoC) with the respective transformation in preparation for the technical analysis.

- **Step 8: Perform Rapid Voltage Change (RVC) Study**

The purpose of the next step is to perform a RVC study in line with the Draft Grid Connection Code for Battery Energy Storage Facilities (BESF), Utility standards, and NRS048-2 and

NRF048-4 guidelines. This is to check that the difference in voltage level between the normal operation and the abrupt switching out of the ESS is not more than the defined RVC limit stipulated in (RSA Grid Code Secretariat, 2014). If a violation is incurred, the ESS size will need to be reduced.

- **Step 9: Perform Load/Generation Rejection (LGR) Study**

Similar to the previous step, the aim of this step is to perform a load and generation rejection study to ensure that in the event the BESS is abruptly disconnected from the network during its peak charge or discharge state, that no significant over and under voltage scenario (steady-state) occurs resulting in insulation breakdown of equipment.

- **Step 10: Perform Fault level Study**

It is understood that in most cases, inverters lack inductive characteristics that are related with rotating machines because an inverter is controlled by power electronics equipment and not by electrical machines. Therefore, in this instance, short circuit contribution is possible by means of inverter control. However, this contribution is typically limited to slightly above 1p.u current (limited overload capability of a semiconductor power electronics device) (Martins, 2018).

It is always technically sound to assess the equipment short-circuit ratings against the simulated fault levels. It is advised to perform the fault level study under maximum loading conditions to assess against the worst case fault level scenario. If no equipment ratings are exceeded in the assessment, therefore, must obtain time-series operation of BESS.

4.5 Procedure Flow Chart

The flow chart below summarises and depicts the advocated process to analyse BESS and FC on MV networks.

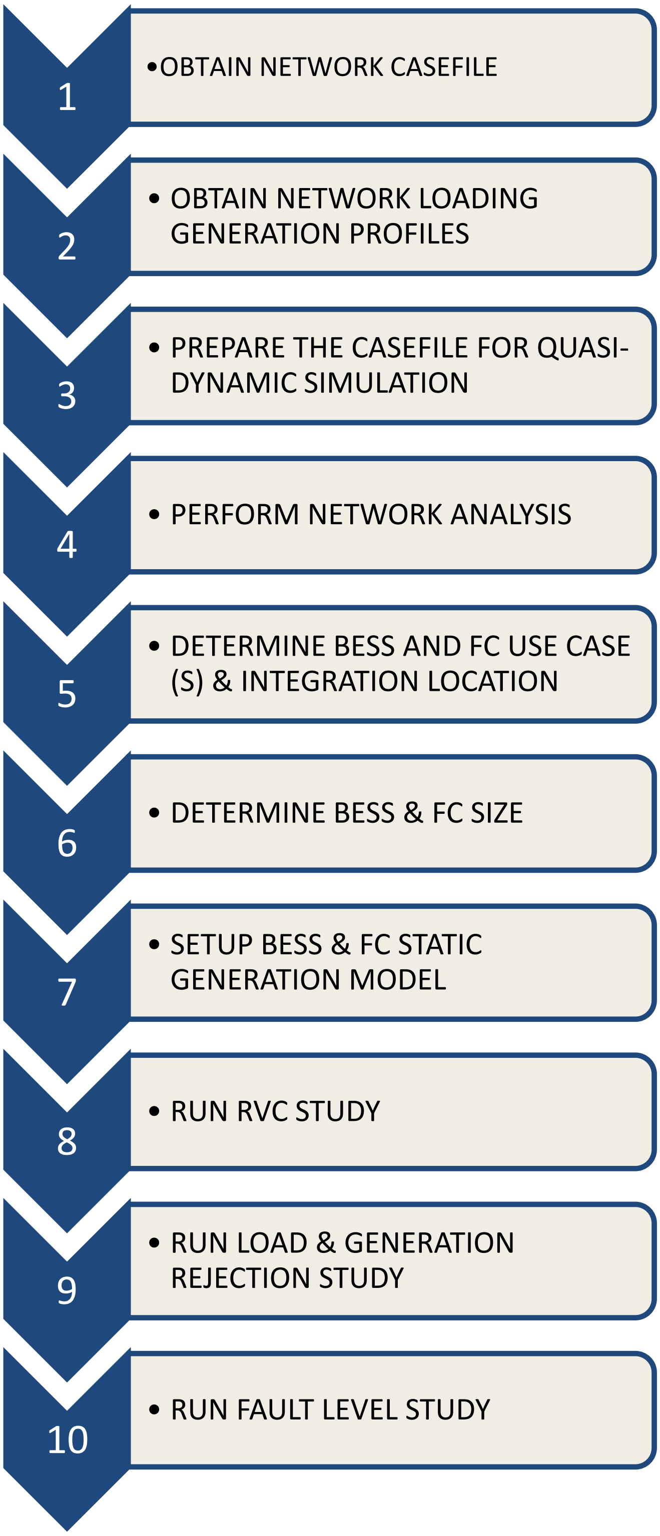


Figure 14: ESS Modelling & Simulation Procedure Flow Chart

4.6 Optimal Economical Analysis Based on Homer Pro Software

For over a decade, Homer software has provided the industry's most trusted energy system modelling for hybrid systems. Homer helps to calculate electricity cost savings by simulating distributed energy systems that cut demand charges or time-of-use-rates. Moreover, Homer has the ability to optimise storage systems and backup based on batteries and hydrogen (fuel cells, electrolyser and hydrogen tanks), and AC and/or DC loads(Castañeda *et al.*, 2012).

Among many reasons behind the use of Homer software for techno-economical optimisation, it is to appropriately design the hybrid system with the aim to fulfil the electricity supply reliability requirement at minimum system cost. For the purpose of this study, the dispatch strategy considered is the load following type.

In this study, Homer is used specifically to perform economic analysis only and other technical analyses are omitted since they are simulated in Digsilent. Homer will perform an hourly simulation of every possible combination of components entered and rank the system according to user-defined specifications, such as cost of energy (COE, US$/kWh) or capital cost(Rohani, Mazlumi and Kord, 2010).

4.6.1 Cost Optimisation

The aim of this study is to achieve peak shaving using energy storage systems and to supply power in the absence of power from the utility grid for short periods, which should be as economical as possible.

The system cost is defined as the summation of Battery cost(C_{BAT}), electrolyser cost(C_{ELEC}), fuel cell cost(C_{FC}), converter cost(C_{CONV}), and hydrogen tank cost(C_{TANK}).

$$C_{SYSTEM} = C_{BAT} + C_{ELEC} + C_{FC} + C_{CONV} + C_{TANK} \tag{4.9}$$

Each component cost being:

$$C_i = N_i * [CCost_i + RCost_i * K_i + OMCost_i] \tag{4.10}$$

$$i = Battery, FC, Electrolyser, Converter, Hydrogen\ Tank$$

Where $N_i$represents the number or size of the system elements, $CCost_i$denotes the capital cost, $K_i$stands for the replacement frequency, $RCost_i$is the corresponding replacement cost, and lastly $OMCost_i$is the system's operational and maintenance cost. The cost of the system components are shown and discussed in the next chapter (Chapter 5). This includes simulation results as exhibited in Figure 29 and breakdown of cost analysis of the architecture are presented in Figure 30.

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Network Casefile

The network in which the energy storage system is to be integrated into is fed from the 15MVA transformer, See Fig.15 below. MV load 1 & 2 illustrates the large power consuming loads with LV load connected to a 2.5MVA transformer, being the least consuming loads of the industrial customer network. The interconnection between the industrial customer and utility distribution network is via specified medium voltage type cables, three Cu PVC underground cables. Appendix 6 depicts the overview in Digsilent.

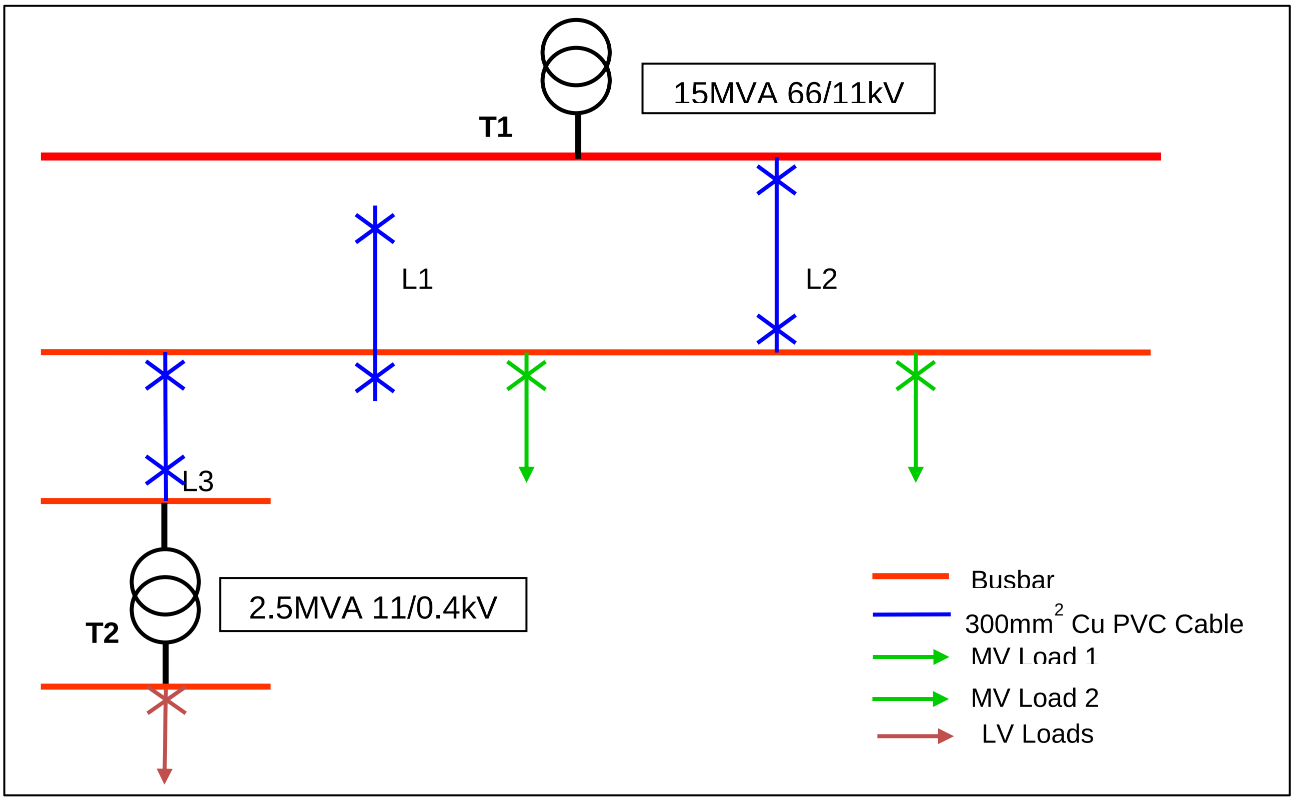


Figure 15: Industrial customer on 11kV network

5.2 Load and Generation Profiles

Currently, the network is not connected to any embedded generators and therefore no metering data is required with respect to embedded generation. Table 2 shows the loads historical statistical metering data for the previous years of the network. In order to determine the percentage loading status of each component, this report specifically considered peak loading values. As stipulated in chapter 2, section 2.3.3 for any of the components that are found to be operating close to their maximum capacity during peaking hours, then this dissertation suggest incorporating energy storage systems to the network to alleviate the load (peak shaving).

Table 3: Component historical data and loading

Component name	Historical Peak loading (kVA)			Thermal Limit (kVA)
	2017	2018	2019	
MV + LV Loads	10573	10994	11268	
Line1				13000
Line2				13000
Line3				6500
T1				0.8*kVA rating
T2				0.8*kVA rating

Source: Author

5.2.1 Industrial customer typical Hourly profile

In general, industrial customers, mostly their power usage begins to escalate from the morning hours until the late ours of the day, reaching their maximum peak demand during the middle of the day. Likewise, in figure 16, is the typical hourly load profile of the investigated industrial customer. As it is depicted in Fig.16, the industrial customer reaches its maximum peak demand value at approximately 12h00 and uses less power between 20h00 in the evening and 06h00 in the morning respectively. The scale considered is 1p.u equivalent to 5MVA.

