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ENHANCEMENT OF POWER TRANSFER CAPACITY IN BIPOLAR HVDC SYSTEM

by

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DECLARATION

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

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ABSTRACT

Economic growth that leads to sustained increase in electricity demand resulted into extension of AC systems. This is due to the correlation between the increase in population and power consumption. It was anticipated that by now the power consumption in developing and emerging countries is expected to have increased by 220%.when such happens the power system will be experiencing problems of uncontrolled loop-flows, overloading and excess of short circuit levels, system instabilities and outages. In order to ensure the continuity of supply, power system enhancement and interconnections needs to have been in place in a form of higher voltage levels, new transmission technologies and renewable energies.

As anticipated, power consumption increased to the point where power systems are constrained. The purpose of the study is to enhance the inherent power transmission capacity of the overhead lines on the overloaded existing sub-transmission and distribution networks. FACTS have been developed with the aim to better load flow and voltage control. However the devices help in increasing transport capacity, in avoiding loop power flows, in improving transient and dynamic stability etc but do not increase the inherent transmission capacity of a line. Point-to-point VSC-based HVDC transmission was used as an alternative to upgrade the existing right of way corridors. This was achieved by transformation of an existing AC line with a DC one, making maximum use of conductors and towers with up to 4 times transfer capacity increase.

The studies were modelled in the software tool Digsilent Power Factory. Three scenarios were simulated under short circuit and contingency conditions where voltage was being monitored on the bursars and the capacity together with overloading were monitored on the HV lines of substations. In chapter one, the background objectives and significance of the study are presented followed by the insight on to classic HVDC transmission networks in chapter two. This matured technology was studied to trace the increased potential of HVDC applications. VSC-based converters are presented in chapter three. Amongst others, the dynamic voltage support, the system stability and the higher power transfer capacity offered by VSC based converters were the most beneficial pertaining to this thesis. Due to challenges encountered in acquiring the land for new electricity infrastructure. It has been noted that urban electrical system require easy solutions that can be attained within urban boundaries and shot lead times.as a consequence the replacement/conversion of existing AC overhead lines with DC is presented in chapter four. Among the system instability problems encountered on the network at study, Voltage instability was a key issue to be addressed and chapter five presents categories of voltage stability and mitigations thereof.

In chapter six the modelling and simulation of the existing AC network to underpin the problem statement for different contingencies is presented. The results are recorded so that they can be compared to results obtained after VSC-HVDC link incorporation. Chapter seven touches on the modelling of VSC-HVDC link on Digsilent Power Factory. Following in chapter eight are the busbar voltage and the loading results after VSC-HVDC incorporation. It was evident that VSC-HVDC incorporation mitigated low voltage and overloading problems in the network. A concluding statement was reached to say the dynamic support of the AC voltage at each converter terminal improved the voltage stability while the transfer capability of the sending and receiving end AC system was improved.

ACKNOWLEDGEMENTS

I wish to thank:

- Dr Raji, I can never thank you enough for endless support and supervision, you kept me moving even under extremely difficult times. Your words of encouragement did not fall on to dry land; I am where I am because of you.
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GLOSSARY

Abbreviations	**Definition**
AC	Alternating Current
CSC	Current Source Converter
DC	Direct Current
FACTS	Flexible AC transmission system
GTO	Gate Turn-Off Thyristor
GW	Giga Watt
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
HV	High Voltage
IGBT	Insulated-gate bipolar Transistor
LCC	Line-Commutated Converter
LV	Low voltage
MMC	Modular multilevel converter
MV	Medium voltage
OPWM	Optimum Pulse Width Modulation
PCC	Point of common coupling
PLL	Phase-locked-loop
PWM	Pulse Width Modulation
ROW	Right of Way
THD	Total Harmonic Distortion
VSC	Voltage source converter
XLPE	Cross-linked polyethylene

DEDICATION

CHAPTER ONE: INTRODUCTION

1.1 Background

In pursuit of providing electricity for all, The network Planners has noticed certain specific scenarios where conventional high voltage (HV) AC networks may not be most convenient, practical or techno-economically justifiable for the loads that may need to be supplied. Limited funds for financing new investments have triggered the need to seek alternative solutions using the existing infrastructure. High voltage direct current (HVDC) is considered in such applications. Today, DC transmission technology is primarily focused on long-distance high-voltage DC (HVDC) transmission systems, industrial distribution, and electric drives. However, technical and economic developments during the last decade, especially in power electronics technology, have given the opportunity to achieve higher power transfers with improved voltage stability in weak AC systems.

1.2 Research Statement

As per the Group Technology roadmap there is a need to start investigating the possibility for VSC-HVDC integration for network capacity enhancement and renewable energy applications. HVDC networks may be superimposed on existing portion of rural and urban HVAC network. The selected portion of a network will be modelled and simulated on DigSilent Power Factory to evaluate the technical feasibility, power transfer capacity enhancement, Stability, security and quality. Such scenario will be applied in Piketburg area where the existing AC rural network experiences low voltages, overloading and reliability problems. The results will be used to verify voltage elevation as well as spare capacity on the modelled network. Furthermore the results will be analysed to see whether the VSC-HVDC is a durable solution to the existing problem.

The aging of sub-transmission network and the consequent need for replacement offers an opportunity for implementing new solutions in which energy efficiency; reliability and power quality are improved. The developed models of the HVDC power transmission system could take advantage of such opportunities.

1.3 Objectives

The main objectives of the project are:

- To provide a techno-economic alternative for HVAC networks.
- To enhance the power capacity through HVDC
- Boost voltage levels on rural feeders.
- Evaluate and confirm feasibility of HVDC distribution network.
- To provide sustainable electricity solutions to grow South African economy.
- To improve power quality.

1.4 Motivation

Eskom embarked in a strategic initiative aiming to increase the competence and availability of engineering specialists. This research will provide an In-house expertise thereby cutting cost of outsourcing the required skill. Also contributes to hosting and developing intellectual property for the improvement of Eskom’s long-term business and more generally contribute to the development of the South African economy.

Upon completion, the research must provide answers in such a manner that it resolves current operational issues at Master – Dilly 66kV line Soutfontein leg. Possibility of Increased power accessibility in rural communities at low costs may be realised. A scenario exists in the Western Cape operation unit where AC networks may not be most convenient. Similar cases may exist in other regions. Consultation with the various regions in order to determine the specific scenarios where solution could benefit that particular business unit are needed

1.5 Significance of the study

Master–Dilly 66kV line Soutfontein leg feeds a sparsely populated rural area with bulk customers being fed directly from the high voltage side .The existing sub-transmission network is said to be old and suffers from low voltage as well as loading problems when interconnected to other feeders. The cost of replacing the whole electrical network was estimated to be R325 million. The choice lies between upgrading the network and declining all applications for additional loads, however the problem persists and possible solutions are needed as everybody has a right to electricity in South Africa.it is important to identify the weak links regarding both bottlenecks and reliability to avoid wrong investments. Possibility of operating the line on DC may be useful in enhancing declining and volatile plant performance that leads to unplanned breakdowns.

1.6 Scope of Research

Master Substation which is situated on the Piketberg area is supplied from Malmesbury/Klipfontein and Aurora/Kerschbosch by means of 2 x 132 kV overhead lines. The substation supplies 66kV ring network which contains Master–Dilly 66kV line with couple of T-off substations. The substation is firm as there are two transformers supplying the load.

Moorreesburg – Soutfontein 66kV Line, with Willy substation teeing off at Soutfontein linking substation and with Billy substation teeing off at Picketberg linking substation is the area of concern. It is furthest from the source and therefore suffers from Low voltages as well as loading problems.

The load flow studies will be performed on Master–Dilly 1 66kV line Soutfontein leg. The technical data below sets the boundaries of load flow analysis.

Table 1.1: Master–Dilly 66kV line Parameters

Voltage	66kV
Power (MVA) peak load	22MVA
Length of line	29km
Type of Conductor	Hare (50)
Volt drop	0.88 pu
Maximum current carrying capacity	200A

1.7 Thesis outline

The research work is comprised of chapters covering the history of HVDC, converter topologies with more focus on the development of IGBT-based Voltage source converters, changing the power pool requirements, stability concepts, the modelling and discussion of results.

Chapter one is an introduction where background, motivation and objectives of this research are described.
Chapter two covers the history and theory of HVDC transmission network
Chapter three deals with IGBT-based VSC technology, its power transfer, operating principles, control methods and the advantages at large.
Chapter four discusses conversion of AC to DC lines to accommodate the present power pool requirements
Chapter five Voltage stability is studied to gain insight of the causes and mitigating techniques
Chapter six deals with simulation and discussion of the existing overloaded AC network. Results and conclusion
Chapter seven covers the modelling of VSC-HVDC link.
Chapter eight simulation and discussion of the results obtained after VSC-HVDC incorporation on to the overloaded network and conclusion thereof.

CHAPTER TWO: CLASSIC HVDC TRANSMISSION NETWORKS

2

2.1 Dawn of Confidence in HVDC

In the majority of cases the point of electrical generation, i.e. power station, is far removed from the point at which the electrical energy is required, in order to transport this energy, overhead transmission lines are required. This transportation can be split into two main categories called transmission and distribution. Transmission can be broadly classified as the transmitting of electrical power from the point of generation to the general area of use. This is usually accomplished using overhead transmission lines for economic reasons (Clarke, 2002).

There exist certain specific scenarios where High Voltage Direct-Current (HVDC) transmission has advantages over Alternating-Current (AC) transmission. In such cases where AC networks may not be the most convenient, practical or techno-economically justifiable, Utilities often use High Voltage Direct-Current (HVDC) transmission for long distance bulk power transmission (Kundur, 1994) .The same scenarios exist in medium voltage distribution lines and the Organisations such as Cigre and EPRI are already discussing technical issues related to DC grids and the integration of renewable energy resources seems technically viable using DC technology. FACTS devices also offer the potential of managing power quality issues on adjacent AC networks.

As the need to supply large amount of electricity rises, several major challenges on AC networks became evident. Voltage constraints, power system stability control, system operating conditions and current constraints were said to be the limitations of AC networks over great distances. According to Arrillaga et al., 2007 some of these limitations are said to be caused by surge impedance that produces high voltage at the receiving-end unless some form of intermediate reactive compensation is used. In the view of AC network drawbacks, the HVDC transmission has come into picture; this has given the industry the confidence to start exploring the medium voltage and low voltage direct current.

2.2 Theory of HVDC Transmission Network

The first HVDC transmission system was commissioned at Gotland in 1954. Since then, HVDC technology is being used to deliver large amounts of electricity over long distances and interconnections. The original inspiration for the development of DC technology was its efficiency and the ability to transmit power at lower losses and cost than that of corresponding AC line (Kim et al., 2009). Development of conversion switches capable of withstanding high voltages triggered the optimal use of HVDC. P. Kundur (1994, 463).The IEEE power and energy magazine dated March /April 2014 and literature jointly agrees that mercury arc valve technology was matured enough to be used in the 1954 commercial project. In an attempt to better the HVDC technology, high power forced commutated switches were developed.

2.3 Basic Components of HVDC Transmission Network

The fundamental process of power conversion between AC and DC is made possible by Various components listed below.