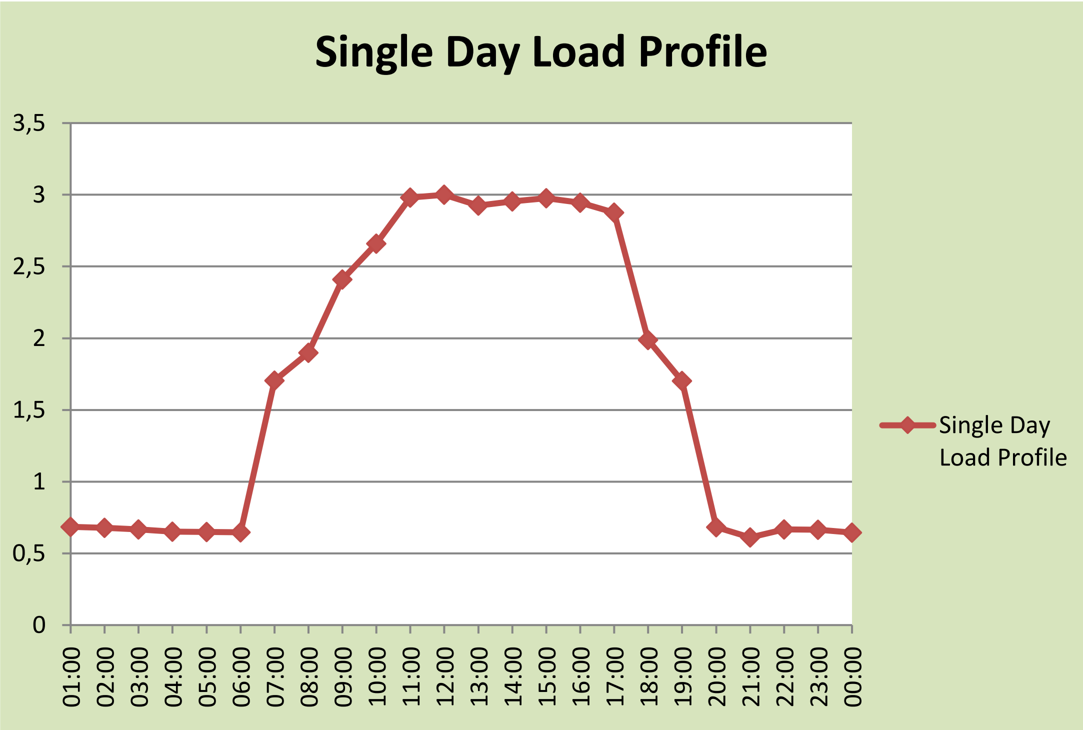


Figure 16: Hourly Load Profile

5.2.2 Load forecasting of the industrial customer

Formula 5.1 below is the method used to determine the percentage growth calculations for short and long term load forecasts. As mentioned previously, this is an industrial consumer that manufactures steel related products, from raw material to fine-tuned end products. Therefore, the growth rate per year is expected to grow at a very low pace.

$$\left(\frac{kVA_f}{kVA_p}\right)^{\left(\frac{1}{n}\right)} - 1 \qquad (5.1)$$

Where:

kVA_f = Future kilo Volt-Amps

kVA_p = Present Kilo Volt-Amps

n = Number of years

Table 4: Short & Long Term Load Forecast

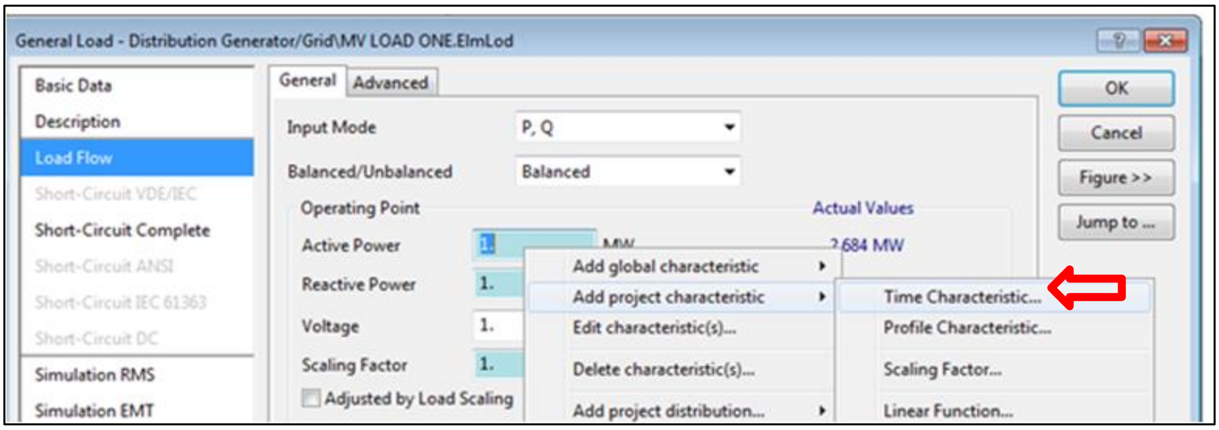
	Maximum Demand (kVA)							
Year	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
MV+LV Loads	10994	11268	11550	11831	12113	12395	12677	12958
kVA/year	282							

Source: Author

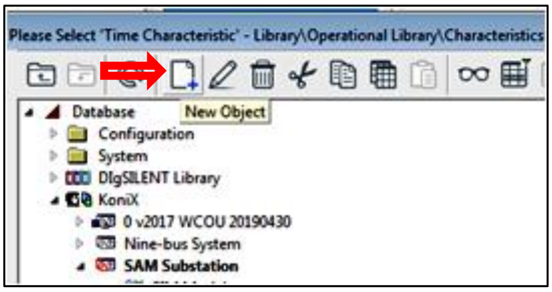
Table 4 shows that the total load for the industrial customer is estimated to grow by at least 2.45% from 2020 up until 2025, which translates to an increase of about 282kVA per year. Therefore, the main feeding transformer (T1) is expected to exceed its maximum thermal limit of 80% in the year 2025 from 75.5% to 86.39%. The feeders 1 and 2 are estimated to be operating roughly at 49.8% of their thermal limit, and line 3 in the region of 30.82% in the year 2025.

5.3 Quasi-Dynamic Simulation

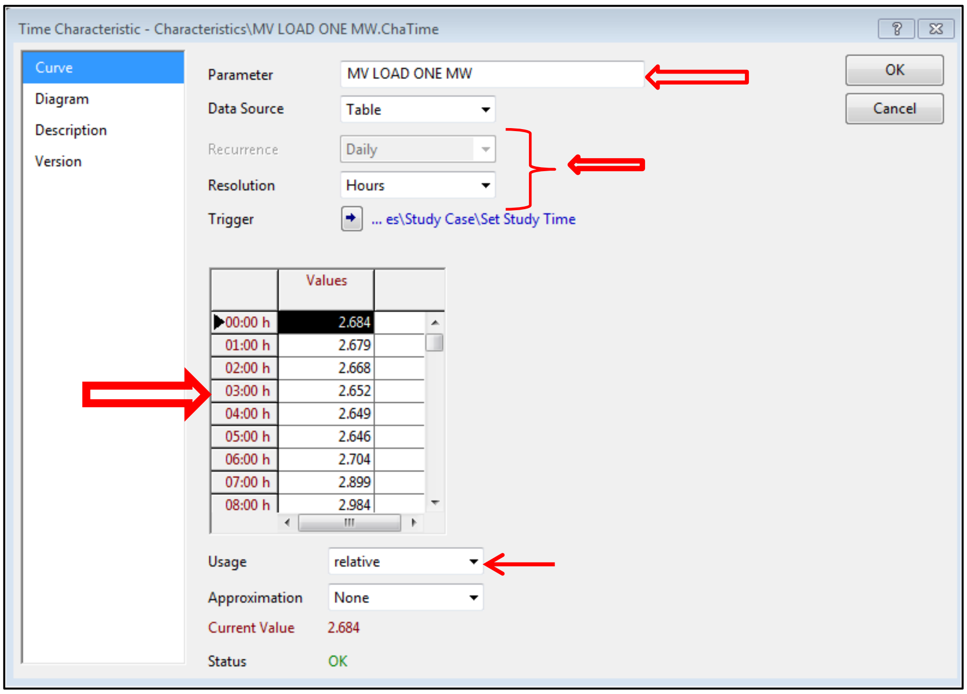
In this section, the aim is to prepare the network casefile for Quasi-Dynamic Simulation (QDS) by applying loading and generation characteristics to the feeders, loads, and embedded generators. In the following snapshots is a detailed process on inserting time characteristics that will assist in performing Quasi-Dynamic Network Simulation and Analysis. To add a time characteristic, right click on the parameter of interest, select “Add Project characteristics” and the select “Time Characteristic” as shown below:



From this window, in order to create new time characteristics, a “New Object” tab is selected:



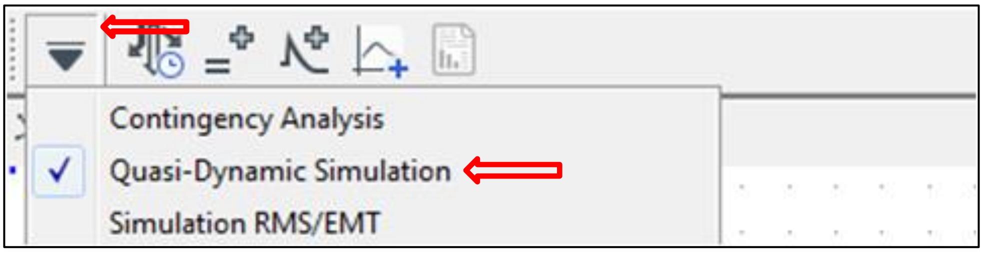
In the time characteristic tab, set a name for the characteristic (i.e. MV LOAD ONE MW), set the recurrence to daily, set the resolution to hourly and set the usage to relative (per unit). This will provide input table for actual hourly loading/generation data for a day as shown below:

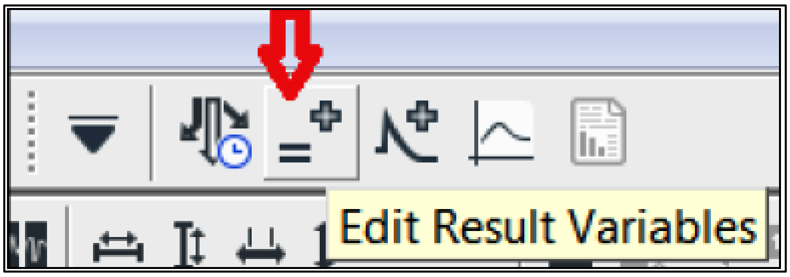


At this stage, enter the hourly loading/generation data manually or by copying and pasting values into the table. The unit values entered are in M (mega) by default:

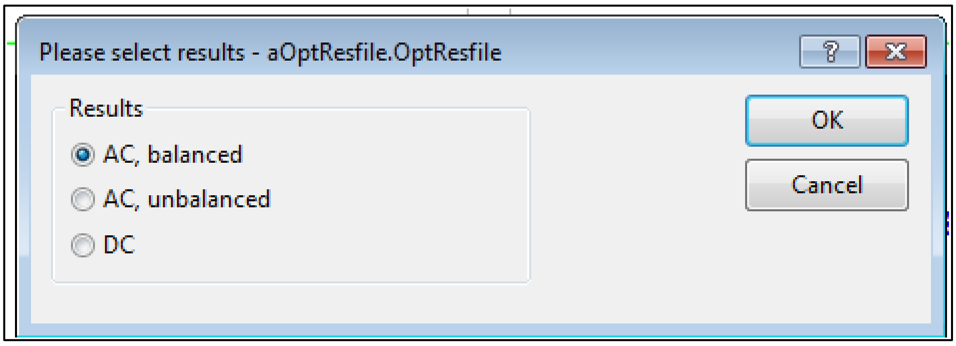
Quasi-dynamic simulation in Digsilent PowerFactory requires the user to select and define the relevant results variables to be monitored such as terminal voltages and equipment loading percentages.

To achieve this, quasi-dynamic pane must be selected and then select the ‘edit result variables” option as shown in the snapshot below.

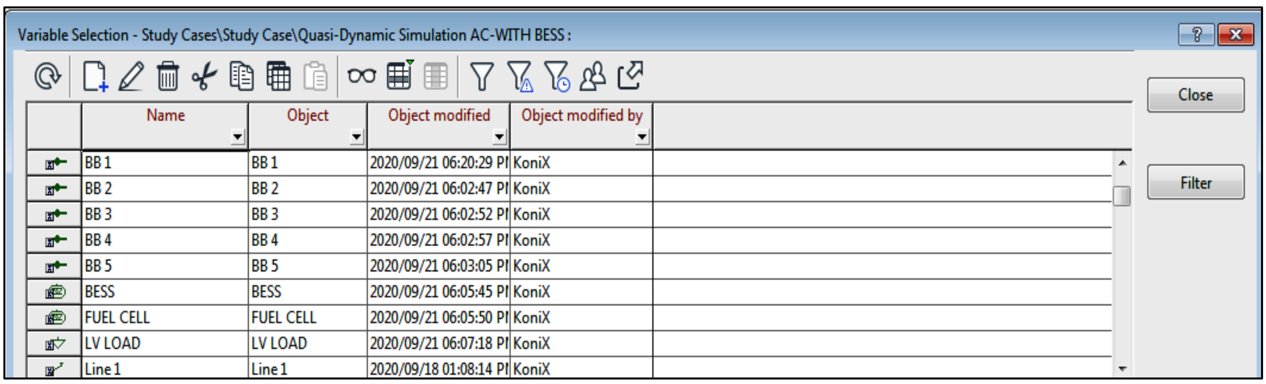




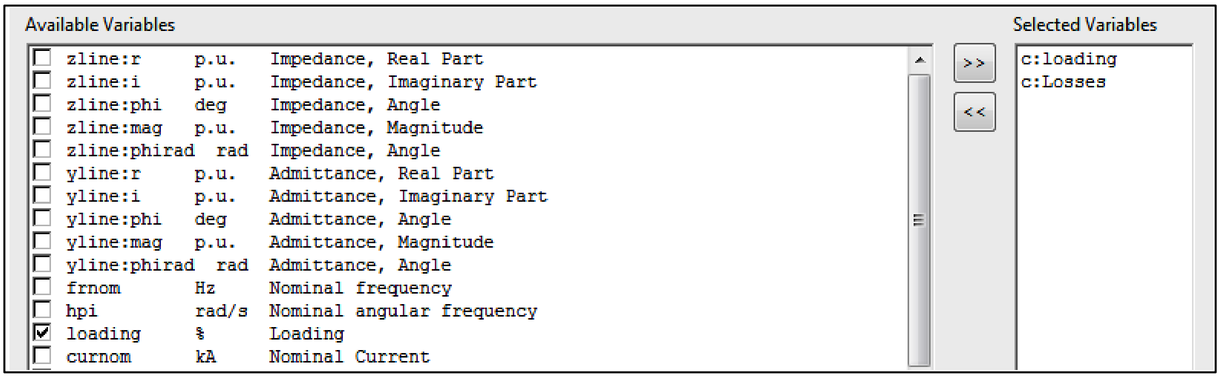
Once clicked, a window will pop up, to select type of results (i.e. AC balanced). This report simulated for AC balanced condition.



Based on the load-flow type selection, the next window will prompt a page where the relevant elements and results parameters were added as shown in the snapshot below:



This results variable list includes all the busbar, line elements and relevant transformer elements with their respective parameters. This also includes all elements and the relevant parameters which need to be assessed against the planning parameters, such as terminal voltages and line/transformer loading percentages.



All the selected relevant variables are shown under the selected variable list as shown in the snapshot above. For the purpose of this dissertation, the following (Table 4) were the selected relevant parameters to be used in the planning for the hybrid connection of the energy storage system which comprises of a battery energy storage and fuel cell energy storage for an industrial customer connected on a utility distribution network.

Table 5: Variable list of different elements

Elements	Variable List				
	P (MW), Q (VARs)	**% loading**	**Losses (kW)**	**Voltage**	**Other**
Feeders	Y	Y	Y	Y	
Busbars	N	Y	N	Y	
Transformers	Y	Y	Y	N	

Source: Author

5.4 Quasi-Dynamic Network Simulation & Analysis without BESS and FC

At this stage, the network model without any energy storage system (BESS and FC) integration is setup for quasi-dynamic simulation and analysis, the next step is to run a quasi-dynamic simulation for the base year and forecasted years of study and thereafter to analyse the network for any constraints (current and future).

The execution of the network simulation using QDS is further shown and discussed in the Appendix 7, from Appendix 7.1 to Appendix 7.6 of the Appendices page.

Herein, will create plots for all relevant elements and their parameters (thermal loading, voltage level etc.) that will form part of the planning parameters assessments. The information will be analysed and all network constraints will be identified. Below are plots for the concerning elements of the network.

5.4.1 Transformer (T1)

Generally, transformers have thermal loading issues towards their ageing period. The IEC60354 recognises that thermal loading on transformers is cyclic, whether due to cyclic variations in the load or hourly variations in the ambient temperature. Transformers have the increased upper MVA limit of 150% of nominal as defined in IEC 60354 (assuming operation at nominal tap) (Nye and Dedekind, 2016). However, for the purpose of this report, when a transformer operates close to 80% of its rated capacity, then this should serve as an alarm for mitigation measures to put in place. Fig.17 below, exhibits the thermal loading of T1 where the industrial customer is connected to the distribution utility network for the base year. T1 Thermal loading for forecasted years can be found as Appendix 8 of the Appendices page.

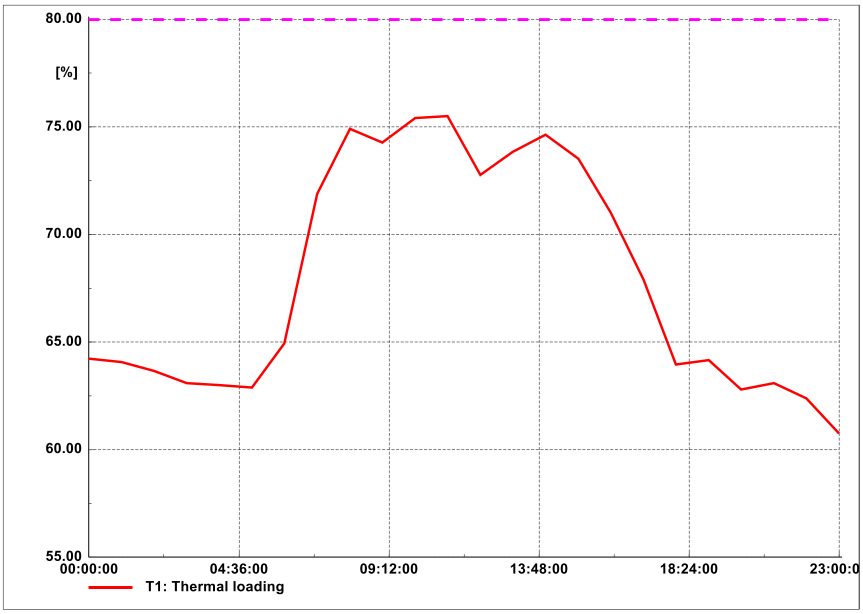


Figure 17: Thermal loading in year 2020

Source: Author

As seen in the graphical form above, during peak loading hours of the day, the transformer operates at 75.5%, which is nearly reaching the 80% of rated capacity. This incline in load will be compensated through the hybrid energy storage system. Similarly, T2 has exceeded its maximum thermal loading limit by 2.4%, see Fig.18 below.

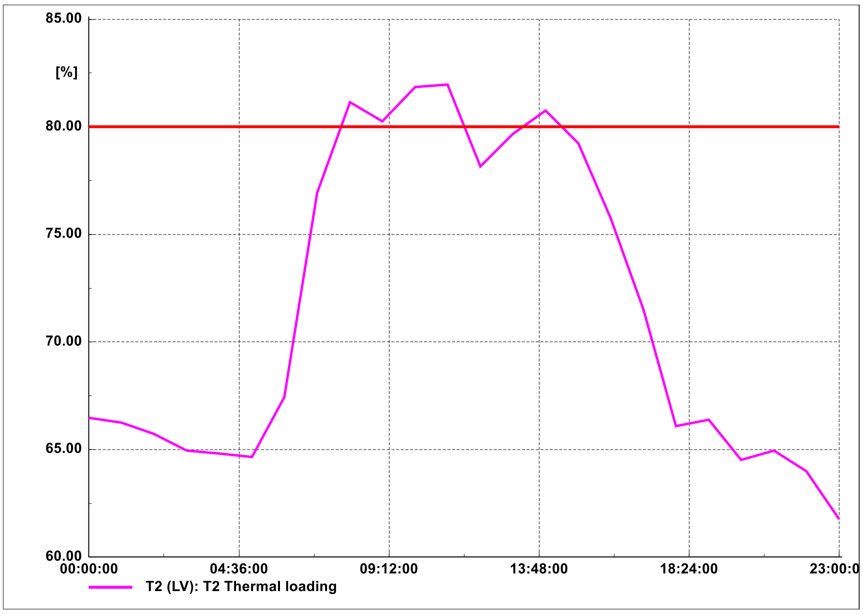


Figure 18: Transformer (T2) thermal Loading in year 2020

Source: Author

5.4.2 Busbar 3

As seen in Fig.19 below, in the base year, busbar 3 is currently approaching the minimum voltage line of 0.95p.u, this is the minimum voltage set limit according to the guidelines of the NRS 048-2, 2007 document which specifies compatibility levels, limits, voltage characteristics, and assessment methods, which are meant to be used by utilities, their customers, in managing the level of power quality supplied by licensees at the point of supply to individual customers (AJ *et al.*, 2007). The highest operating voltage on BB3 is 0.965p.u which falls under the set maximum allowable operating voltage of 1.05p.u of this report.

Graph 1 Voltage drop

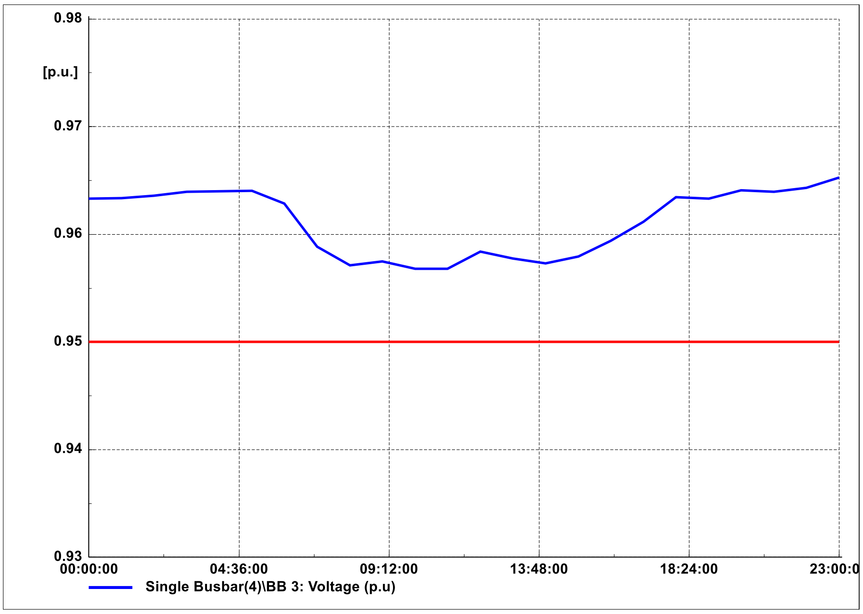


Figure 19: voltage drop on the BBs

Source: Author

Busbar 3 and Busbar 4 are operating at similar voltage ranges and therefore their graphic display will resemble each other. In addition, BB 1, 2 and 5 are operating at acceptable voltage ranges, and are summarised in table 6.

Table 6: QDS Report for Voltage Ranges

	Quasi-Dynamic Simulation Report: Voltage Ranges				
Study Case:	Industrial Distribution Network				
Max. voltage	1.05				
Min. voltage	0.95				
Start Time	2020.09.18 00:00:00				
End Time	2020.09.18 23:00:00				
Terminal	**Branch, Substation or Site**	**Voltage Max. [p.u.]**	**Time Point Max**	**Voltage Min. [p.u.]**	**Time Point Min**
BB 5	Single Busbar(6)	1.044	2020.09.18 22:00:00	1.034	2020.09.18 11:00:00
BB 1	Single Busbar(7)	1.000	2020.09.18 00:00:00	1.000	2020.09.18 00:00:00
BB 2	Single Busbar(3)	0.976	2020.09.18 22:00:00	0.971	2020.09.18 11:00:00
BB 3	Single Busbar(4)	0.964	2020.09.18 22:00:00	0.957	2020.09.18 11:00:00
BB 4	Single Busbar(5)	0.963	2020.09.18 22:00:00	0.956	2020.09.18 11:00:00

Source: Author

Mitigation measures will only be considered for the busbars with poor voltage levels. For the purpose of this study, the maximum and minimum per unit set voltage are 1.05p.u and 0.95p.u respectively.

5.5 Quasi-Dynamic Network Simulation & Results with BESS and FC

Thus far, all the constraint and concerning elements of the network have been identified, the next step is to model the BESS and FC into the network and thereafter observe the improvements as a result of the integration. Herein, are graphs/plots showing improvement of the network devices that reached or exceeded their safe operating ratings during peaking load hours

5.5.1 T1 and T2 Peak Shaving

Peak shaving is similar to load levelling but is primarily used for reducing peak demand. In cases of peak load coinciding with the cost of peak energy prices, peak shaving can reduce this energy cost. Peak shaving in addition can be used to increase the capacity of the existing network infrastructure (Pillay, Heerden and Ramdhin, 2019). In Fig.20, with battery and fuel cell storage at proposed MV substation, transformation capacity during peak periods is increased due to peaking load sinking the storage power. When the energy storage system in integrated to the network, the peak demand drops from 75.5% to 62.616%, the network is alleviated almost by 15% meaning more loading can be catered for and provides less strain on other network elements as well.