- Circuit breakers (CB)
- Converters
- Filters
- Reactive Power Source
- Smoothing Reactor
- HVDC overhead line or Cable
- Electrodes

Most literature uses the traditional HVDC components to demonstrate the basic structure and the functions of HVDC technology. Figure 2.1 below shows the basic schematic of a bipolar HVDC system

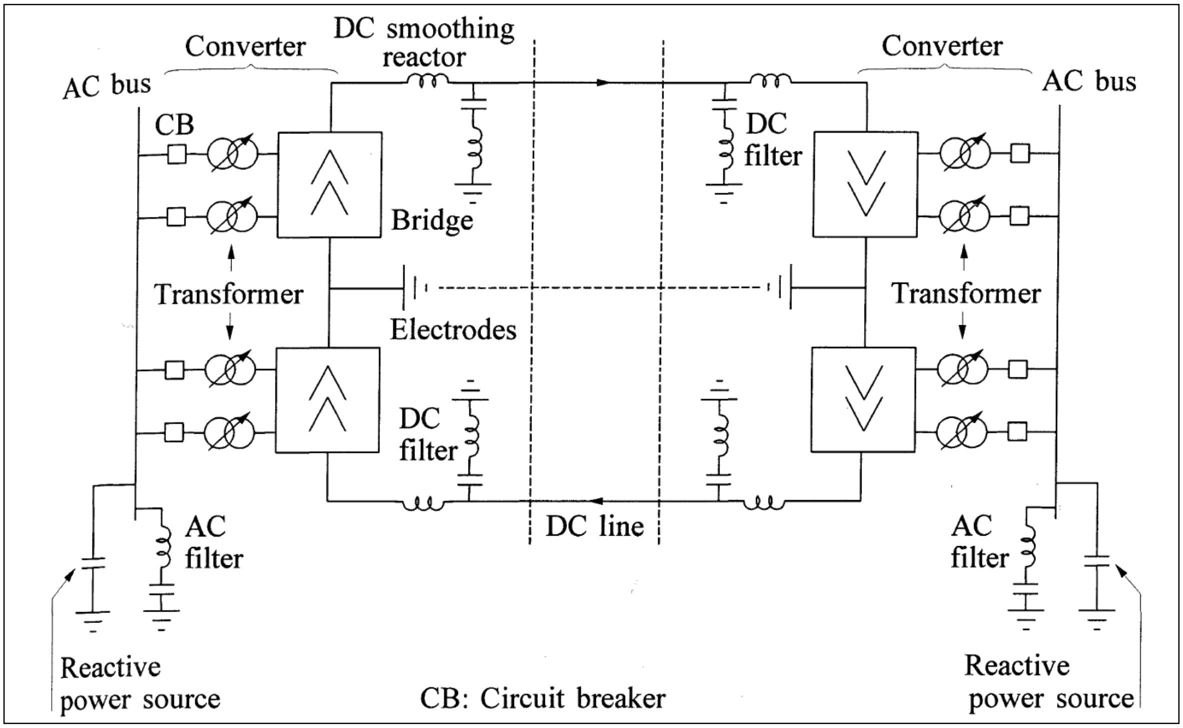


Figure 2.1: Basic components of HVDC system (Kundur, 1994)

2.3.1 Circuit Breakers

Helps with clearing of transformer faults as well as isolating the dc link. CB's are said to be used on the AC side only as the DC faults are cleared by converters. It is an interface between AC busbar and HVDC system (Kim et al., 2009)

2.3.2 Converters

It is said to be the most essential element for HVDC transmission (Kim et al., 2009).The function of a converter is to convert electrical energy from AC to DC and DC to AC (Sood, 2006).according to Siemens brochure dated march 2011, The HVDC converters are mostly built as 12-pulse circuits made up of two 6-pulse converter bridges connected in series. Figure 2.2 below shows such a setup. According to V.K, Sood converters are basically configured in two types, namely current source converters and voltage source converters. The latter will be discussed in chapter 3

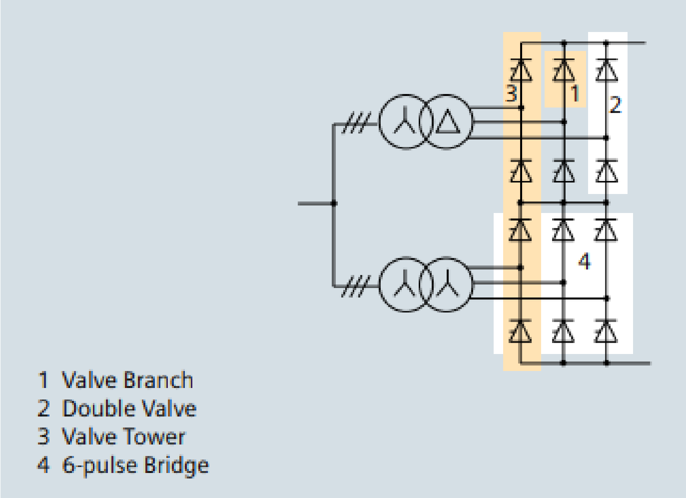


Figure 2.2: 12-pulse bridge (Siemens, 2011)

2.3.3 Filters

As a result of power conversion process, harmonics are generated due to slicing of voltages and currents, this then cause poor quality of supply (Sood, 2006).

Filters are there to mitigate harmonic voltages and currents generated by non-linear converters. These harmonics have got the potential to cause overheating in capacitors and generators. They also cause the interference with telecommunication systems.

2.3.4 Reactive power Source

These are usually in a form of capacitor banks or synchronous compensators .they Compensates for the reactive power that the converter consumes during the conversion process. I t has been noted that consumption of reactive power is much higher under transient conditions. It’s very appropriate when connected to weak AC networks.

2.3.5 Smoothing reactors

The functions of smoothing reactors are nicely explained in (Arrillaga et al., 2007) where it is stated that they decrease the harmonics in currents and voltages in the DC line.by virtue of reducing the harmonic currents and voltages, the commutation failures are reduced.

2.3.6 HVDC Overhead line or Cable

The transmission of bulk energy takes place through cables and overhead lines (Kim et al., 2009). More insight will be given to overhead lines due to the nature of this thesis. Transmission lines are said to be mechanically designed for AC lines. The main differences between AC and DC are insulation design, electric field requirements and conductor configuration (Siemens broche, 2011).this implies that the basic principle in determining overhead lines and towers are the same (Arrillaga et al., 2007).

2.3.7 Electrodes

Electrodes are electrical conductors that provide a reference potential point for the HVDC system. These electrodes are said to be designed for normal operation as well as fault conditions in HVDC systems (Arrillaga et al., 2007).

2.4 HVDC system configurations

HVDC system can be configured according to available flexible technology that fits operational requirements and cost (Arrillaga et al., 2007). There are five basic configurations illustrated in schematic diagrams and briefly discussed below.

2.4.1 Back-to-Back link

This type of link is mainly used for power control, for instance when transmitting power from one region to another under contractual basis.it is also the preferred one when planning the transmission between asynchronous systems (Arrillaga et al., 2007).converters are situated on the same site, this makes it to be more economical as there are no transmission line or cable required. They are usually designed for voltages between 50 and 150kV.

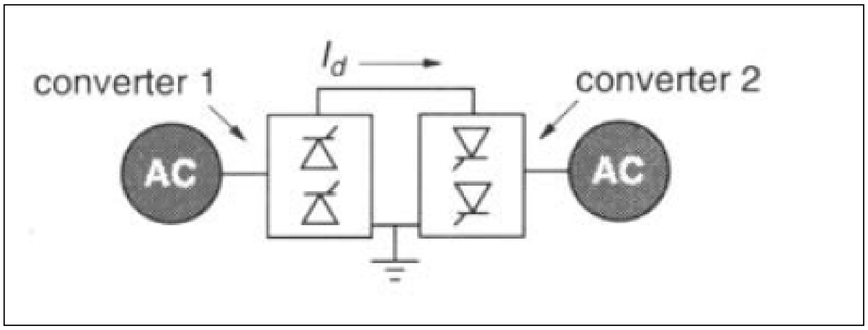


Figure 2.3: Back-to-Back link (Arrillaga et al., 2007)

2.4.2 Monopolar link

The monopolar link has single conductor of negative polarity connecting converters at each end. (Sood, 2006) explains the use of negative polarity as opposed to positive polarity.in this configuration earth or sea is used as return path for current. According to Arrillaga the ground return is rarely permitted in this set up due to corrosion and magnetic interference problems. For this reason, metallic return is used.

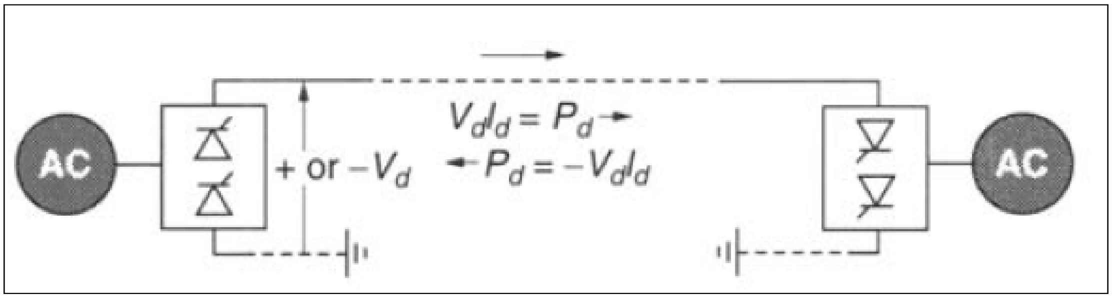


Figure 2.4: Monopolar link (Arrillaga et al., 2007)

2.4.3 Bipolar Link

The bipolar link has two conductors one is negative and the other one is positive.it consists of two converters of equal ratings at each end. The earth electrodes are connected right in the middle of converter stations. This is the most commonly used configuration due to its capacity to be operated as monopolar link when one of its links is faulty (Sood, 2006)

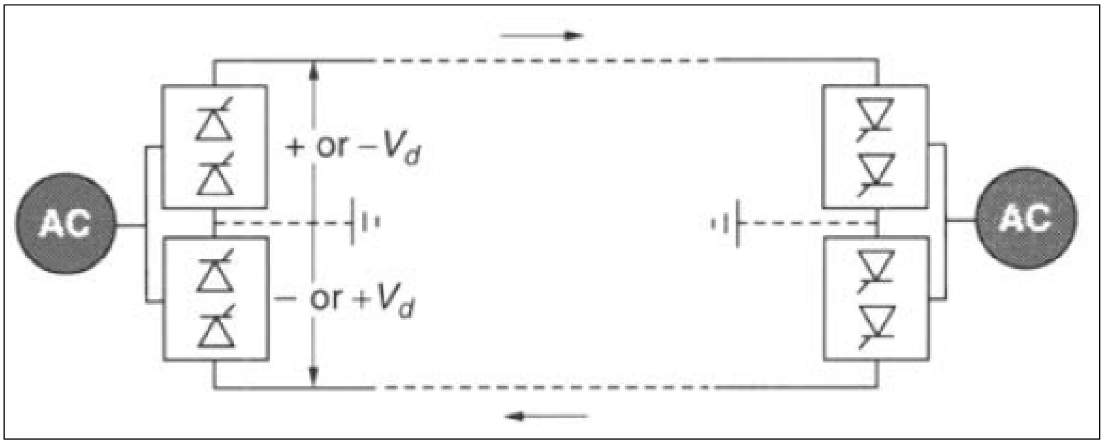


Figure 2.5: Bipolar link (Arrillaga et al., 2007)

2.4.4 Multiterminal links-parallel configuration

The multiterminal link has more than two sets of converter stations. The converter function is apportioned as per network requirements where some will work as rectifiers and some as inverters. Figure 2.6(a) and 2.6(b) shows the parallel and series configurations respectively.

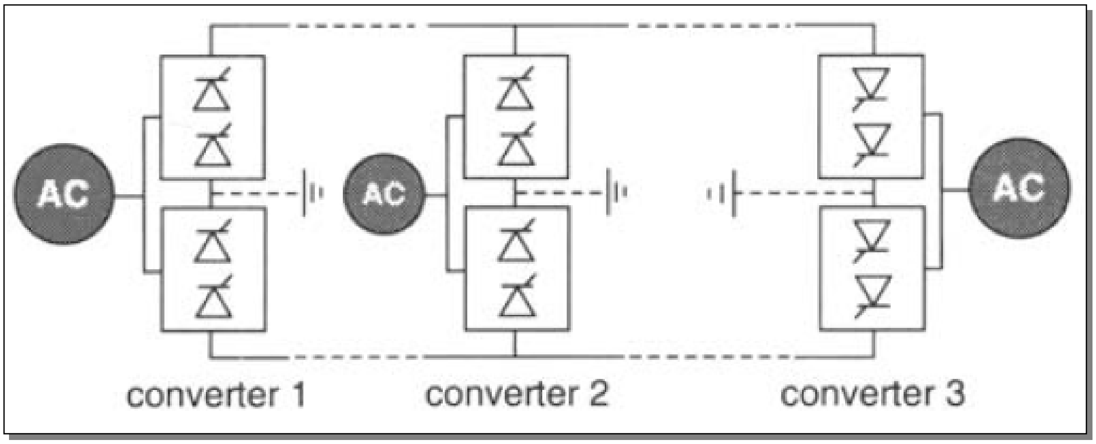


Figure 2.6(a): Multiterminal parallel connection (Arrillaga et al., 2007)

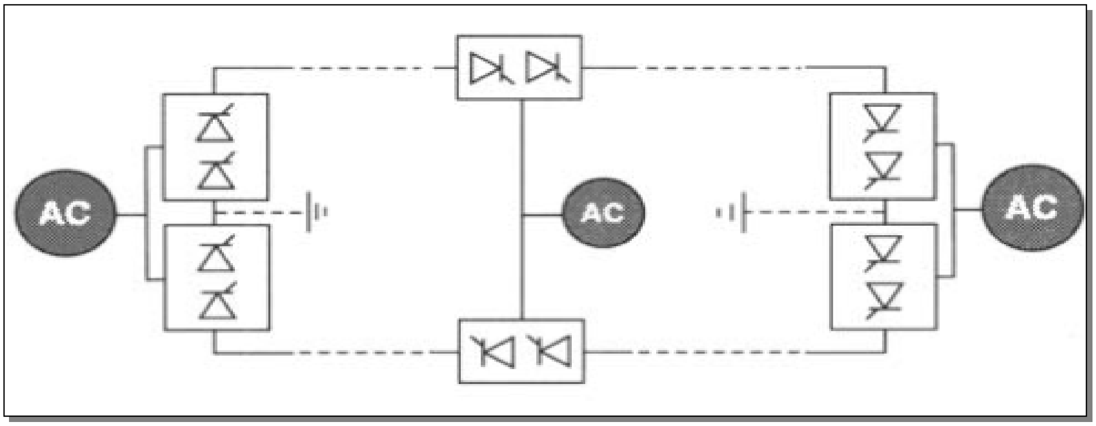


Figure 2.6(b): Multiterminal series connection (Arrillaga et al., 2007)

2.5 Applications of HVDC Systems.

The Traditional benefit of HVDC system is said to be bulk power transmission over long distances however with the advances in power electronics, HVDC system is used in various applications in the diverse energy industry. These benefits have been evaluated, applied and endorsed according to technical and economic considerations in the literature and electricity industry at large.