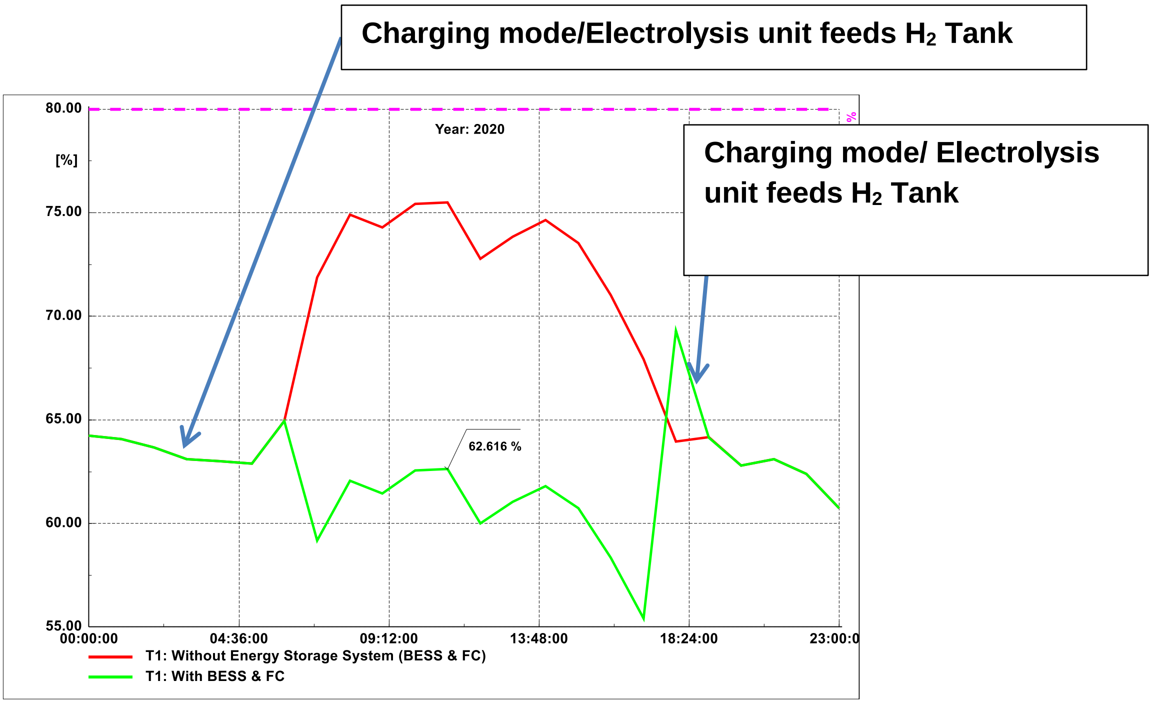


Figure 20: T1 with Energy Storage System integrated to the network

Source: Author

Where the two graphs are equal, the storage system is in charging mode (act as a load), and immediately as the load begin to peak then the storage system goes into discharging mode (act as a generator).

Fig.20 (a) and (b) shows the operating performance of transformer T1 when the energy storage components (BESS and FC) are separately connected to the network. The spike that happens in Figure 20 (a) is for a short period of time and is the representation of the Battery going into charging mode after a deep discharge since it requires high current to charge, and will thereafter gradually decrease and continue to charge in floating mode.

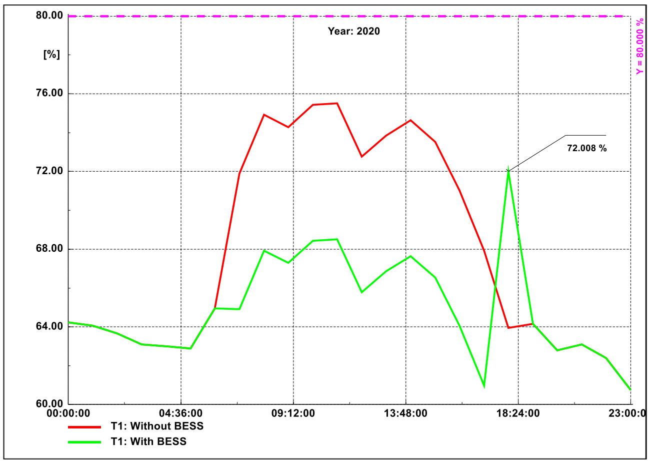


Figure 20 (b) with BESS

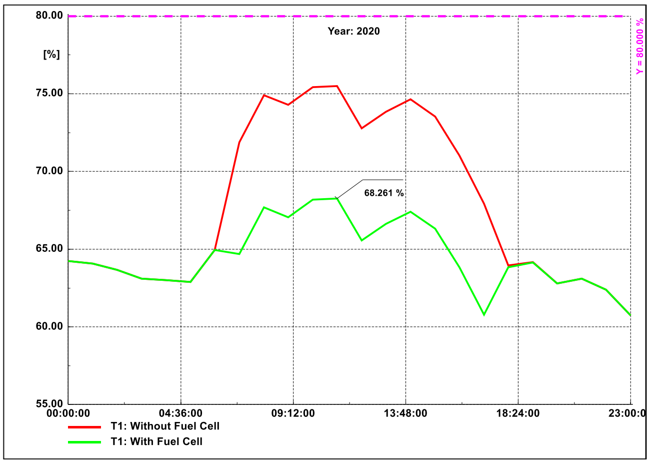


Figure 20 (a) With FC

Similarly, Transformer T2 in Fig.21 below demonstrates how the load is reduced by the hybrid energy storage system. As it can be seen on the graph, between the afternoon (18h00) up until early morning (06h00) the Battery is in charging mode and the electrolysis unit of the Fuel Cell feeds the tank with hydrogen simultaneously, and both at this time are acting as loads, this is to set the two Embedded Generators to be on standby and ready to supply when the load begins to escalate. For T2 that feeds low voltage (LV) loads, the peak demand sinks from 82.4% to 72.3%, and therefore peak shaving is achieved.

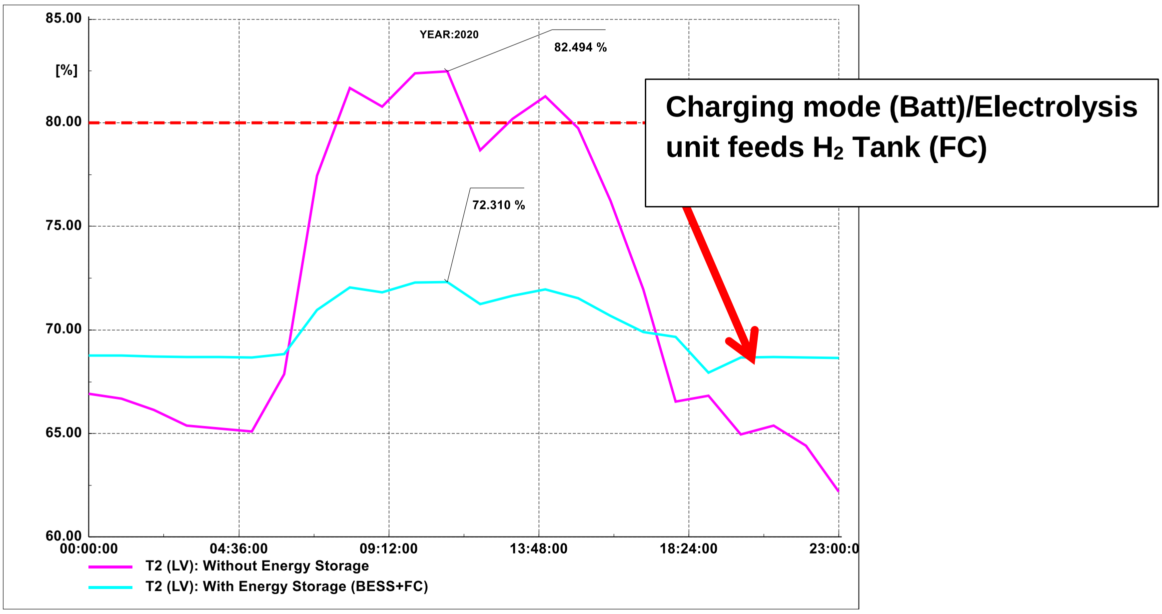


Figure 21: T2 peak shaving through Energy Storage System

Source: Author

5.5.2 Electrical Losses (kW) due to the integration of the ESS

As mentioned previously, the partial peak loads supplied by the transformers is now supplied by the hybrid energy storage system coinciding with peak load times. This as a result reduces the amount of electrical (kW) losses on the line and transformers, provided that the network is relatively strong in terms of adequate fault level which will be discussed in the next following paragraphs.

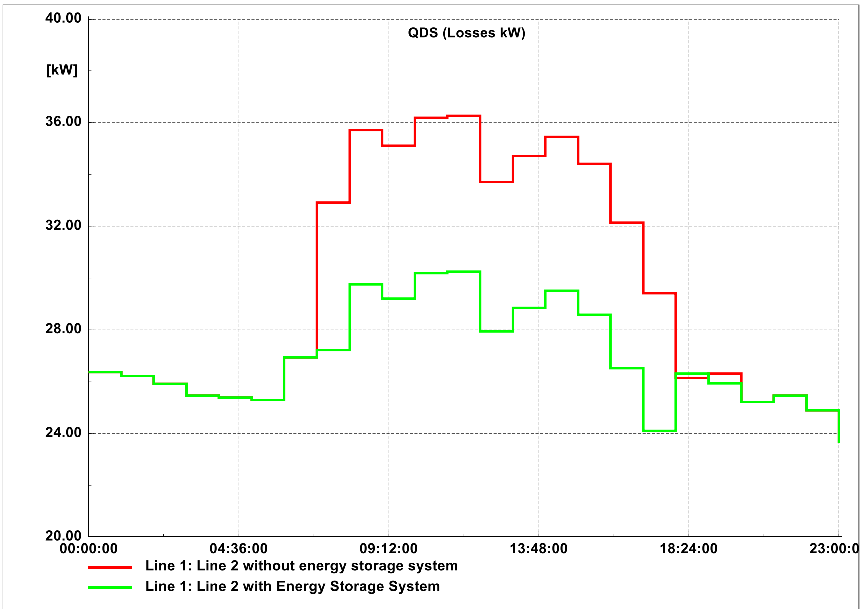


Figure 22: Electrical Line Losses (kW)

Fig.22 above clearly shows the reduction benefit in electrical line losses through incorporating the energy storage system to the distribution network. The line 1&2 losses have been reduced by 16.6% from 36.3kW to 30.2kW.

5.5.3 Network Voltage Profile

The influence of the Distributed Generator voltage magnitude is such that when the voltage angle is zero (i.e. θ=0) and $V_{DG} > V_{Grid}$, the reactive power Q is positive, this is reactive power transferred from the Battery and Fuel cell to the utility distribution grid. The reactive power transfer is also accompanied by the transfer of some active power (Doumbia and Agbossou, 2005).

To analyse the effectiveness of the hybrid energy storage system for an industrial customer connected on a utility distribution in terms of voltage improvement, the Simulation RMS/EMT of Digsilent software is used.

5.5.3.1 Simulation RMS/EMT

Powerfactory provides the stability analyses function (RMS) and electromagnetic transients (EMT) tool to analyse the network transients for mid-term and long-term under both unbalanced and balanced conditions. These transients include switching, temporary over-voltage, inrush currents etc.

For the purpose of this study, as mentioned previously, the tool is used to analyse the voltage behaviour when the energy storage switches online as part of the network. In Fig.23 below are the settings for the RMS/EMT simulation in a flow-chart diagram:

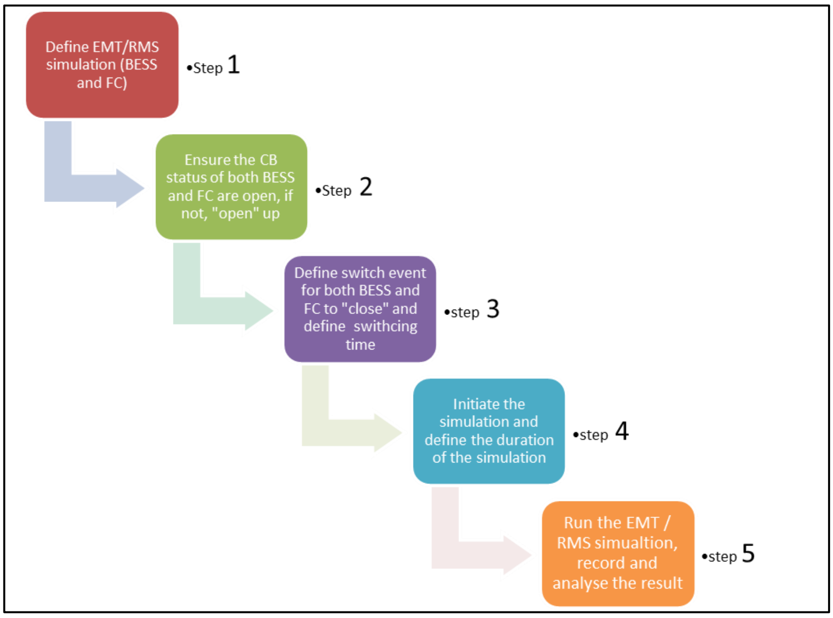


Figure 23: RMS/EMT Simulation setting in flow chart

For the purpose of this study, the execution time is set to 30 minutes (1800s) for the circuit breaker of the BESS and FC to close, and the stop time is set to1h23min (5000s). As tabulated in table 6 of this study, BB3&4 were showing decline in terms of voltage levels, but Fig.24 below shows the voltage improvement on BB3&4 due to the BESS and FC connection to the utility distribution grid, recording 0.99p.u in steady state operation.

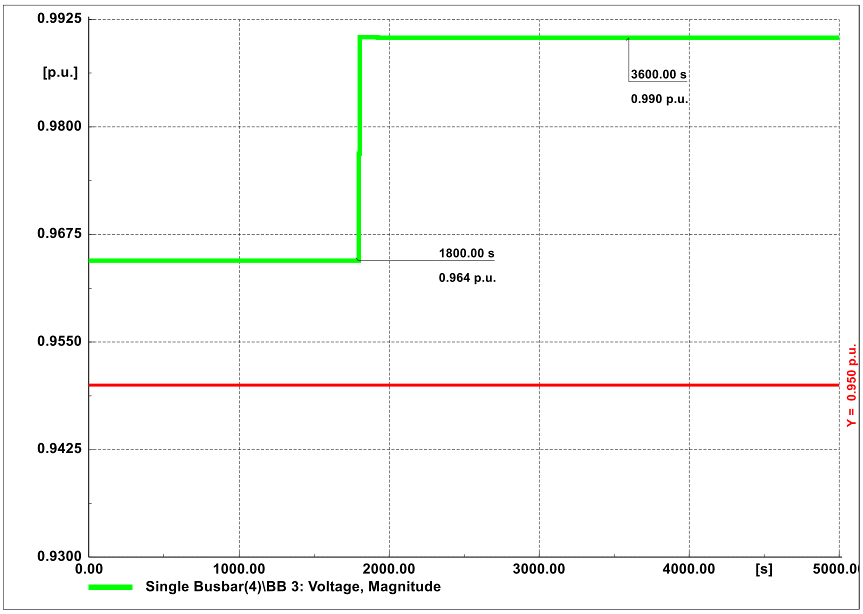


Figure 24: Improved Voltage levels

Source: Author

5.5.4 Rapid Voltage Change (RVC) Limit

Rapid voltage change (RVC) is a phenomenon that is experienced by the power system network when a sudden uncontrolled switching (on/off) of a load /generator occurs (Soni and Songo, 2019). This situation can be expected, when the grid tied battery and fuel cell energy storage system trips unexpectedly.

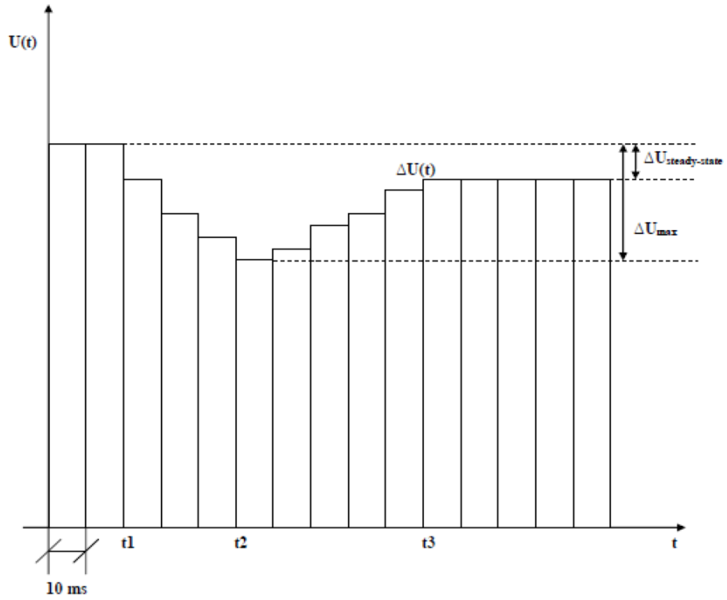


Figure 25: General characteristics for RVC (Jaeger *et al.*, 2013)

With reference to Fig.25 above, RVC can be calculated using Eq. (5.1):

$$RVC = \frac{\Delta U_{max}}{U_{permitted}} \qquad (5.1)$$

Where: ΔU_{max} is the voltage following the event. $U_{permitted}$ is the steady state voltage before the event. Fig.25 also illustrates the steady state voltage which is the voltage after the network has acted to self-correct the voltage.

Various studies were undertaken to investigate the allowable RVC limit at the Point of Coupling (POC) and some of the findings are tabulated below:

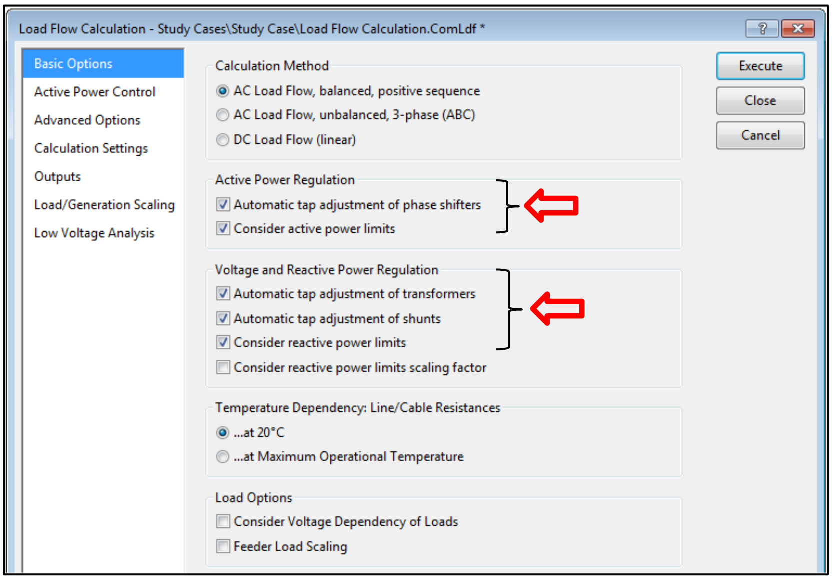
Table 7: Rapid Voltage Change limits

Research Institute	Bases	Installation	RVC Limit
Norwegian Energy Regulator(Jaeger *et al.*, 2013)	<24 times/day	MV	≥5%
EPRI Report(EPRI, 2010)		MV and LV	5%
Eskom Standard(Dedekind, 2019)		MV	5%
Draft BESF Grid Code(RSA Grid Code Secretariat, 2014)		HV/MV/LV	Use own discretion on a safe RVC limit
NRS048-2(AJ *et al.*, 2007) and NRS048-4(NRS, 1999)	For less than 1-1000 events per hour	MV and LV	4%

Source: Author

As seen in table 7 above, there different research based opinion with regards to the rapid voltage change (RVC) limits. Therefore, this study, as a guideline, will adopt the RVC limit proposed by Electric Power Research Institute (EPRI) and Network and Grid Planning Eskom standard respectively.

To test for RVC, this study uses the Digsilent simulation software to simulate the BESS and FC discharging at their peak ratings with corresponding minimum leading power factor under load-flow tab. All the automatic tap adjustment of transformers and shunts are activated.



The measured voltages at the PoC and surrounding nodes are recorded in table 8.

The database in Powerfactory with transformers and shun taps is also activated as follows:

De-select “P, Q of Loads”

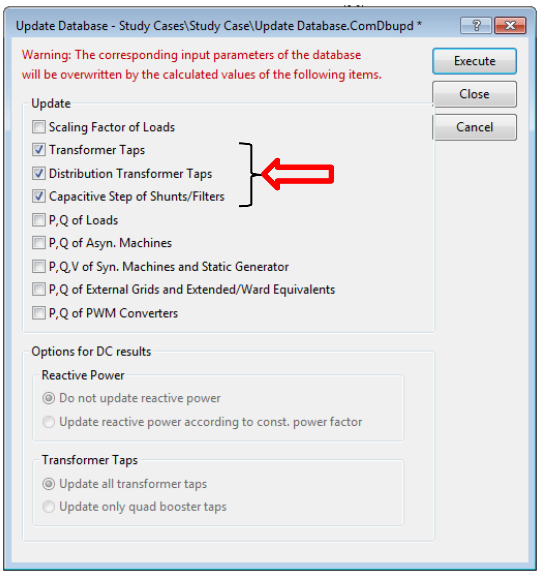


Table 8: Point of Coupling voltages before and after abrupt switching

Nodes/PoC	$V_{before\ abrupt}$(p.u)	$V_{after\ abrupt}$(p.u)	RVC (%)
BB 2	0.981	0.977	0.4
BB 3	0.972	0.966	0.6
BB 4	0.967	0.961	0.6
BB 5	1.041	1.041	0.7

Source: Author

The next step is to switch off the BESS and FC, de-activate automatic tap adjustment of transformers and shunts, re-run a static load flow simulation and measure the voltage at the PoC and surrounding nodes. The difference in voltage level between the normal operation and abrupt switching out of the BESS and FC should not be more than the defined RVC limit specified in (EPRI, 2010) and (Dedekind, 2019). According to table 8 above, there is no violation incurred.

5.5.5 Load and Generation Rejection (LGR)

This study is carried out as a precaution to ensure that at any instance whenever the BESS and FC are abruptly disconnected from the network during their peak operation state, that no significant over or under-voltage scenario (steady-state) occurs resulting in insulation breakdown of equipment.

This study follows the same approach when assessing the RVC limit. Therefore, the results are extracted (in Table 8) during the studies done in the previous study of Rapid Voltage Change limit. The study shows that there are no violations incurred and that all equipment will work under safe voltage operating limits.

5.5.6 Fault level analysis

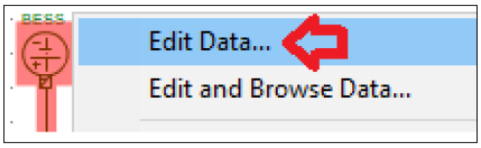
Fundamentally, the fault level philosophy ensures that no equipment is subjected to fault level higher than the manufacturers rating of the equipment. This is to ensure that no equipment is stressed beyond its limit.

Moreover, this is to ensure adequate network fault levels are maintained to ensure adequate power quality. Furthermore, sufficient fault levels are required for the correct operation of protective devices to safeguard against electrical faults. Too low fault levels will create grading difficulties for the protection settings as the differentiation between fault current and load current may be too close to each other.

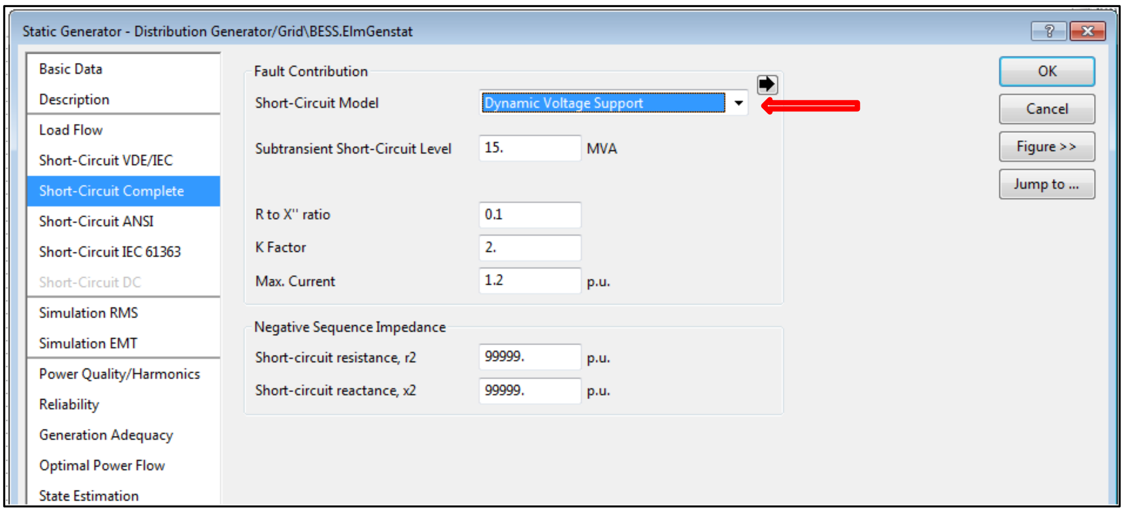
Fault level is also important to maintain network stability as it reflects the extent to which the system impedance can absorb a disturbance without resulting in an undesirable oscillation. The fault level of a network becomes an important factor when considering power quality aspects especially when considering the effect of the installation of an Energy Storage System (ESS) on the distribution network.

The power electronics devices such as the PWM-converter are not considered by the IEC60909/VDE0102 norm and therefore short circuit calculation is not possible with BESS and FC. However, PowerFactory offers the possibility to calculate a short circuit using the "complete" method, see snap shot below. The complete method takes the load flow into account (DIgSILENT GmbH, 2010).

To perform the fault level study, the BESS/FC static generator model is utilised:



Setting up the "*complete method*" short circuit parameters for the model;



Subtransient Short-Circuit Level is the inverter plant rating expressed as an MVA value.

R to *X* ratio is the impedance ratio used for fully rated converter plants (typical 0.1)

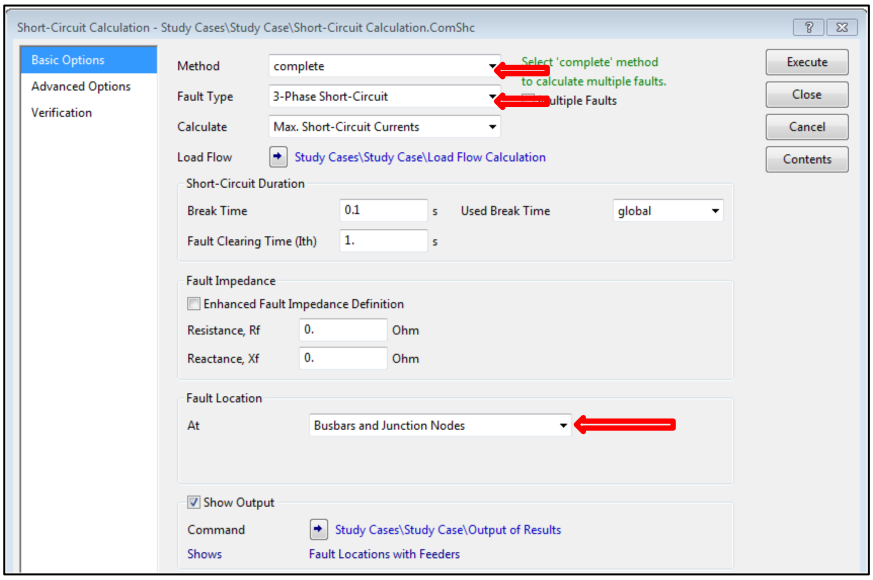
K Factor is the maximum amount of reactive current that can be injected into the grid during a fault to support the voltage.