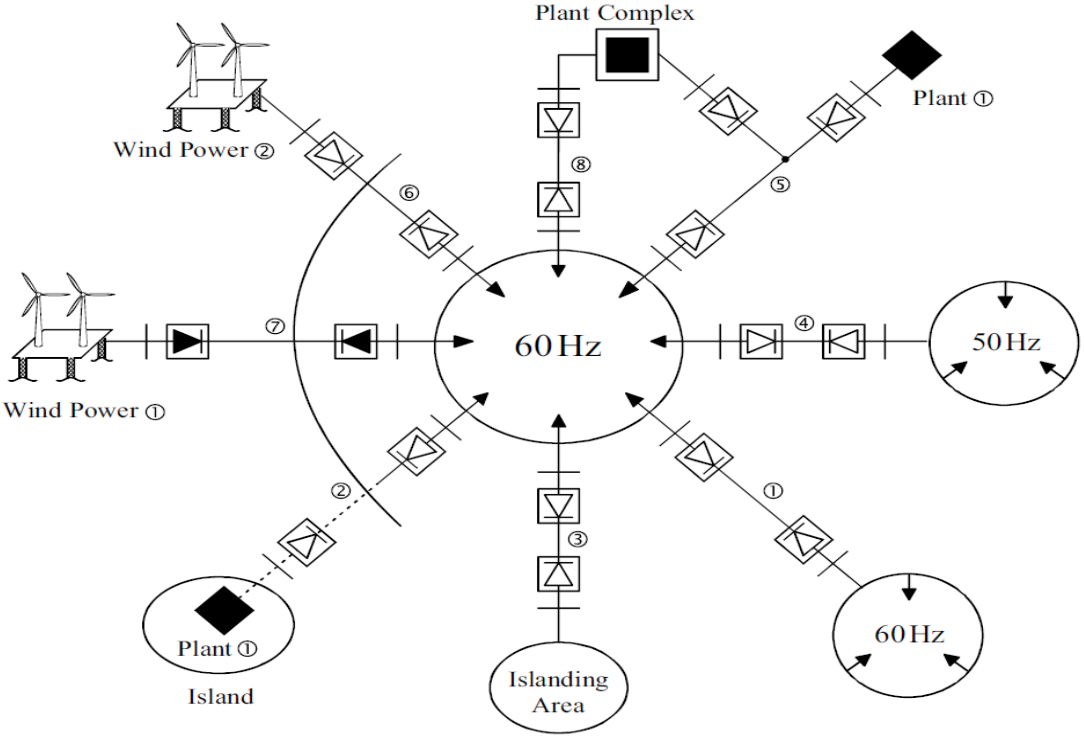


Figure 2.7: Different applications of HVDC systems (Kim et al., 2009)

2.5.1 Long Distance Bulk Power Transmission

HVDC has been found to be the cheaper option when transmitting large amount of energy over long distances due to lower losses and cost than that of equivalent AC line (Arrillaga et al., 2007).Encompassed on this benefit, the link is usually intended to deliver from remote source to loading centre. The example of such link is Cahora bassa (Mozambique) and Apollo here in South Africa.in this case the evaluation was mainly concerned with cost of transmission. Figure 2.8 shows the variation of transmission cost with distance of AC and DC lines. It has been noted that the breakeven distance can vary depending on the per unit line cost. On overhead lines it varies between 400 to 700 kilometres and between 25 to 50 kilometres with cables (Sood, 2006). However we can see that beyond the breakeven distance, HVDC shows the ability to transmit large amount of power with less capital cost and lower losses than corresponding AC.

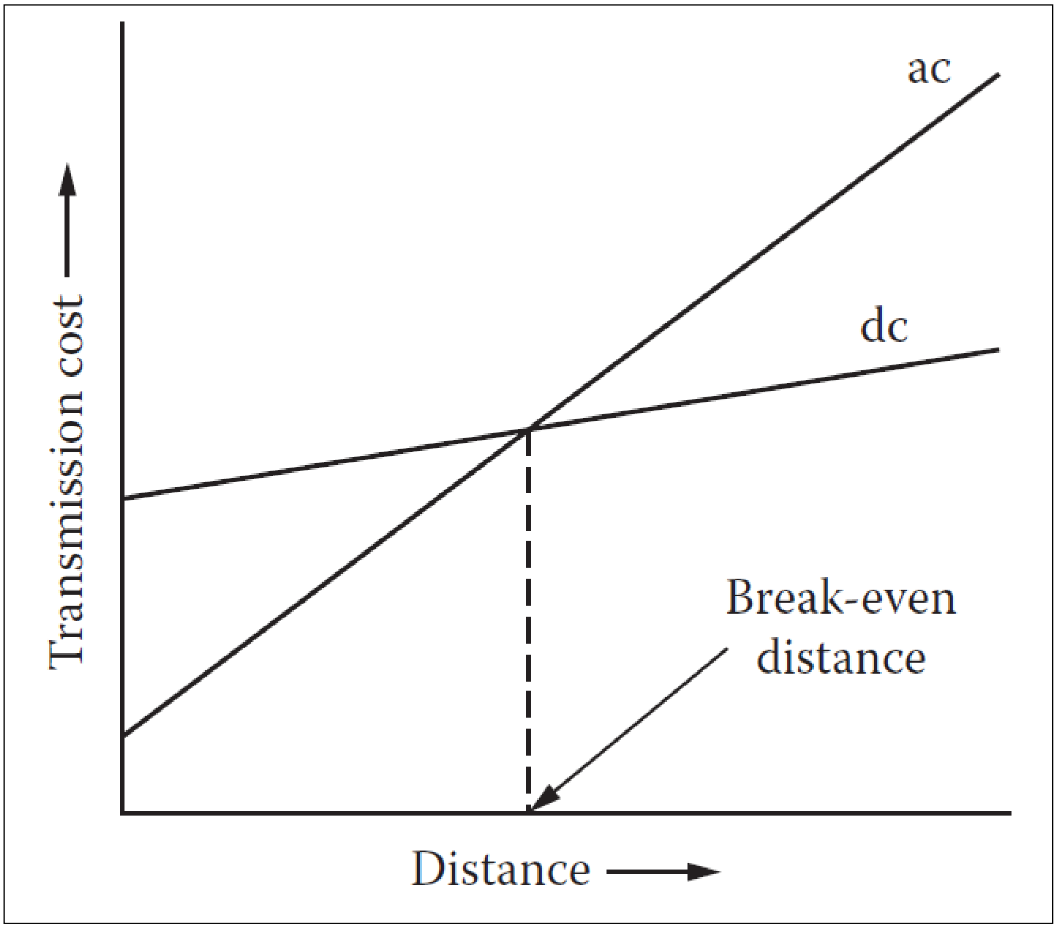


Figure 2.8: Cost comparison of AC/DC lines (Kim et al., 2009)

2.5.2 Possible Asynchronous Interconnections

With HVDC systems, the asynchronous operation is said to be possible between regions having different electrical parameters (Frequency, Voltage, power etc.). Figure 2.7 labelling number 4 demonstrates the HVDC's ability to interconnect two independent systems of different frequencies (50Hz system being connected to 60Hz System).With AC links the Interconnections between power systems must be synchronous. Thus different frequency systems cannot be linked. Security, reliability, voltage and frequency control would be threatened by such operation if it were to be applied on AC systems hence the HVDC system is the preferred option. Back-to back links are frequently used for interconnection purpose.

2.5.3 HVDC Multiterminal systems

HVDC systems help with the transmission of power from remote generation areas across various regions of the same country or different countries (Kim et al., 2009).Some energy sources are often located far from the load centres e.g. Kaxu solar plant in Northern Cape region of South Africa. If the intended use of power generated by Kaxu Solar plant included Cape Town as well, HVDC would reliably deliver electricity with low losses. It is further mentioned again that the interconnection of two or more power systems can be exploited without adhering to AC common rules.

2.5.4 Stabilization of Power Flow

(Sood, 2006) indicates that the power flow can be uncontrollable in AC ties particularly under disturbance conditions; this then leads to overloads and stability problems. According to Arrillaga the DC link can be operated to improve the stability of AC systems thereby modulating the power in response to the power swing. The reversal of power flow is also achieved

2.6 Advantages of HVDC Systems

Each HVDC transmission link has its own requirements leading to it being the technology of choice over AC system (Arrillaga et al., 2007). Some of the most common benefits are listed below

- Carries more power per conductor as compared to corresponding AC
- No line length restrictions as there is no reactance in DC lines
- Limit short circuit currents
- Environmentally friendly as compare to AC
- Ability to connect independent power systems

2.7 Classifications of HVDC technologies

According to ABB brochure dated August 2017, there are two types of HVDC namely the traditional or classic technology that uses thyristors for conversion process and the voltage source converter (VSC) technology that uses integrated gate bipolar transistors. The first commissioned HVDC link was using line commutated current source converters (LCC). (K Sood, 2006) mentions that it is possible to use line commutation (LC) or circuit commutation (CC) techniques for the conventional thyristors. However due to direct dependence of the firing angle alpha to the AC voltage, line commutation has been identified to absorb reactive power from the AC system and therefore poses limitations to this technology.it is further elaborated that power systems are subject to disturbances which lead to commutation problems for the thyristor-based converters. Another limitation is the inability to control reactive power (Sood, 2006).in search to overcome the line commutation limitations, forced commutation or self-commutation were introduced. The circuit commutation artificially generates voltage needed to achieve commutation. This thesis will make us of the voltage source converter theory and it will be discussed in the next chapter.

CHAPTER THREE: VSC-HVDC TECHNOLOGY

3

3.1 VSC IGBT based Transmission

The fundamental current conversion process from AC to DC is achieved by means of rectifiers and inverters. The conversion can be achieved by using natural commutated, circuit commutated or self-commutated converters. According to (Sood, 2006), conventional thyristors are called circuit-commutated devices and GTOs (Gate Turn-Off Thyristors), IGBTs (Insulated Gate bipolar Transistors) and other such devices are called self-commutated devices. The VSC-based power conversion provided a great flexibility in HVDC systems due to its ability to provide reactive power in either direction at each end of the HVDC link (Arrillaga et al., 2007). The first commercial VSC HVDC system was launched by ABB in island of Gotland. ABB named this technology as HVDC light. The market is expanding as a result Siemens and AREVA are the competitors offering similar technology named HVDC plus and HVDC Extra respectively (Kim et al., 2009).The VSC IGBT based technology, valves are built by IGBT and the pulse width modulation PWM) is used to create the desired voltage waveform. A typical basic VSC interconnection is shown in figure 3.1 below followed by component discussion.

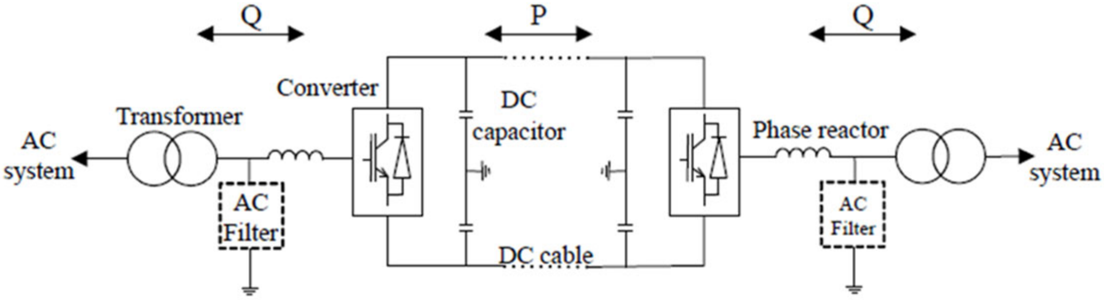


Figure 3.1: VSC interconnection (Du; 2007);

3.1.1 Transformer

Interface between AC system and converter thereby keeping secondary voltage level as required by the converter. By adapting the converter voltage and providing the reactance between AC system and converter unit, it is said that this operation controls the AC output current. Spurred

3.1.2 AC filters

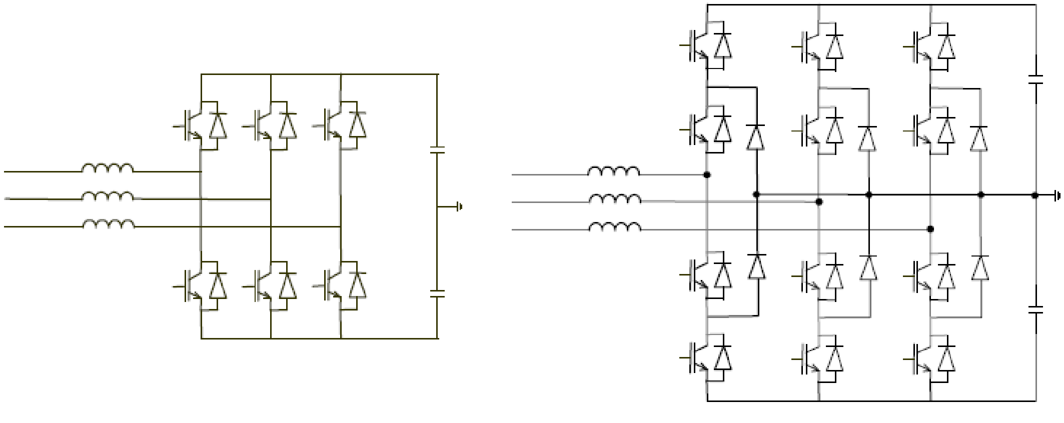
The switching of IGBTs Inherently produces AC voltage output which contains harmonics. Filters are necessary to eliminate the undesirable harmonics. Because the PWM technique used in VSC eliminates low order harmonics, high pass filters are installed between the transformer and the converter to mitigate high order harmonic content. Unfiltered harmonics result in the malfunction of AC equipment, losses, Radio frequencies and telecommunication (Du, 2007). The amount of filters installed in VSC is reduced as compared to LCC HVDC and therefore cheaper.