Max Current is the fault current contribution from the inverter plant (1.2p.u as a worst case scenario).

Negative Sequence Impedance short-circuit components are not applicable for inverter based technologies, therefore are kept at the default value of 99999.

For the purpose of this study, short-circuit calculation are performed only at the MV busbars and terminal in the casefile.

The fault location is set to busbars and junction nodes. This fault level study is performed under maximum loading conditions with contingencies to asses against the worst case fault level scenario.



A detailed report of the output results is attached as Appendix 9 of the Appendices page of this study. As stated previously, the fault level calculation focused mainly on the busbars connecting the MV network of the casefile (BB2, BB3, and BB4), in the graph below is the total fault levels of all elements connected to the respective busbars.

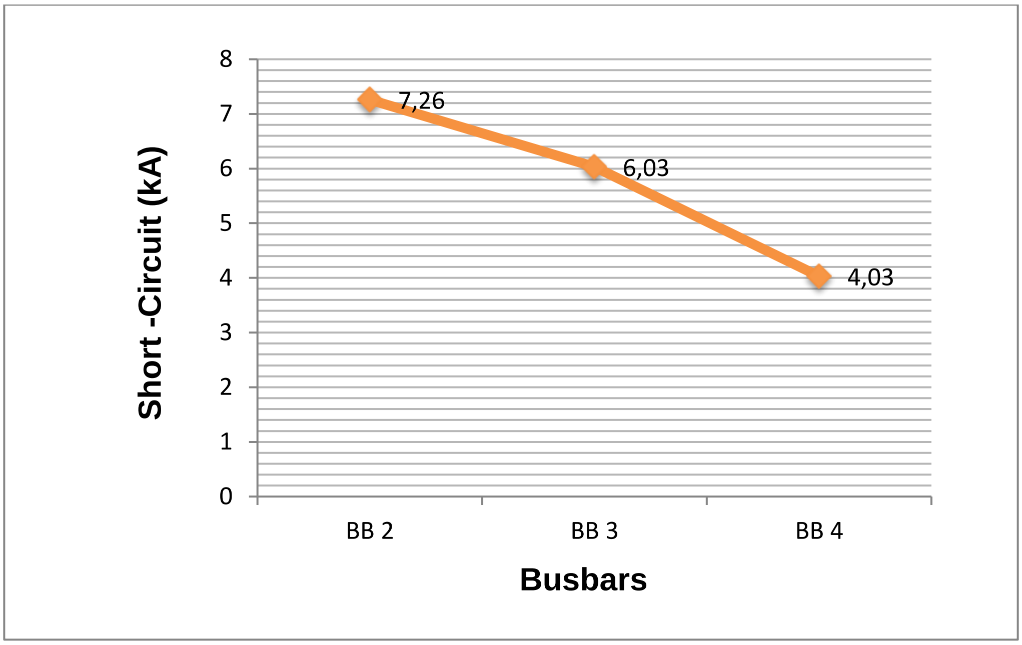


Figure 26: Short-Circuit output Results

Source: Author

As seen in Fig.26 above as the busbars are located far from the main source, the fault levels decreases. Busbar 4 is the furthest from the main supply and only one load connected to it, hence short circuit levels have dropped by 33%. Busbar 3 has dropped by 16.9% from Busbar 2. The fault levels indicate that all equipment assessed will not be stressed beyond their carrying capacity.

5.6 Economic Feasibility Analysis results in HOMER

For the purpose of this study, as it has been stated earlier in Chapter One, HOMER will be solely used for the economic evaluation point of view. However, it is imperative for any power generating system to consider its load. The average energy consumption considered scaling the loads and the scale peak loads are shown in Table 9 & 10. The daily average load profiles are also shown as Fig.27 (a) MV Load #1and (b) MV Load #2.

Table 9: MV Load #1

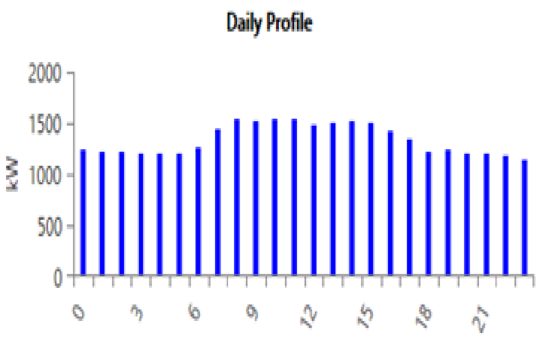
Metric	Baseline	Scaled
Average (kWh/day)	32,061	24,000
Average (kW)	1,335.8	1,000
Peak (kW)	2,694.9	2,017.3
Load Factor	0.50	0.50

Source: Author

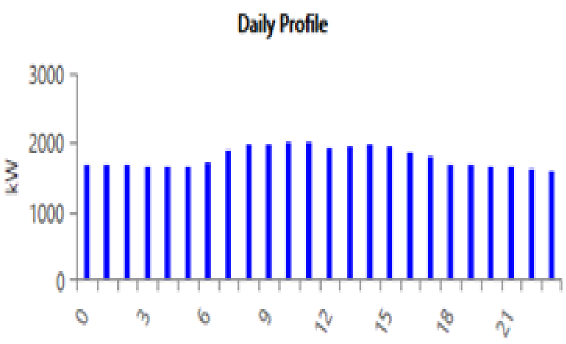
Table 10: MV Load #2

Metric	Baseline	Scaled
Average (kWh/day)	42,861	24,000
Average (kW)	1,785.8	1,000
Peak (kW)	3,503.4	1,961.7
Load factor	0.51	0.51

Source: Author



(a) MV Load # 1



(b) MV Load # 2

Figure 27: Load Profiles

5.6.1 HOMER Model

In this present study, the selection and sizing of components of hybrid power system has been done using National Renewable Energy Laboratory, NREL's HOMER software which are extracted from the work of (Rohani, Mazlumi and Kord, 2010). The following are the input information to be inserted in HOMER software: electrical loads, component technical details, and costs, dispatch strategy, economics, etc. in Fig.28, is the proposed system configuration in HOMER.

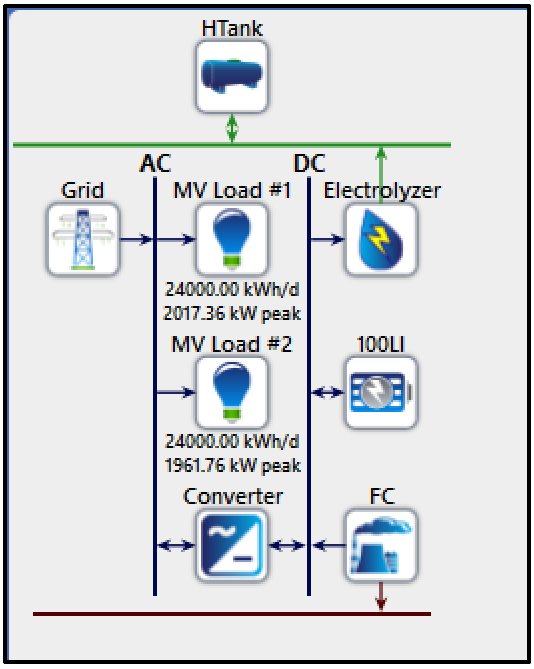


Figure 28: proposed system architecture in HOMER

In this work, the nominal discount rate considered is 6. The expected inflation rate was set to match that of the SA inflation rate currently recording 4.12. The project lifetime considered is 25 years. The currency is in South African Rand (R).

5.6.2 HOMER Results

Each component in the system has its own direct effect on the system's cost. However, the distribution grid record the highest total cost value of R33, 995, 958.96 (US$2.056million), this is mainly associated with the operation and maintenance activities. The high cost associated with the Fuel Cell component is because of the commercial status, as the newly commercialised technology, FC still needs to gain public acceptance as a safe and dependable technology. The Levelised Cost of Energy (LCOE), Net Present Cost (NPC) and Operating

Cost are R0.1055 (US$0.0064), R36, 936, 360.00(US$2,234million) and R1, 789, 352.00 (US$108,233) respectively. Fig.28 presents the cost of the system elements.

Component	Capital (R)	Replacement (R)	O&M (R)	Fuel (R)	Salvage (R)	Total (R)
Distribution Grid	R0.00	R0.00	R34,995,958.96	R0.00	R0.00	R34,995,958.96
Generic Li-Ion	R133,000.00	R92,985.99	R25,303.47	R0.00	-R63,770.56	R187,518.90
Generic Electrolyzer	R250,000.00	R114,687.39	R998,821.22	R0.00	-R31,965.20	R1,331,543.42
Generic Fuel Cell	R750,000.00	R0.00	R0.00	R0.00	-R389,575.81	R360,424.19
Hydrogen Tank	R50,000.00	R0.00	R0.00	R0.00	R0.00	R50,000.00
System Converter	R8,513.44	R3,254.61	R56.69	R0.00	-R907.11	R10,917.63
System	R1,191,513.44	R210,927.99	R36,020,140.34	R0.00	-R486,218.69	R36,936,363.09

Figure 29: Summarised system costs

Fig.29 shows that the system's capital cost evaluated at R1, 191, 513.44 (US$72,071), representing the cost associated with each component. But over the 25 years of the project lifetime the O&M cost are inevitable and evaluated at R36, 020, 140.34 (US$2.178million), while some components such as the electrolyser, system converter, and lithium ion batteries will be replaced at a value of R210, 927.99 (US$12,758) between 10-15 years. The salvage for the system is evaluated at R486, 218.69 (US$29,410) of which is financially sound as technology prices are expected to decline throughout the years.

The breakdown cost analysis of the configuration is presented in Pie chart format as seen in Fig.30. The Electrolyser is in the lead, holding nearly 68% of the total cost and the system converter coming last by only claiming 0.56% of the total cost. This excludes O&M grid cost.

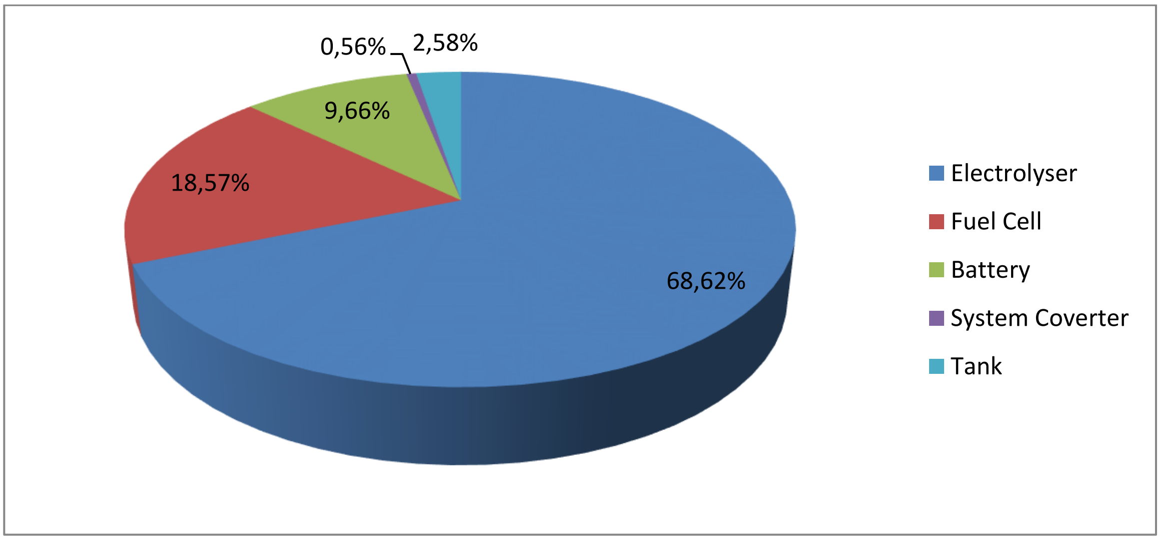


Figure 30: Breakdown of Cost Analysis of Configuration

CHAPTER SIX
CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

This thesis work investigated the value of energy storage system for an industrial customer connected to the utility distribution network. The energy storage system considered for this research was the Battery Energy Storage System (BESS), Lithium-ion being the type of interest connected in parallel with the Fuel Cell Storage System (FC), PEM being the type of interest. The energy storage system achieved the energy reliability and security requirements by the customer by maintaining the voltage levels at the permissible limits and showed minimal impact on the environment through the reduction of greenhouse emissions, and quietness, and cutting the load during peaking demand period.