3.1.3 Phase reactors

Reactors also play a role in mitigating of high frequency harmonic content of the AC current. They provide the control of real and reactive power flow thereby controlling the current through it.

3.1.4 Converter configuration

Converters are regarded as the main component of HVDC transmission as their primary function is to convert electrical energy from AC-DC and vice versa. The basic configuration of VSC is a two-level converter (figure 3.2(a)) which can be used in the building up of a three-level VSC bridge (figure 3.2(b)) and subsequently multi-level converters (MMC).The operation of the circuit requires the DC voltage to be maintained constant. This function is achieved by installing DC capacitors and the switching is performed through IGBTs. The free-wheeling diodes installed across each valve helps with the current diversion during commutation if the main valves (Sood, 2006).series connection


(a) Two-level VSC

(b) Three-level VSC

Figure 3.2: VSC Configuration (Du; 2007)

3.1.5 DC link Capacitors

DC storage shunt connected capacitor for the purpose of Keeping DC voltage within limits and controls DC voltage ripple. The DC capacitor size is characterized as time constant:

$$\tau = \frac{1}{2} C \frac{U_{DCN}^{2}}{S_N} \qquad (3.1)$$

It is defined as the ratio between the stored energy at the rated DC voltage and the nominal apparent power (Du, 2007); where

C= Capacitor

U_{DC}=rated Dc voltage

S_{N}= nominal apparent power of the converter

3.1.6 DC cables / Overhead transmission line

Transmitting medium from one point to other .The developments in XLPE cables made VSC HVDC transmission even easier. The previous technology that suffered from moisture or water ingress is now replaced by DC cables with insulation of extruded polymer. There are no length limitations as compared to the corresponding AC cables. Cables are more preferred than overhead lines due to effects imposed by overhead line on the environment.

3.2 Advantages of VSC Based Transmission

The self-commutated VSC based transmission has several advantages which lead to it being the most competitive at transmission distances of over 100km and power levels between 200 and 900 MW.

- It has the ability to generate and absorb reactive power independently from Active power flow.
- It significantly reduces the generation of harmonics.
- No AC system voltage source needed for commutation
- It eliminates problems of over-voltages

3.3 Applications

The advantages mentioned in 3.2 made the following application possible with regards to VSC HVDC (Kim et al., 2009).VSC HVDC is the preferred system for use in various transmission applications, using overhead lines, land and sub-marine cables or back-to-back connection (ABB Brochure, August 2017)

3.3.1 Power provision over long distances through transmission lines

Electricity generating sites are often situated far from consumers; electricity must cross long distances to get where it is needed. According to literature and ABB HVDC is the most reliable and efficient way of getting it there. Caprivi link connecting Zambezi and Namibia is a reference project where 350km long overheard line of about 350kV DC was built

3.3.2 Energy provision in urban areas experiencing rapid load growth

Urban loads are increasing and businesses are continuously increasing their power loads in order to meet the demand. This in turn is overloading the existing AC network. Acquiring the land for new electricity infrastructure has become a challenge. Also the environmental effect posed by transmission lines is another hick-up. It has been noted that urban electrical system require easy solutions that can be attained within urban boundaries and shot lead times. Replacement of existing AC overhead lines with DC cables is said to be an opportunity to use same ROW and get 2-3 time more power than comparable AC system (ABB Brochure, August 2017).another reference project is a link connecting Long Island and Connecticut in new York

3.3.3 Delivering energy to independent systems

ABB further educates us on the coupling of previously separated electricity markets and ever increasing commercial interconnections especially with the integration of renewable energy.it is precisely stated that in order to operate effectively, these interconnections will require controllable power flows. Having different characteristics between renewable energy and traditional energy mix, controllability and flexibility of power flow is a requirement. VSC HVDC offers the frequency and voltage regulation, emergency power support, stability enhancement, power flow control. These are all features needed for integration between these two systems.

3.3.4 Interconnections

Liberation of energy markets resulted in dozens of electrical interconnections across the continents in the world. These are helping to create secure and sustainable supply of electricity. VSC HDVC is said to be the possible technical solution especially when interconnecting countries of different frequencies.

3.4 Comparison of VSC HVDC and LCC

The VSC was initially used in low voltages by industries for motor drives providing fast desirable continuous control of frequency and voltage magnitude. Due to this perception and other advantages presented by LCC, Most of present HVDC transmission networks use LCC technology. The first commercial HVDC link mentioned in 2.2 uses the LCC technology. The LCC HVDC uses thyristors in a current source converter (CSC) topology. With the advent of solid-state electronics and the silicon-controlled rectifier, the development of thyristor valve converter began to replace mercury arc-valve converters. Thyristor valves completely replaced mercury-arc valves due to their strong features, reliability, low maintenance, and cost and gave real momentum to HVDC.The use of Thyristor based switches provided HVDC flexibility however it is said to be restricted by switching characteristics of silicon controlled rectifier. Thyristors can only switch off when the current through them becomes zero and its commutation process depends on the normal operation of AC grid. Another restriction is the delayed firing of thyristors that result in the current lagging the voltage and thereby reactive power abortion by the HVDC link. It is said that the power direction can be changed if DC voltage is reversed which turns to be a time consuming operation.

For these inherent limitations LCC HVDC is feasible for long distance transmission at extra high voltages. This further necessitated more research as Dr Hans-joachim Knaak from Siemens mentions the HVDC/FACTS challenges ahead. he articulates that HVDC will move from being an isolated point-to- point connection to being an integrative part of the grid where there will be a need to overcome the above mentioned Inherent LCC HVDC limitations.

The VSC IGBT-based Transmission technology presented more advantages than LCC HVDC technology. The IGBTs used in VSC scheme can be switched on and off so many times per cycle. Their operation is not limited by zero crossing current and the operation of the surrounding AC grid. According to (Arrillaga et al., 2007), VSC does not suffer from commutation failures. There is no reactive compensation required as the VSC can control the feeding and absorption of power in to the system. Other added advantages are the bidirectional power transfer without polarity reversal, compact design, black start capabilities and less filters. VSC technology can be connected to the network in many different ways depending on the particular application. It is not only limited on long distance transmission. It fulfils a situation where HVDC systems can be applied and expanded in a manner similar to AC substations (Andersen , 2013:4)

3.5 Operating principle of VSC

Two-level single phase VSC in figure 3.3 below is used to demonstrate the operating principle of VSC. The two-level was chosen due to proven technology, simplicity and the fact that it allows the IGBTs to be connected in series depending on the required supply voltage. The converter valves and transformers are assumed to be lossless with negligible ripple on DC capacitors. Since the inherent conduction in solid-state switches is unidirectional, freewheel diodes are connected in parallel to eliminate negative voltage across the load, while current flow in both directions. The basic principle of single phase two-level VSC where switching circuit and corresponding voltage wave form are shown in figure 3.3.It can be noted that the AC terminals are switched in a bipolar manner between voltage levels of +V_d and-V_d

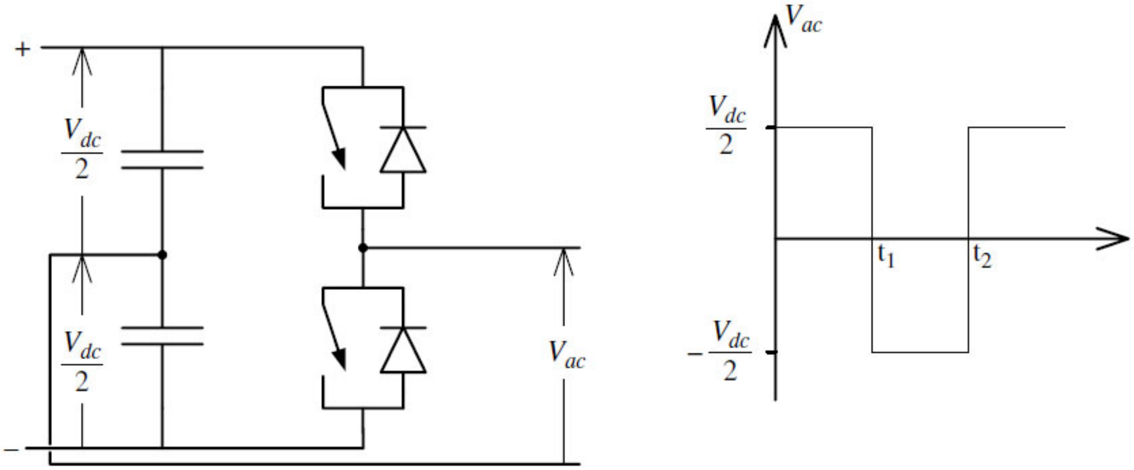


Figure 3.3: Basic Operation of two-level VSC (Arrillaga et al., 2007)

The four possible current paths are shown in figure 3.4

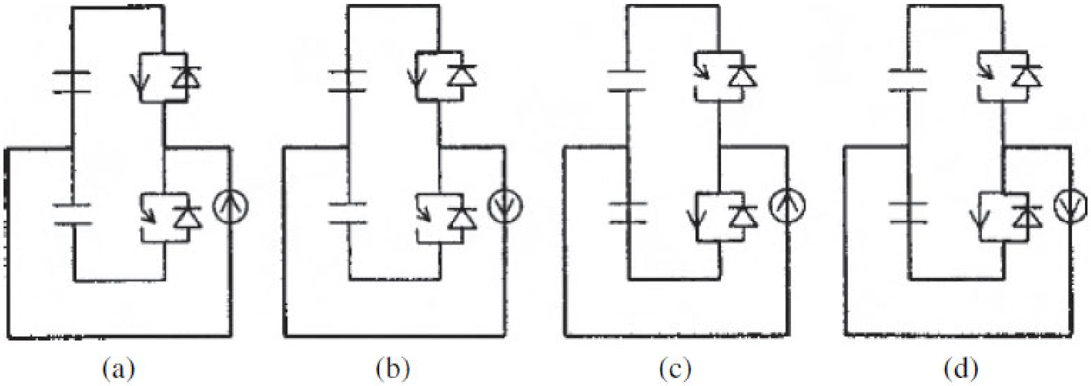


Figure 3.4: Current Path in a two-level VSC (Arrillaga et al., 2007)

When the upper switch is closed the output voltage is +Vd/2 and the flow of current is demonstrated on figure 3.4(a) and 3.4(b).when the lower switch is on the output voltage is -Vd/2 and the flow of current is shown on figure 3.4(c) and 3.4(d).uncontrolled rectifier is formed when both switches are blocked, in this state the external AC voltage charges the DC capacitors to the peak value.it has been noted that a fully charged DC capacitor together with connection of external sources can kick start the operation of VSC.

3.6 Power Transfer in VSC

VSC was initially built for transmission and sub-transmission power transfer of between 5 to 150MW however due to availability and increasing power ratings of IGBT, the VSC power capabilities are in hundreds of megawatts. VSC-based HVDC has the ability to control power in the system. The operation of the switches ought to block a unidirectional voltage yet be able to conduct current in either direction when bidirectional power flow is required. The Active and reactive power components are expressed as:

$$\mathbf{P} = \mathbf{V_1}\left(\frac{\mathbf{V_2}\sin(\delta)}{\mathbf{X}}\right) \tag{3.2}$$

$$\mathbf{Q} = \mathbf{V_1}\left(\frac{\mathbf{V_2}\cos(\delta)-\mathbf{V_1}}{\mathbf{X}}\right) \tag{3.3}$$

Where:

V_1= is the system AC Voltage,

V_2=is the VSC output voltage,

δ= the phase angle

X= reactance between V_1 and V_2

According to arrillaga, if the converter is connected to an active DC network, a four quadrant operation can be achieved as shown on figure 3.5 below. In this operation the converter can act as a rectifier or inverter with leading or lagging reactive power. The flexibility offered by VSC allows the operation at any point within the circle.