Chapter two discusses the different types of Energy Storage Systems (ESS). Firstly, the Fuel Cell technology was extensively researched and discussed separately from the other energy storage systems. Fuel cells offer pleasing benefits of low to zero emissions, high efficiency, reliability, fuel flexibility, energy security, durability, and quiet operation. Moreover, fuel cells can be conveniently placed near consumer site, thus reducing losses and cost.

The review briefly explained the different types of ESS, their basic operation principles, and their applications. However, the literature review extensively discussed the Battery Energy Storage System, the preferred solution. The interesting functions of the BESS are voltage regulation, emergency back-up, power quality, and peak shaving.

Chapter three was dedicated to the description of the energy storage network components, clearly defining the type of customer, outlining the behaviour of the system and subsystem components.

Chapter four presented the network modelling using two simulation software packages, namely, Digsilent PowerFactory for Technical Analysis (TA) and HOMER for Economic Analysis (EA).

6.1.1 Quasi-Dynamic Simulation Language (QDSL)

The study used the Quasi-Dynamic Simulation Language (QDSL) to model the network. This programmable logic enables the user to define how the energy storage system operates, including setting limits and measurements that get calculated autonomously. Quasi-Dynamic Simulation was coded to determine when the BESS and FC should charge and discharge. This was successfully achieved through the QDS plot/graphs showing Peak Shaving of the load, improvement of the voltage magnitude, and reduced electrical losses.

6.1.2 Hybrid Optimisation of Multiple Energy Resource (HOMER)

In this study HOMER software was strictly used to perform Economical Analysis of the Energy Storage System (ESS) interlinked with the utility distribution network. Since the industrial customer understudy is connected to the utility distribution grid, HOMER results revealed extremely high O&M cost margin with respect to the grid. In spite of that, the system's cost is financially feasible. The software found the NPC value to be R36, 936, 360.00(US$2,234million), the LCOE was R0.1055 (US$0.0064), and the Operating cost was R1, 789, 352.00 (US$108,233) respectively.

6.2 Recommendation for future research

This study embarked on a journey to evaluate the value of energy storage for an industrial customer connected on a Utility Distribution Network. The study showed how this reduces the over loading of equipment, reduces electrical losses, improves voltages, etc.

Therefore, this dissertation recommends that for future research; evaluate how the energy storage system connected in the similar manner can appreciably;

- Improve or control Frequency
- Eliminate or influence harmonics
- Improve Power quality
- Operate Off-Grid (Islanded) completely

6.3 Publications Related to the Dissertation

Koni X and Kahn MTE, "The value of energy storage for an industrial customer on a utility distribution network", AIUE Proceedings of the IET on CAMPUS Industrial and Commercial Use of Energy Conference 2020, 25 November 2020, pp 35, 39, 56

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APPENDICES

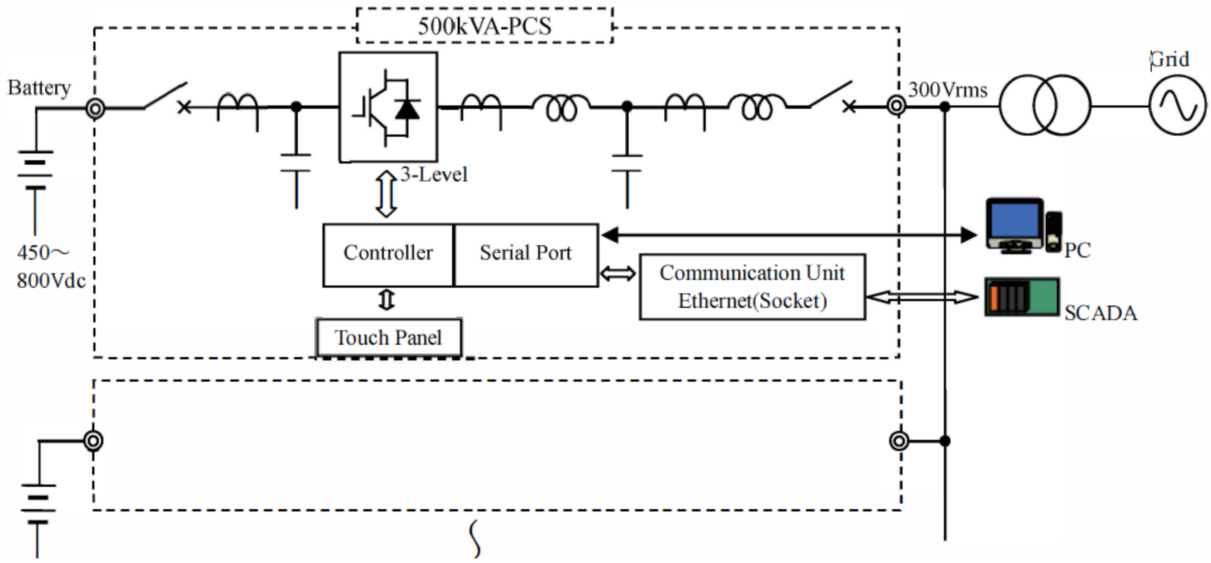
Appendix 1: Battery Energy Storage Technologies Comparison

Technology Type	Maturity Level	Risks/Barriers	Disadvantages	Advantages	Best Suited Applications **
Lead-Acid Battery	Mature	➢ Environmental consideration	➢ low cycle life and DoD ➢ Deteriorates with micro cycles ➢ limited lifetime	➢ Very mature technology ➢ Low capital cost	CEMS
Advanced Lead Acid Battery	Mature	➢ Environmental consideration	➢ Low cycle life and limited DoD	➢ Better performance than lead-acid ➢ Capital cost relatively low	AS, GIS, CEMS
Nickel-Cadmium Battery	Mature	➢ Environmental - toxic cadmium	➢ Low cycle life ➢ Exhibits memory effect ➢ low energy-to-weight ➢ Relatively expensive	➢ Few maintenance requirements ➢ Can operate in low temperatures	CEMS
Sodium Sulfur Battery	Mature	➢ Safety - containment issues ➢ Competition from other technologies	➢ limited cycle life ➢ requires external heat system ➢ high temperature system ➢ large daily self-discharge	➢ high power and energy density ➢ Longer discharge times than Li-ion	BES, AS, GIS, CEMS
Pumped Hydro storage	Mature	➢ Environmental consideration	➢ Geographical limits ➢ High capital costs	➢ Reliable bulk storage	BES
Lithium Iron Phosphate	Commercial	➢ Safety ➢ More expensive than lead acid	➢ Lower energy density	➢ Increased safety ➢ Longer cycle life	BES, AS, GIS, CEMS
Lithium Ion Battery	Commercial	➢ Safety - thermal runaway ➢ More expensive than Lead-Acid	➢ limited but improving cycle life ➢ Deep discharge cycles lower lifetime ➢ Requires monitoring / BMS	➢ high round trip efficiency ➢ high energy-to-weight ratio ➢ continuing performance improvements ➢ continuing manufacturing cost reductions	BES, AS, GIS, CEMS
Sodium Nickel Chloride	Commercial	➢ Competition from other technologies	➢ Large daily self-discharge ➢ high temperature system	➢ Able to operate in relatively harsh climates	CEMS
Vanadium Redox Flow	Commercial	➢ New at utility scale ➢ Rx stack membrane degradation	➢ lower round trip efficiency ➢ low energy density ➢ requires mechanical systems ➢ high cost of Vanadium	➢ Power and energy scale independently ➢ Mature for a flow technology ➢ Vanadium is a local resource ➢ high cycle life, full DoD	BES, AS, GIS, CEMS

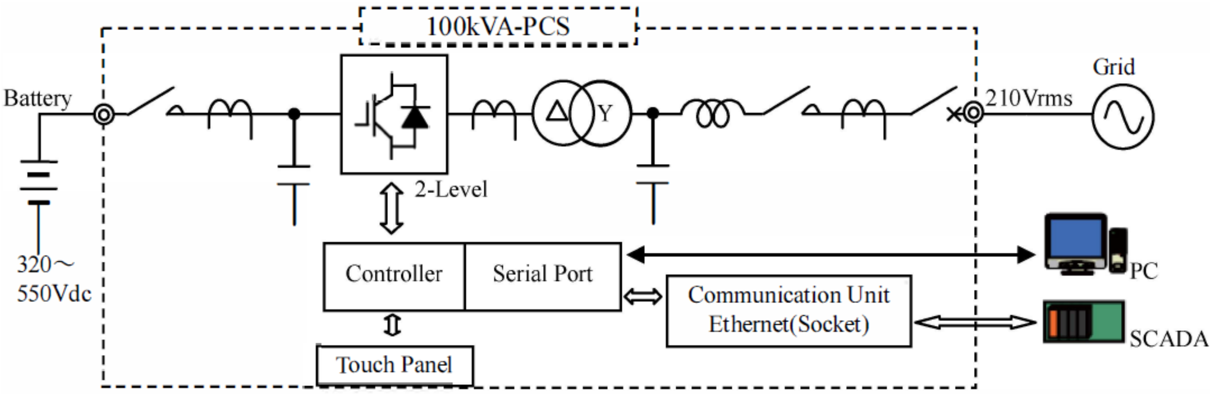
Appendix 2: High level comparison of battery energy storage

Technology	Maturity	Risks/Barriers	Disadvantages	Advantages	Best Applications **	Future potential for SA utility-scale energy storage
Lead-Acid Battery	mature	environmental consideration	• low cycle life and DoD • Deteriorates with microcycles • limited lifetime	• Very mature technology • Low capital cost	**CEMS**	none
Advanced Lead Acid Battery	mature	environmental consideration	Low cycle life and limited DoD	• Better performance than lead-acid • Capital cost relatively low	**AS, GIS, CEMS**	Moderate-, near-, to mid-term
Nickel-Cadmium Battery	mature	environmental - toxic cadmium	• Low cycle life • Exhibits memory effect • low energy-to-weight • Relatively expensive	• Few maintenance requirements • Can operate in low temperatures	CEMS	none
Lithium Ion Battery (chemistry dependent)	commercial	• Safety - thermal runaway • More expensive than Lead-Acid	• limited but improving cycle life • Deep discharge cycles lower lifetime • Requires monitoring / BMS	• high round trip efficiency • high energy-to-weight ratio • continuing performance improvements • continuing manufacturing cost reductions	**BES, AS,** GIS, **CEMS**	Significant near- to long-term
Sodium Sulfur Battery	mature	• Safety - containment issues • Competition from other technologies	• limited cycle life • requires external heat system • high temperature system • large daily self-discharge	• high power and energy density • Longer discharge times than Li-ion	**BES, AS, GIS,** CEMS	Moderate near-term
Sodium Nickel Chloride	commercial	Competition from other technologies	Large daily self-discharge	Able to operate in relatively harsh climates	CEMS	limited
Vanadium Redox Flow	demo	• Not proven at utility scale • Rx stack membrane degradation	• lower round trip efficiency • low energy density • requires mechanical systems • high cost of Vanadium	• Power and energy scale independently • Mature for a flow technology • Vanadium is a SA resource • high cycle life, full DoD	**BES, AS, GIS, CEMS**	Significant now & long term
Iron-Chromium Flow	demo	• Not proven at utility scale • Toxicity of Chromium • Less mature than other flow batteries	• lower round trip efficiency • low energy density • requires mechanical systems	• Power and energy scale independently • small daily self-discharge • high cycle life, full DoD	**BES, AS, GIS, CEMS**	Moderate mid- to possibly long-term

Appendix 3: 500kVA-PCS system configuration



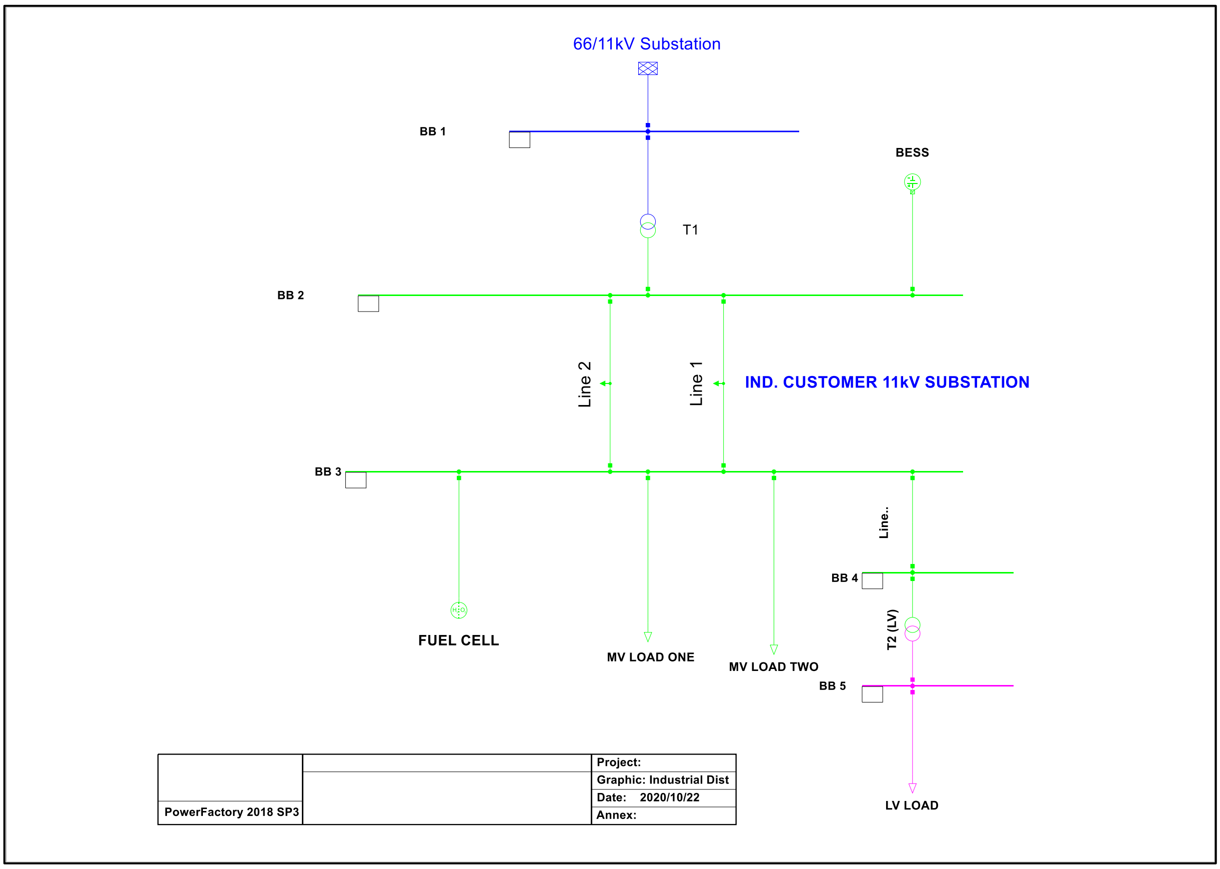
Appendix 4:100kVA-PCS system configuration