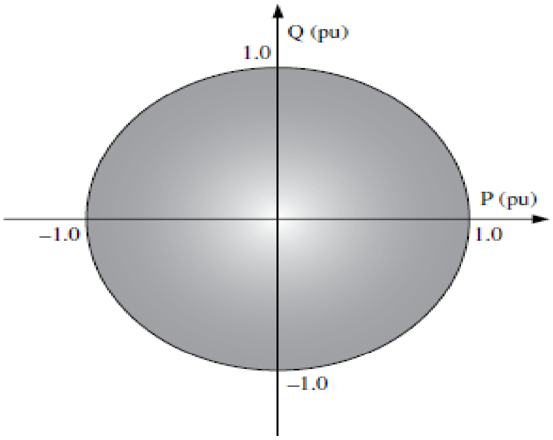


Figure 3.5: VSC Four-quadrant operation (Arrillaga et al., 2007)

It has been confirmed that when changing the amplitude between the converter bus voltage and the valve bus voltage control the reactive power flow between the valve and transformer bus and consequently between the converter and the AC network (ABB brochure, 2017).The phasor diagram in figure 15 illustrates the operating mode of VSC as a reactive power controller Where :

V2 = V1; I=0

V2 > V1; I leads V by 90°

V2 < V1; I lags V by 90°

When V_1 is equal to V_2 in the converter voltage V_2 and AC system voltage V_1 are in phase, the VSC operates as reactive power compensator. There is no exchange of reactive power between converter and the system.in this mode, the current is said to be zero (I=0).When V_2 is greater than V_1 the current leads voltage by 90° , here the converter generates and supply reactive power into the system. When V_2 is less than V_1 the current lags the voltage by 90° , here the converter absorbs the reactive power from the system. Thus the VSC scheme can operate as power transmission system or two independent STATCOMS if there is no power available of required.

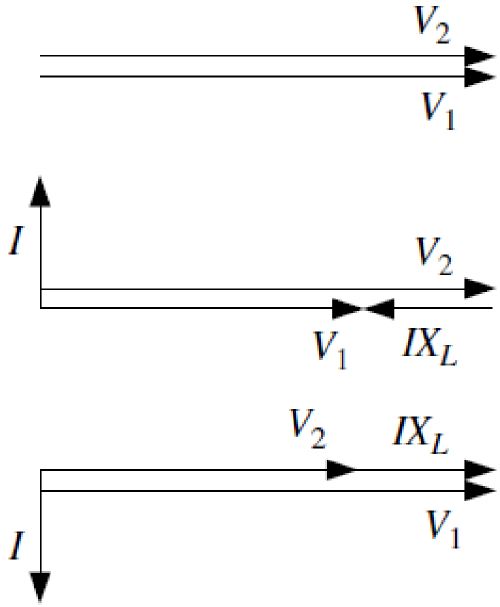


Figure 3.6: VSC Phasor diagram for reactive Power Control (Arrillaga et al., 2007)

3.7 VSC PWM Methods

Pulse width modulation is characterized by high-frequency switching of the fixed DC voltage where output waveform is filtered to produce specified fundamental component of controllable magnitude.in this process the lower order harmonics are eliminated by modulating the width of voltage pulses (Arrillaga et al., 2007).

The PWM method used in the operation of VSC is said to have an advantage of instantaneously controlling the voltage magnitude and phase. Furthermore it provides different types of schemes to generate PWM patterns amongst them are Space vector, triangular-wave and trapezoidal modulation. It should be noted that the most accurate scheme of the PWM pattern may not necessarily be the optimal choice.one should always evaluate the economic, harmonic and switching losses aspects when choosing the scheme. Tabulated below is the comparison on the PWM schemes. When applying a VSC technology, the objective is coupled with minimising harmonics as much as possible, reduction of losses and low cost.

Table 3.1: Evaluation of PWM schemes (Kim et al., 2009)

Aspect	Space-vector	Triangular-wave	Trapezoidal
Harmonics	Small	Medium	Large
accuracy	Large	Medium	Small
economics	Large	Medium	Small

According to (Arrillaga et al., 2007) the use of VSC pulse width modulation in power transmission is practical if the Three phase system is symmetrical and the output waveform should contain only odd harmonic orders. The choice of modulation principle is governed by three ratios namely frequency, control and utilisation ratios. These ratios are mathematically expressed as

$$\mathbf{p} = \frac{f_p}{f} \tag{3.4}$$

$$\boldsymbol{\gamma} = \frac{\mathrm{V}_{\mathbf{1}}}{\mathrm{V}_{\mathbf{1}(OM)}} \tag{3.5}$$

$$\boldsymbol{K} = \frac{\mathrm{V}_{\mathbf{1}(\mathbf{MAX})}}{\mathrm{V}_{\mathbf{1}(OM)}} \tag{3.6}$$

Where: p is the frequency ratio

f_p is the modulation frequency

f is the output frequency

$\boldsymbol{\gamma}$ is the control ratio

$\mathrm{V}_{\mathbf{1}}$ is modulated waveform

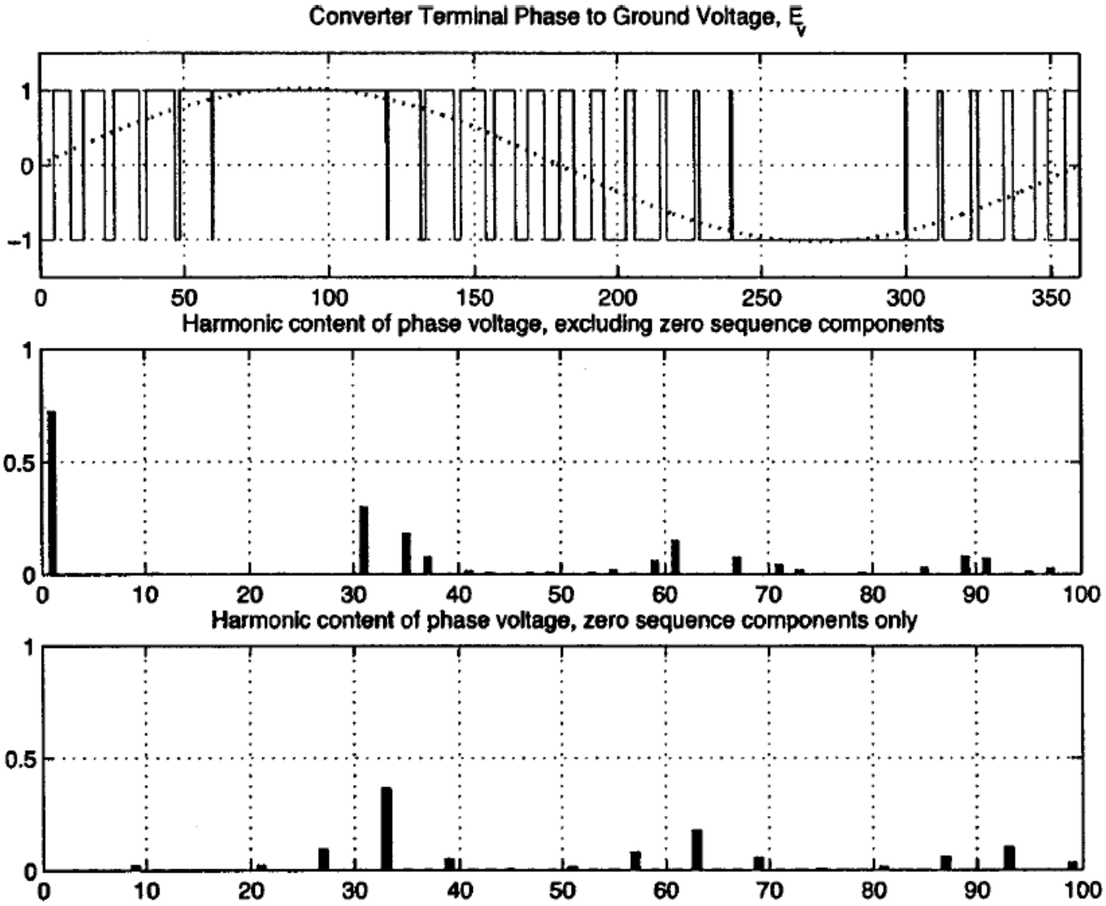
$\mathrm{V}_{\mathbf{1}(OM)}$ is the unmodulated waveforms

$\boldsymbol{K}$ is the utilisation ratio

$\mathrm{V}_{\mathbf{1}(\mathbf{MAX})}$ is the maximum available voltage

Frequency ratio is defined as the ratio of modulation frequency to the output frequency.

Control ratios are the ratio of the fundamental components of modulated to unmodulated waveforms and lastly the utilisation ratio is a measure of how well the modulation principle uses the maximum available voltage. The quality of supply offered by transmission and distribution networks ought to be free from harmonics. The waveforms needs to be further improved by means of AC filters and series reactors. From the various PWM schemes mentioned above, the incorporation of optimal pulse width modulation (OPWM) technique would be beneficial to reduce converter losses and elimination of harmonics. The effects of OPWM are illustrated in the figure below where fundamental component is shown as the dotted line and the phase to ground converter terminal voltage.



Converter Terminal Phase to Ground Voltage, E_v

Harmonic content of phase voltage, excluding zero sequence components

Harmonic content of phase voltage, zero sequence components only

Figure 3.7: Harmonic cancellation through VSC-PWM (Arrillaga et al., 2007)

When the VSC using PWM is designed for optimal cancellation of harmonics, the individual harmonics are said to be reduced to 1 percent and the total harmonic distortion (THD) is reduced to 2.5 percent. The harmonics are concentrated in a narrow bandwidth. PWM –VSC technology provides :

Frequency control: by regulating power delivered to or taken from the AC system.

AC voltage control: by regulating the magnitude of the fundamental frequency component of the VSC output AC voltage on the converter side of the transformer.

Active power control: by regulating phase angle of the fundamental frequency component of the converter –generated AC voltage.

Reactive power control: by regulating magnitude of the converter AC voltage source.

DC voltage control: by regulating power required to charge or discharge the capacitor to maintain specified DC voltage level.

3.8 VSC HVDC System Control

The intended purpose of VSC with regards to this thesis is to control active and reactive power while keeping a constant voltage at the DC terminals. VSC can be controlled in four controlled modes depending on the desired outcome. Below are the control modes:

- Active power control mode
- Reactive power control mode
- AC voltage control mode
- Constant DC voltage control mode

These control modes are taking place in VSC internal structure shown in figure 3.8 below.

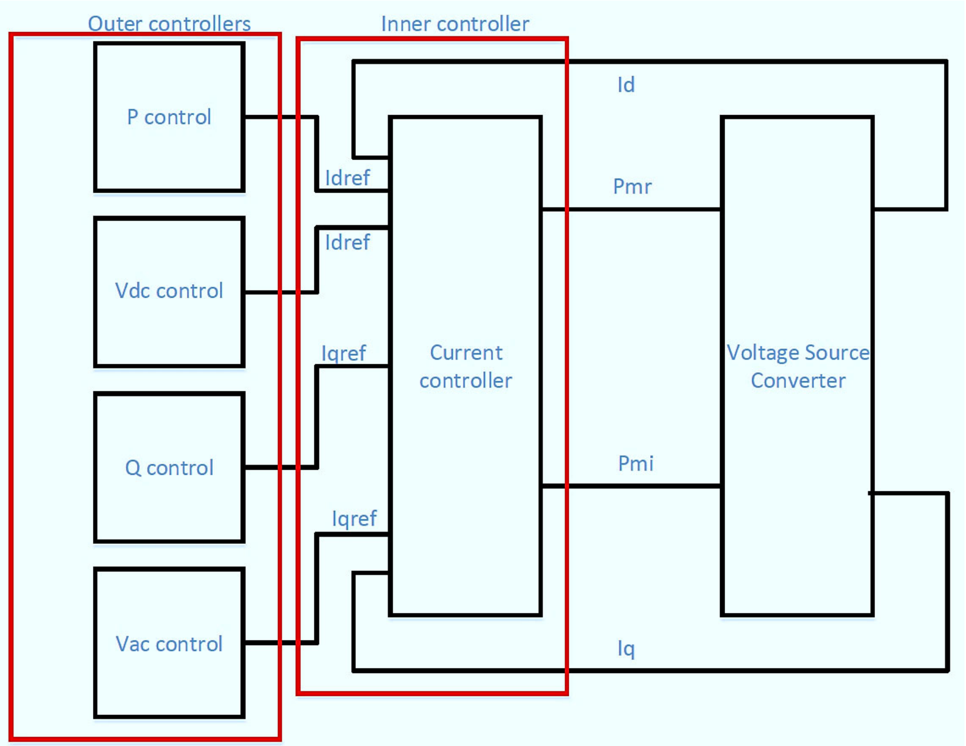


Figure 3.8: VSC internal control structure (Ruihua et al., 2005)

The VSC control structure consists of outer control loop and inner control loop. The outer loop controllers are project specific. The Voltage at AC terminals, reactive power and active power at rectifier side are all controlled by outer loop. The controller can alternate between controlling the reactive power and AC bus terminal voltage as shown in figure 3.9 below. This is achieved by employment of PI controllers within the outer and inner loop controllers, Where a proportional gain and an integral gain controls the desired value to a given reference value in this form

$$\boldsymbol{K_s} = \left(\boldsymbol{K_p} + \frac{\boldsymbol{K_i}}{\boldsymbol{s}}\right)$$

(3.7)

Where $\boldsymbol{K_p}$ is the proportional gain and $\boldsymbol{K_i}$ is the integral gain.

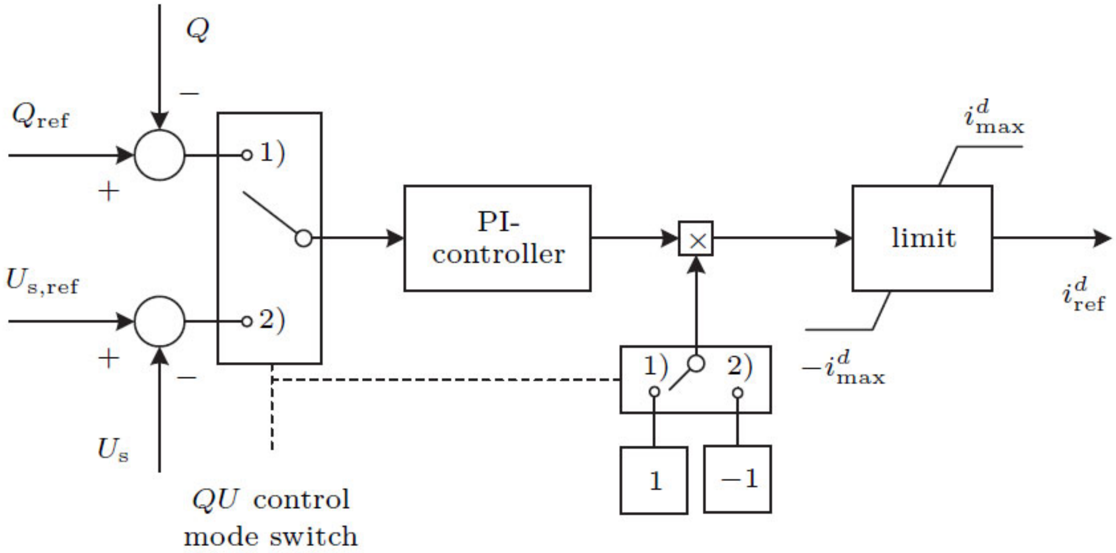


Figure 3.9: Reactive power and AC voltage controller (Imhof, 2015)

According to (Imhof, 2015) the inner control loop controls the currents to the reference values received from outer loop. Today's VSC-HVDC schemes are designed to keep DC voltage fixed and the control of AC voltage output is varied by means of a modulation index signal (λ).direct control and vector control are the two possible approaches to implement modulation index. In figure 3.10, it can be observed that the modulation index or phase angle is adjusted directly from the parameters being controlled, while in figure 3.11 the currents components are first transformed to d-q axes, which are then synchronized with AC system Voltage through phase-locked loop (PLL).this current loop is said to be slowing down the desired response speed as the d-q voltages generated by vector control are transformed in to three-phase quantities and converted into line voltages by VSC. However it protects the valves from overloading (Arrillaga et al., 2007).

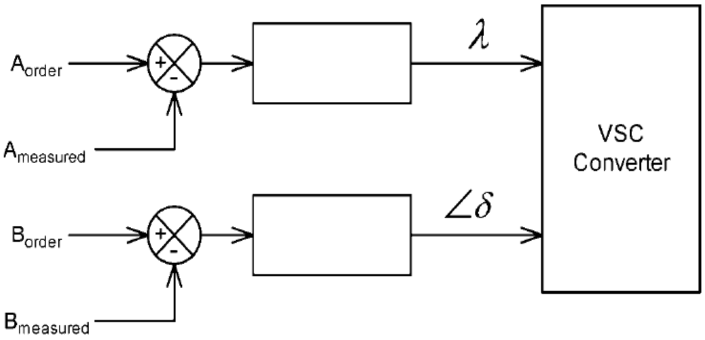


Figure 3.10: Direct Control of Modulation Index (Arrillaga et al., 2007)

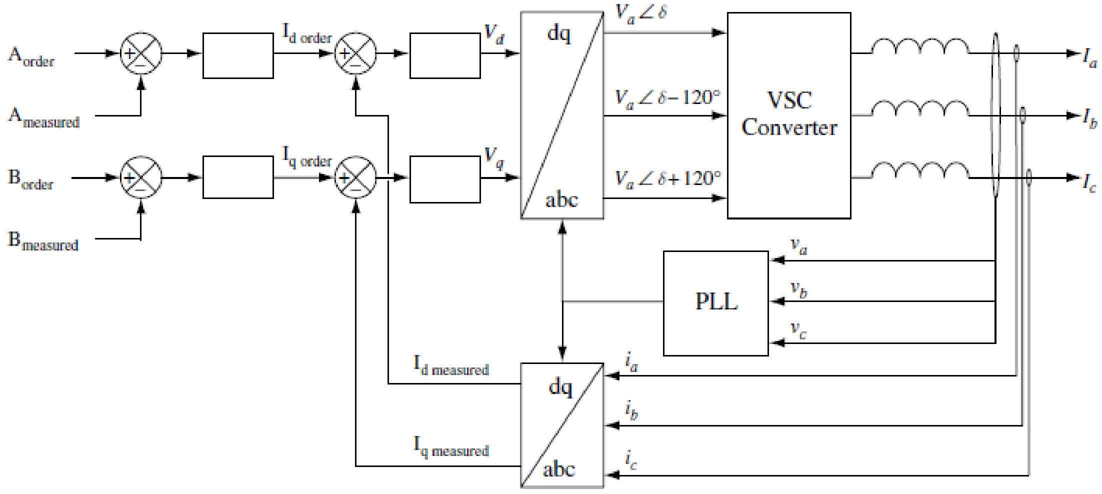


Figure 3.11: Vector control via d-q axis (Arrillaga et al., 2007)

The conversion of three-phase sinusoidal system is achieved by applying Park's transformation matrix. Within the Park's transformation matrix there is an intermediate α-β-0 transformation and the phase rotation matrix transformation which then result in d-q-0 frame control. This is represented in 3.8 below.

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = [P(\theta)] \times \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{3.8}$$

Where $[P(\theta)]$ is the parks transformation matrix aiding the reproduction of d-q-0 terms .The whole transformation is done to prohibit the three-phase sinusoidal system from being time variant. This means they are transformed into DC terms. At the end of the transformation process, it ought to be noticed that in a VSC, through d-q-0 change, the amounts are changed over to DC constants.

3.9 Conclusion

The VSC HVDC technical aspects were discussed where it became clear from the advantages and applications that VSC HVDC has interesting qualities. The basic and different methods of operation were highlighted, the incredible progress in fast switching devices like IGBTs has encouraged the interest in the study of shunt and series filters. As a result of PWM inverter technology together with "d-q theory" power filters can now be used in industrial field. The stand-alone feature of the ability to control the transfer of reactive power as well as terminal voltage has made VSC IGBT-based technology an attractive option for HVDC transmission.

CHAPTER FOUR: AC to DC CONVERSION

4

4.1 Changing the Power Pool Requirements

South Africa's main source of electrical energy is generated from Fossil Fuels. However the development of existing and future generation power pools to meet the Countries energy demand by 2030 was analysed taking into account three potential main generation pools namely, underground coal gasification, nuclear power stations, and gas supplemented by renewables. The generation power pool triggered the strategic analysis of the requirements of the future power corridors to meet the expected load growth and integrate the potential future generation scenarios. The approach was to design the different power corridors to be as independent of other power corridors and generation scenarios as possible. The major advantage of this approach was the flexibility to respond to different generation scenarios that may eventually manifest.

Economic and technical evaluation was done where HVAC and HVDC transmission lines were proposed at different voltage levels to achieve the desired power corridor. However due to current generation surplus, country's financial status ,political influence and other factors, The anticipated generation power pool differed from original plan. This had an impact on proposed power corridors in such a way that some of the sub-transmission projects were put on hold. It must be noted that the load continues to grow and the present HVAC sub-transmission network cannot handle the load demand. Certain areas cannot add new customers to the grid due to network that already suffers from low voltages, thermal loading and instability. Certain existing transmission lines should be considered for recycling from a single circuit to a double circuit structure, larger conductor bundles or higher voltages. The enhancement of existing power transmission capacity of the lines through DC will be studied in this chapter.

4.2 Converting AC lines into DC

As part of the capacity enhancement in the existing transmission networks, it makes more sense to utilise the existing transmission infrastructure as opposed to building new transmission network that will take time to be developed. Converting HVAC overhead lines into HVDC might provide a significant increase in transfer capacity for a relatively little cost less time and little environmental impact. It has to be noted that before the conversion of AC into DC line, certain conversion criteria has to be met. This includes the thorough analysis of existing AC line where most critical electrical parameters, structures, protection and environmental aspects are evaluated for the alignment with HVDC. Different conversion topologies and criteria will be discussed as follows.

4.2.1 Single Circuits AC lines

According to (Larruskain et al., 2014) article, Single circuits AC lines can be adapted to bipolar, tripolar and modulated bipolar DC lines. The article puts more focus on single circuits as it stipulates that they are the more complex ones when it comes to conversion due to its odd number of conductors. When the single circuit AC line is converted to bipolar DC line, the HVDC line will have three circuits with one conductor per pole. However it must be noted that the proposed VSC technology has two poles with opposite polarities as seen in chapter 3 figure 3.3, as a consequence a conductor per pole is used leaving one spare conductor which can be used as return conductor in emergency situations. Figure 4.1 below shows the VSC based HVDC configuration.

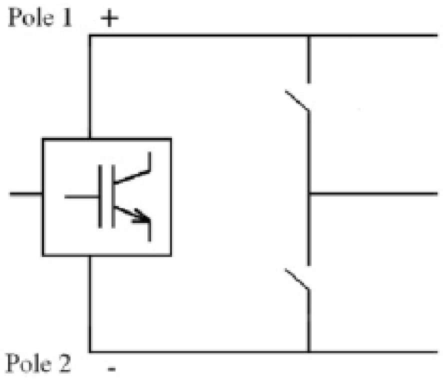


Figure 4.1: VSC based HVDC Line (Larruskain et al., 2014)

Looking at the capacity enhancement, the power transmitted by the adapted DC line is

$$\begin{aligned} P_d &= I_d V_d + I_d V_d \\ &= 2 I_d V_d \qquad (4.1) \end{aligned}$$

Where:

P_d = is the power transmitted by converted DC bipolar line

V_d = is the pole-to-ground voltage

I_d = is the rated current of both poles

Another method of single AC line conversion is the modulated bipolar DC line, in this configuration there is a positive pole, negative pole and the third pole changes polarity between negative and positive as required by the system. All three conductors are in use with one conductor per pole as shown in figure 4.2 below. It can be seen that the positive and negative poles are the outermost conductors and the polarity of the middle conductor is commutated with IGBTs.

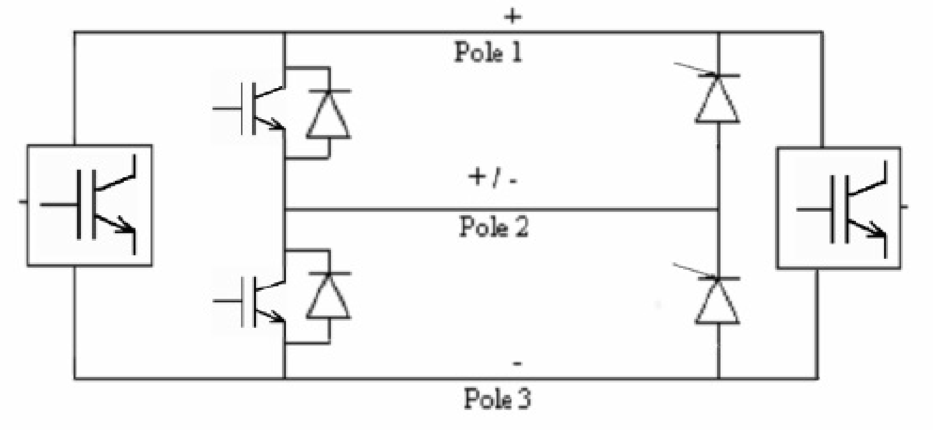


Figure 4.2: VSC based Modulated Bipolar DC line (Larruskain et al., 2014)

According to (Arrillaga et al., 2007) the modulated DC transmission was introduced as an effective way of achieving the maximum power carrying capacity by making use of third conductor in bipolar configuration. The modulated bipolar system can be configured in such a manner that one conductor is sending and the other two are return conductors and vice versa. (Larruskain et al., 2014) states that if the bipolar configuration has one sending conductor, it is overheated due to the fact that it withstands a higher current that it's rated value. While the two return conductors share the current and consequently operate lower than rated current. This operation is shown in figure 4.3 where sequential alternate between High current state and low current state is demonstrated.