Appendix 5: Outline of 500kVA-PCS (a) and 100kVA-PCS (b)

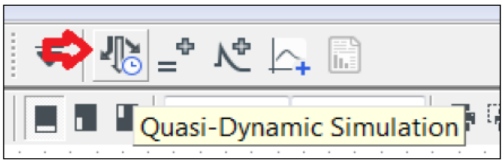
(a) (b)

Appendix 6: 66/11kv Substation Overview in Digsilent

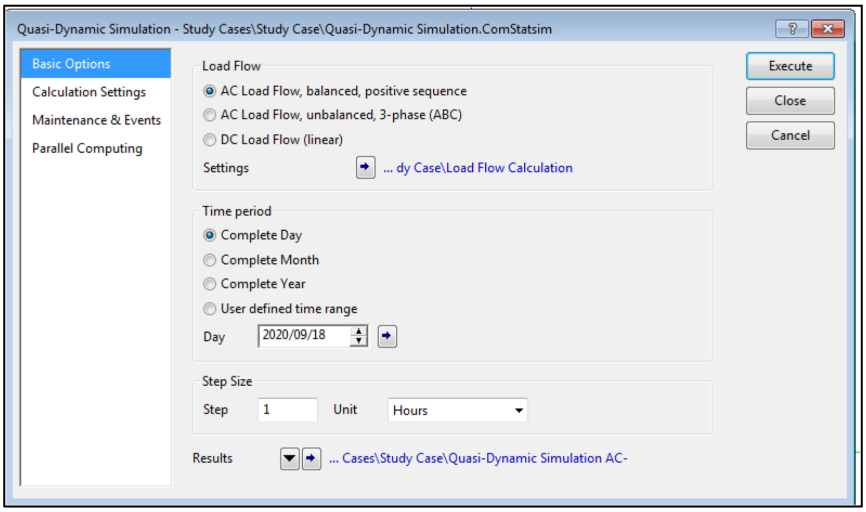


Appendix 7 Quasi-Dynamic Simulation Load Flow

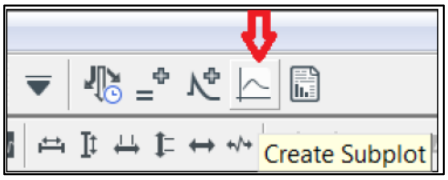
Once the model is setup, the next step is analysing the network for any constraints (Current or future). This is done by selecting the quasi-dynamic load-flow button shown below:



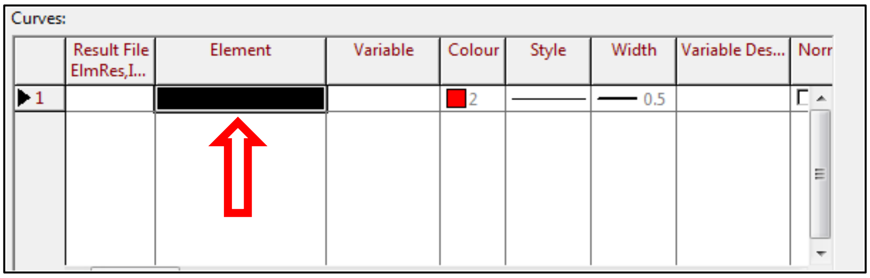
Once prompted with a screen as shown below, it is important to ensure that the load flow calculation settings are populated correctly. To speed up the simulation in PowerFactory, the use of the parallel computing capability is recommended.



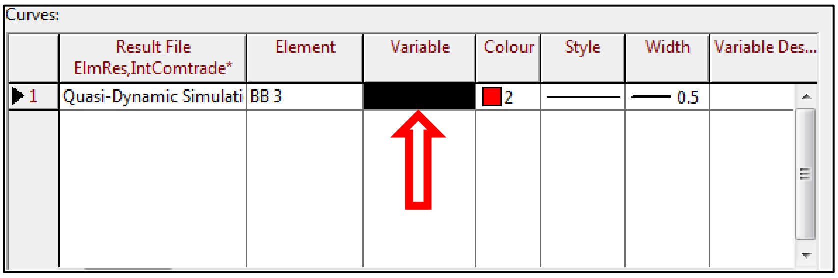
Once the QDS is completed, this allows for the population of graphs (plots) to visualize or export the results. “Create subplot” button under the quasi-dynamic simulation pane is available to create a plot. See below:



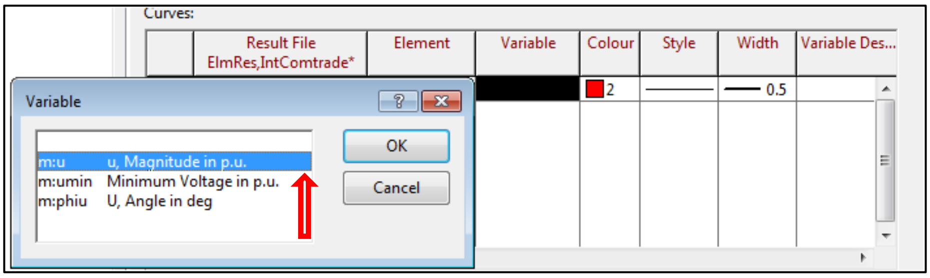
Select the element(s) (see appendix 4.5) from the result variable list by double-clicking on the element block as shown below: it is also possible to select multiple elements from the list at the same time.



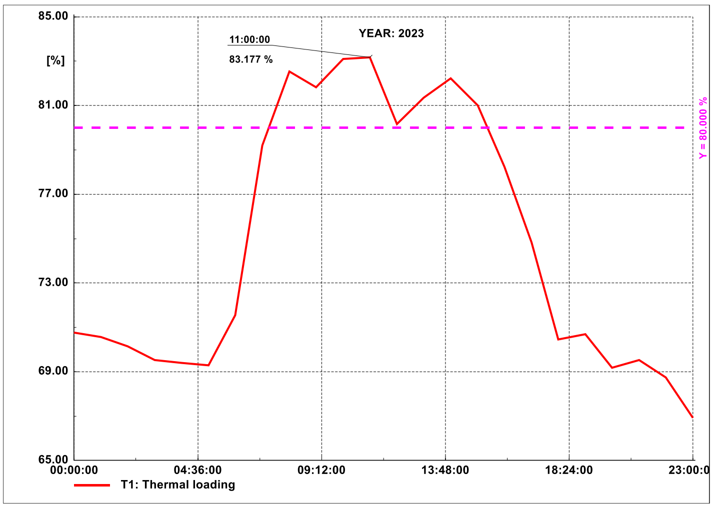
Select the variable to display for the element(s) by double-clicking on the variable block, see below:

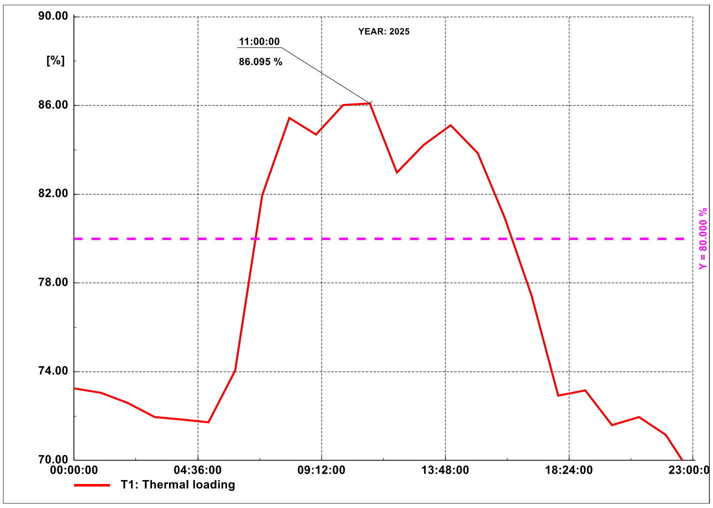


Once variable is selected, the edited variable list discussed in chapter 5.3 of this document will show up for selection. Click any desired variable as shown below in appendix 4.6 and a plot shall appear.



Appendix 8: T1 Thermal Loading in 2023 and 2025





Appendix 9: Fault Levels Output Results for the MV Network

```
|                  |                                                                    |   DIgSILENT   | Project:                  |
|                  |                                                                    | PowerFactory  |---------------------------
|                  |                                                                    |   2018 SP3    | Date:  2020/10/09         |
----------------------------------------------------------------------------------------------------------------------------------
| Fault Locations with Feeders                                                                                                   |
| Short-Circuit Calculation / Method : complete                         3-Phase Short-Circuit    / Max. Short-Circuit Currents |
----------------------------------------------------------------------------------------------------------------------------------
| Short-Circuit Duration                   | Fault Impedance                    |                                              |
|    Break Time                  0.10 s |     Resistance, Rf          0.00 Ohm |                                              |
|    Fault Clearing Time (Ith)   1.00 s |     Reactance, Xf           0.00 Ohm |                                              |
----------------------------------------------------------------------------------------------------------------------------------
| Grid: Distribution Generat System Stage: Distribution Ge |                                         | Annex:           / 1      |
----------------------------------------------------------------------------------------------------------------------------------
|                      rtd.V.   Voltage      c-      Sk"          Ik"            Ik'        ip       Ib      ib      Ith |
|                       [kV]    [kV]   [deg] Factor   [MVA]      [kA]    [deg]   [kA]  [deg]   [kA]     [kA]    [kA]    [kA]|
----------------------------------------------------------------------------------------------------------------------------------
|Single Busbar(3)                                                                                                                |
|  BB 2               11.00    0.00    0.00  1.00   138.38 MVA  7.26 kA -117.4   7.56 -118.8  19.00 kA   7.54   12.91    7.48 |
|    Line 1           Single Bus                      7.20 MVA  0.38 kA   62.8   0.45   57.5   0.99 kA                        |
|    Line 2           Single Bus                      7.20 MVA  0.38 kA   62.8   0.45   57.5   0.99 kA                        |
|    T1               Single Bus                    108.99 MVA  5.72 kA   62.5   5.72   62.5  14.96 kA                        |
|    BESS                                            15.00 MVA  0.79 kA -117.3   0.94 -123.0   2.06 kA                        |
|                                                                                                                                |
|Single Busbar(4)                                                                                                                |
|  BB 3               11.00    0.00    0.00  1.00   114.88 MVA  6.03 kA -111.4   6.28 -112.8  13.83 kA   6.26    8.93    6.09 |
|    Line 1           Single Bus                     49.99 MVA  2.62 kA   69.5   2.68   69.0   6.02 kA                        |
|    Line 2           Single Bus                     49.99 MVA  2.62 kA   69.5   2.68   69.0   6.02 kA                        |
|    Line 3           Single Bus                      0.00 MVA  0.00 kA    0.0   0.00    0.0   0.00 kA                        |
|    FUEL CELL                                       15.00 MVA  0.79 kA -117.7   0.94 -123.4   1.81 kA                        |
|    MV LOAD ONE                                      0.00 MVA  0.00 kA    0.0   0.00    0.0   0.00 kA                        |
|    MV LOAD TWO                                      0.00 MVA  0.00 kA    0.0   0.00    0.0   0.00 kA                        |
|                                                                                                                                |
|Single Busbar(5)                                                                                                                |
|  BB 4               11.00    0.00    0.00  1.00    76.87 MVA  4.03 kA -103.0   4.15 -103.7   7.92 kA   4.14    5.86    4.06 |
|    Line 3           Single Bus                     76.87 MVA  4.03 kA   77.0   4.15   76.3   7.92 kA                        |
|    T2 (LV)          Single Bus                      0.00 MVA  0.00 kA    0.0   0.00    0.0   0.00 kA                        |
```