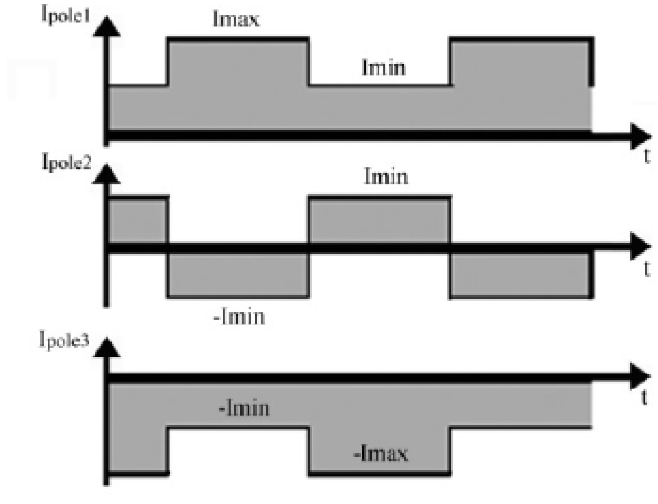


Figure 4.3: Operation of Modulated Bipolar DC Line (Larruskain et al., 2014)

This configuration is capable of transmitting 1.26 times higher power than bipolar configuration. The power transmitted is defined by:

$$P_{dc} = 1.26I_dV_d + 0.63I_dV_d + 0.63I_dV_d \quad (4.2)$$

$$=2.53I_dV_d$$

$= 1.26\ P_d$

Where $1.26I_d$ is the high current state at pole 1 and $0.63I_d$ is the low current state at pole 2 and 3.

The third method is the adaptation of single AC line into tripole DC line. This configuration also makes use of all three conductors. There is positive pole, negative pole and the third pole which changes polarity.it is said that this system was originally implemented with LCC converters as a result the third pole is connected to thyristor based system as shown figure 4.4

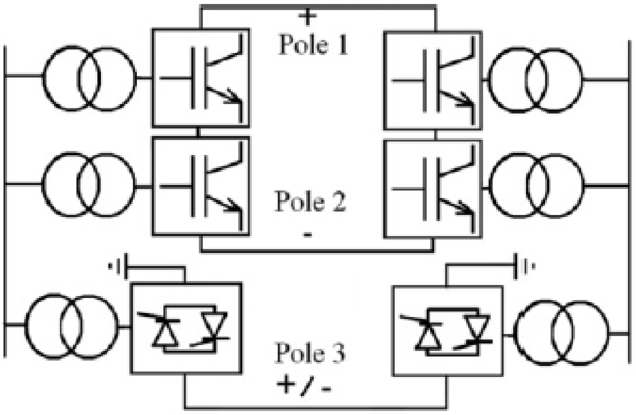


Figure 4.4: VSC based Tripolar DC line (Larruskain et al., 2014)

The distinct characteristic of this configuration is that all conductors use their full thermal capacity unlike on modulated bipolar where only one conductor would experience overheating due to exceeding rated current. Positive and negative pole alternate between high current state and low current state while pole 3 is said to be reversing its polarity periodically, sharing positive and negative current with poles 1 and 2.the operation is shown in figure 4.5 below. This configuration is capable of transmitting 1.37 times higher power than bipolar configuration. The power transmitted is defined by:

$$P_{dc} = 1.37I_dV_d + 0.37I_dV_d + I_dV_d \tag{4.3}$$

$$=2.74I_dV_d$$

$$= 1.37\ P_d$$

Where $1.37I_d$ is the high current state at pole 1 and $0.37I_d$ is the low current state at pole 2 and I_d is the rated current of pole 3.

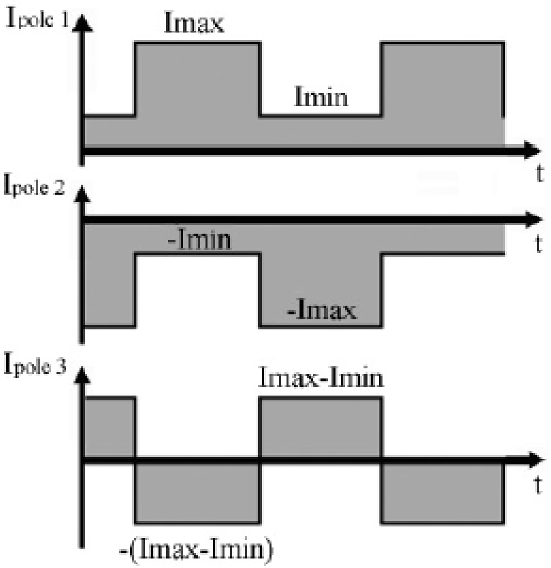


Figure 4.5: Operation of Tripolar DC Line (Larruskain et al., 2014)

From the three different adaptation methods discussed above, Bipolar system is seen as the most simple and economical configuration. However from the Power formula in (4.1) it can be seen that it transmits less power than Modulated bipolar and tripolar systems. The bipolar configuration operates similarly to the tripolar configuration but one needs to take note of the third pole that that uses thyristor based system on the latter.

4.2.2 Double Circuits AC lines

Double circuits AC lines consist of six conductors. This type of configuration can be adapted to three bipolar DC circuits. This is said to be the most productive method of conversion. Each circuit will consist of $\pm \boldsymbol{V_d}$ conductors (Arrillaga et al., 2007).The power that can be transmitted by AC line is defined by

$$\boldsymbol{P_{ac} = 6E_p I_L} \tag{4.4}$$

The corresponding DC line can transmit:

$$\boldsymbol{P_{DC} = 6I_d V_d} \tag{4.5}$$

Adapted Double circuits DC line can transmit up to three times the power transmitted by bipolar system.

4.2.3 Insulation

Insulation is considered as one of the most important aspects when converting an AC line to DC line. According to Kim et al., 2009 Insulation ascertains the number of flashovers to be expected on a statistical basis thereby ensuring the reliability of the DC line. Insulation must be properly selected such that it withstands overvoltage’s that resembles switching surges, flashovers due to contamination, lighting overvoltage and adverse environmental conditions.

Selection and sizing of line insulation is governed by the ratio between the continuous working withstand voltage between AC and DC systems. For a given insulation length, the ratio of continuous working withstand voltage is

$$\boldsymbol{k} = \frac{DC\ withstand\ voltage}{(rms)AC\ withstand\ voltage} \tag{4.6}$$

Kim et al., 2009 states that the environmental conditions of the route of the line have a conclusive influence on its reliability. Insulation contamination can be caused by the presence of polluted air, dew, fog etc. all these have major influence on the occurrence of flashovers. Arrillaga 2007 additionally notes that if a line is passing through a reasonably clean area k may be as high as $\sqrt{\mathbf{2}}$, corresponding to the peak value of rms alternating voltage. However (Larruskain et al., 2014) confirms that from the past experiments, a ratio of $\mathbf{k} = \mathbf{1}$ should be considered on overhead lines due to unfavourable effects of pollution on insulators. For cables $\mathbf{k}$ is at least 2.

Switching surges occur in a bipolar HVDC overhead line due to one pole experiencing a conductor-to-pole flashover (Kim et al., 2009). The potential of the other pole is said to be elevated. This in turn causes over voltages. With that being noted, (Arrillaga et al., 2007) suggested that a transmission line has to be insulated for over voltages during faults and switching operations. To properly select and size the insulation, the AC lines need levels of insulation corresponding to an AC voltage of 2.5 to 3 times the normal rated voltage as shown in equation below.

$$\boldsymbol{k_1} = \frac{AC\ insulation\ level}{\text{rated}\ AC\ \ voltage(E_p)} = \mathbf{2.5} \tag{4.7}$$

In contrast with suitable converter control, the corresponding DC insulation ratio is

$$\boldsymbol{k_2} = \frac{DC\ insulation\ level}{\text{rated}\ DC\ \ voltage(V_d)} = \mathbf{1.7}$$

(4.8)

It can be seen that the relationship between DC pole-to-ground voltage ($\boldsymbol{V_d}$) and the AC phase-to-ground voltage ($\boldsymbol{E_p}$) exist.

$$\boldsymbol{insulation\ ratio} = \frac{insulation\ length\ required\ for\ each\ AC\ phase}{insulation\ length\ required\ for\ each\ DC\ pole} \tag{4.9}$$

$$= \left(\boldsymbol{k} * \frac{\boldsymbol{k_1}}{\boldsymbol{k_2}}\right)\left(\frac{\boldsymbol{E_p}}{\boldsymbol{V_d}}\right) \tag{4.10}$$

Apart from ensuring the reliability of the DC line, Outdoor insulators are known for isolation of conductors from towers. Three types of insulators are classified into porcelain, glass and composite. Figures 4.6-4.8 show the kinds of outdoor insulators.

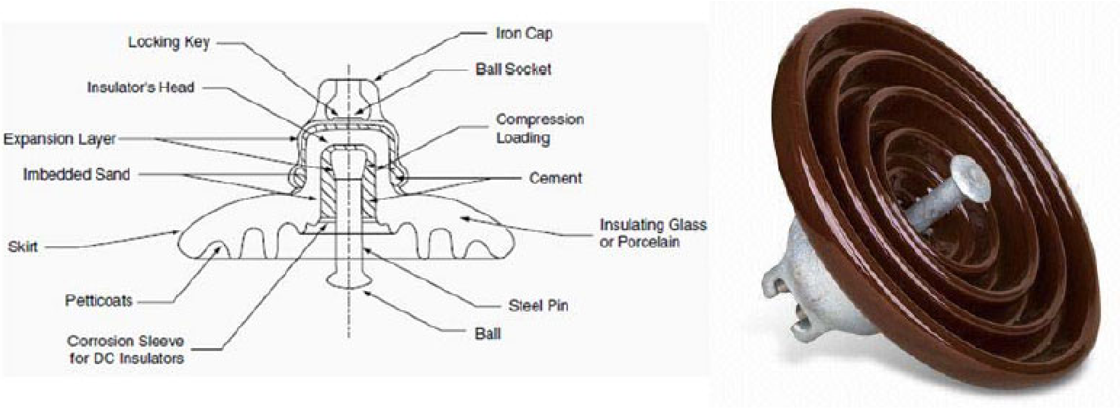


Figure 4.6: porcelain insulator (He , 2013)

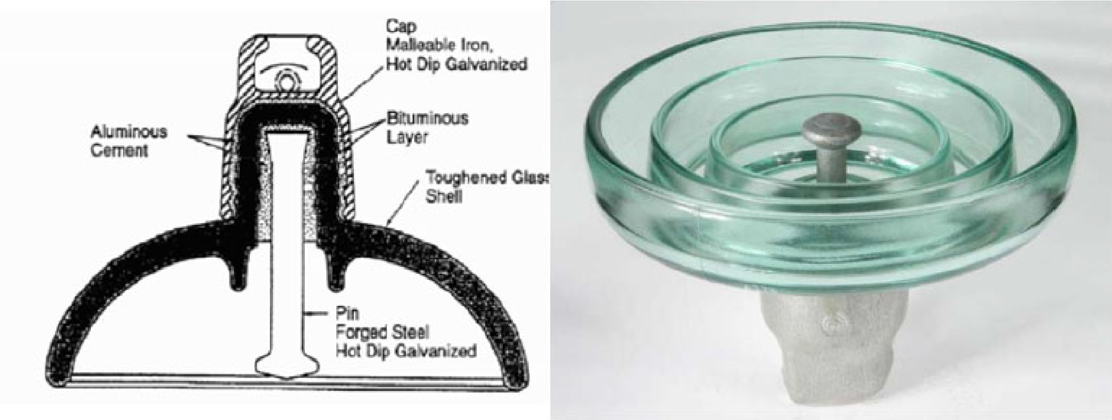


Figure 4.7: Glass Insulator (He , 2013)

Kim et al., 2009 states that there has been a debate in the in the industry with regards to relative merits of glass and porcelain caps. There were claims that when the porcelain insulator surfaces are wet, water tends to form a continuous film which could lead to significant decrease in surface resistivity. Glass insulators were identified as prone to fracture under stress. With improved design the glass insulators were seen as stronger that porcelain insulators due to their immunity to erosion. Additionally it is believed that it is easy to notice defects in glass insulators while they remain invisible in porcelain cap and pin. Nevertheless these two are said to be equivalent.

With the advancement in technology, Composite insulators were introduced to eliminate the effects of pollution thereby preventing line flash-overs. They have shown excellent behaviour in polluted areas. They came in reduced weight and high creepage on short length when compared to porcelain and glass. The distinct characteristic of composite insulators is the hydrophobia of the surface. No water film is formed on its surface .this type of insulator has been used in HVDC for more than a decade and it is supposedly the future insulator.

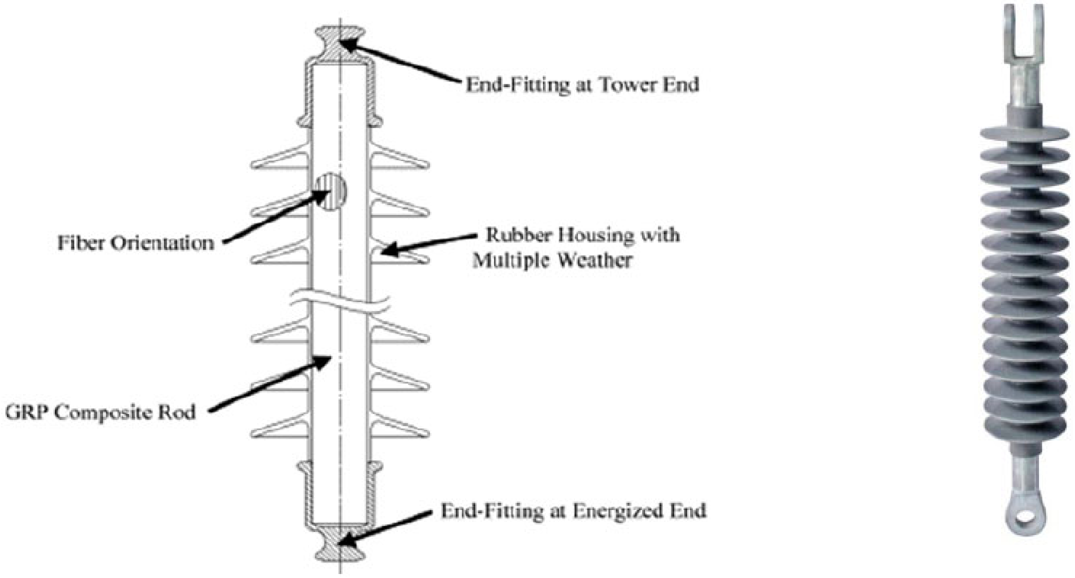


Figure 4.8: Composite insulator (He , 2013)

4.2.4 Conductors

In most adaptations of AC lines to DC lines, same conductor is used.it should be noted that the choice of the conductor depends largely on corona and field effect considerations. It has been reported that corona and field effects do not institute an exceptional problem for DC voltages up to 1200kV.

4.2.5 Right of Way

The process of acquiring land for the new transmission corridors can be expensive and lengthy. On each project it is advisable to consider alternatives of more favourable routes from the point of view of wayleaves and any other limiting factors in the occurrence of faults.

For a given transmission capacity of 10 Gigawatts (GW) The space requirement of HVAC overhead lines can be four times higher than that of corresponding HVDC lines. If we take a look at figure 4.9 below, the 800 kV HVAC line would require a width of 425 meters when transmitting power via a link of 10 GW. While the HVDC line of the same capacity would only require a width of 100 meters (Teske et al., 2015).With HVDC overhead lines, only two towers and less number of conductors compared to corresponding HVAC which uses five towers with significant more conductors. A cost saving in material is also achievable with HVDC technology.

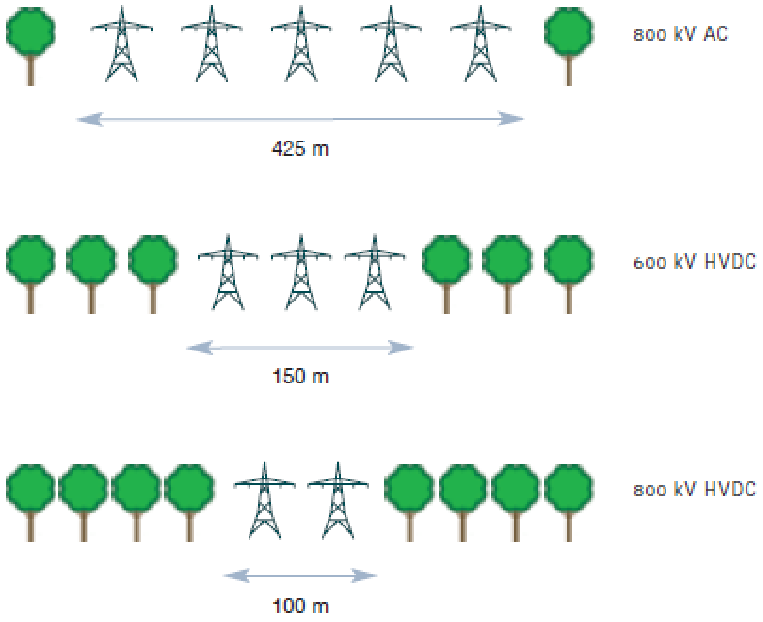


Figure 4.9: ROW comparison (Teske et al., 2015)

4.2.6 Clearance

Most of the existing HDVC lines are of bipolar configuration. The heads of the adapted towers ought to keep the required minimum clearance. It should be noted that the minimum clearance for conductor-to-ground must be adhered to as per national standards, not forgetting the maximum conductor sag at the maximum continuous current. Overhead AC system towers are over dimensioned; this makes the new DC voltage to comply with regulatory requirements as it is commonly within required clearance limits. However if the existing towers do not meet the minimum required clearances, a reconstruction may be done in a form of changing cross arms (Larruskain et al., 2014).one must bear in mind that the cost of reconstruction must always be less than the cost of erecting new towers. The figure below shows minimum clearance in air as a function of overvoltage factor.

Overvoltage factor (pu)	Minimum clearance in m at nominal voltage (kV)			
	250	400	500	750
≤1.5	0.91	1.37	1.83	3.35
1.6	0.91	1.37	1.98	3.66
1.7	0.91	1.52	2.13	4.11
1.8	1.07	1.62	2.20	4.57

Figure 4.10: Minimum clearance in the event of flashover due to overvoltage (Kim et al., 2009)

4.2.7 Environmental Effects

Utilities and engineering profession at large have an obligation to conserve and protect the environment in their business undertaking. Environmental effects posed by overhead transmission lines have been a concern lately. Electric field, Radio Interference, noise and visual impact are the major points of concern.

4.2.7.1 Electric field

In overhead lines, electric field is caused by the potential difference between the conductor and earth and the space-charge clouds produced by conductor corona (Arrillaga, 1998).In conductor cables the effects of corona were found to occur at voltages as low as approximately 15kV/cm (Kim et al., 2009).In case of overhead lines, the highest electric field strength that occurs is approximately 21kV/m for a given 450kV power line in figure 4.11.The electric field problem is less precautious in DC due to lack of steady-state displacement current. The critical point where ionization can start to occur due to field strength has been determined to be 29.8kV/cm.

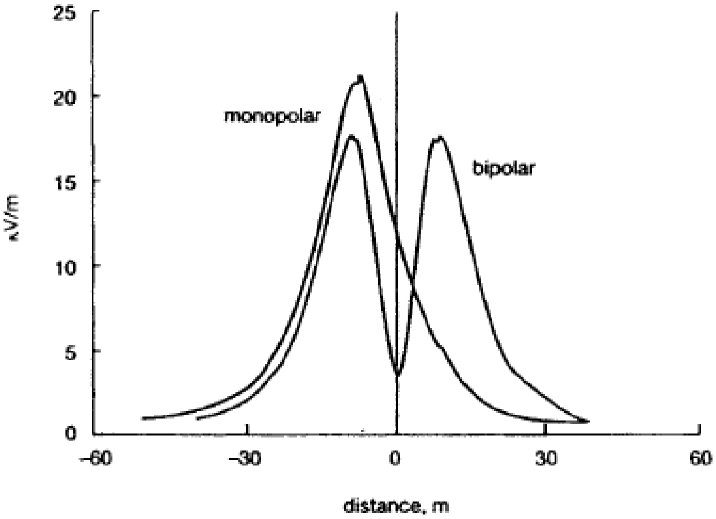


Figure 4.11: Electric field for both monopolar and bipolar lines (Arrillaga, 1998)

4.2.7.2 Corona, Radio Interference and audible noise

Kim et al., 2009 defines corona as the electric discharge with luminous phenomena as a result of the ionization of the air surrounding a conductor. This usually occurs in a non-uniform electric field when the field strength exceeds a critical value. Radio interferences and audible noise are primarily caused by corona discharge.

CHAPTER FIVE: VOLTAGE STABILITY

5

5.1 Stability concepts and definitions

Power system stability as defined by IEEE/CIGRE joint task force is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to physical disturbance, with most system variables bounded so that practically the entire system remains intact (Kundur et al., 2003).Power system instability has traditionally been limited to synchronous machines to remain in synchronism. However the instability issues are not limited to loss of synchronism only, voltage or load instability may lead to power system instability problems. Voltage stability is defined as the ability of a power system to maintain a steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance (Kundur, 1994).

The fast short circuit clearing and powerful excitation system has managed to overcome the synchronization problem. Utilities, researchers and planning engineers are now concerned with voltage stability being the leading factor to limit power transfers. Today's power system is being operated closer to stability limits due to economic and environmental constraints and this poses a threat to power system security. Power system is said to have entered a state of voltage instability when a disturbance, increase in load demand causes a progressive and uncontrollable drop in voltage (Kothari & Nagrath, 2011), (Kundur, 1994).

The principle of voltage stability says that at a given operating condition for every bus in the system, the bus voltage magnitude must increase with an increase in reactive power injection at the same bus. The system is said to be unstable if for at least one bus in the system, the bus voltage magnitude decreases as the reactive power injection at the same bus increased (Kundur, 1994).Consequences of events accompanying voltage instability may lead to voltage collapse, a process by which voltage instability leads to loss of voltage in a significant part of the system.

According to book written by Prabha Kundur, Voltage instability may occur in several different ways. a representation of simplified radial feeder or load area served by a large system through transmission line is demonstrated through figure 5.1.The two terminal network consisting of a constant voltage source (E_S) feeding the load (Z_{LD}) through series impedance (Z_{LN}) can explain a simple case of voltage stability (Kundur, 1994). The current expression is given by

$$I = \frac{E_S}{Z_{LN} + Z_{LD}} \tag{5.1}$$

$$= \frac{E_S}{Z_{LN}\angle\theta + Z_{LD}\angle\varphi}$$

The magnitude of the current is given by

$$I = \frac{E_S}{\sqrt{(Z_{LN}\cos\theta + Z_{LD}cos\varphi)^2 + (Z_{LN}\,sin\,\theta + Z_{LD}sin\varphi)^2}}$$

This may be written as:

$$I = \frac{E_S}{Z_{LN}\sqrt{F}} \qquad (5.2)$$

Where:

$$F = 1 + \left(\frac{Z_{LD}}{Z_{LN}}\right)^2 + 2\left(\frac{Z_{LD}}{Z_{LN}}\right)\cos(\theta - \varphi)$$

The magnitude of the receiving end voltage is given by

$$V_R = Z_{LD}I$$

$$= \frac{E_S}{\sqrt{F}}\frac{Z_{LD}}{Z_{LN}} \qquad (5.3)$$

The power supplied to the load is given by

$$P_R = V_R I cos\varphi$$

$$= \frac{Z_{LD}}{F}\left(\frac{E_S}{Z_{LN}}\right)cos\varphi \qquad (5.4)$$

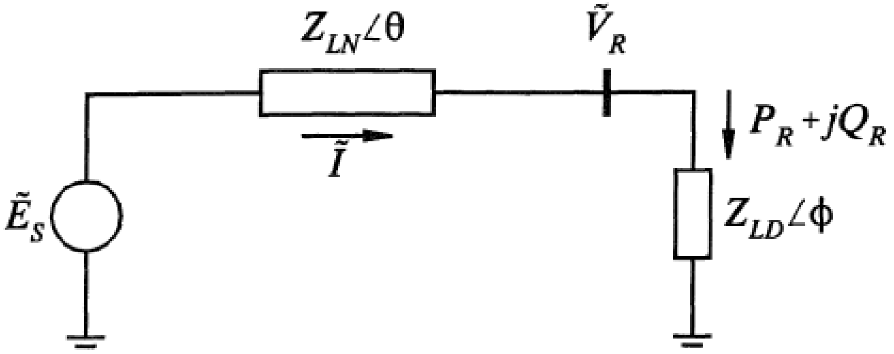


Figure 5.1: Voltage stability phenomenon (Kundur, 1994).

The picture of simplified voltage stability phenomenon in figure 5.2 is drawn by plotting receiving end voltage(V_R), current (I) and power (P_R)as a function of load demand$\left(\frac{Z_{LN}}{Z_{LD}}\right)$.As the load demand increases by reducing load impedance, the power supplied to load increases rapidly in the beginning then slowly before reaching a maximum. The power plot in green shows that there is a maximum value of active power that can be transferred through impedance from a constant voltage source. The reduction in load power takes effect due to load impedance being less than series impedance which then results in the receiving end voltage.

When the maximum power reaches a critical value, a critical operating condition is experienced. The correspondence between critical value and maximum power represents the limit to sufficient operation. For hire load demand, reducing power by means of reducing load impedance would result in unstable system as the load characteristics govern the system stability. With respect to constant impedance static load characteristics, the system stabilizes at power and voltage levels lower than desired values. While with constant power load characteristics, the instability is caused by collapse of the load bus voltage.as it was mentioned earlier that the driving force for voltage instability is usually the load characteristics.it can be seen that most of the instability issues are due to load stability which is sometimes called voltage stability. Though this phenomenon is not limited to load stability, other characteristics are due to transmission line and transformer effects (Kundur, 1994).

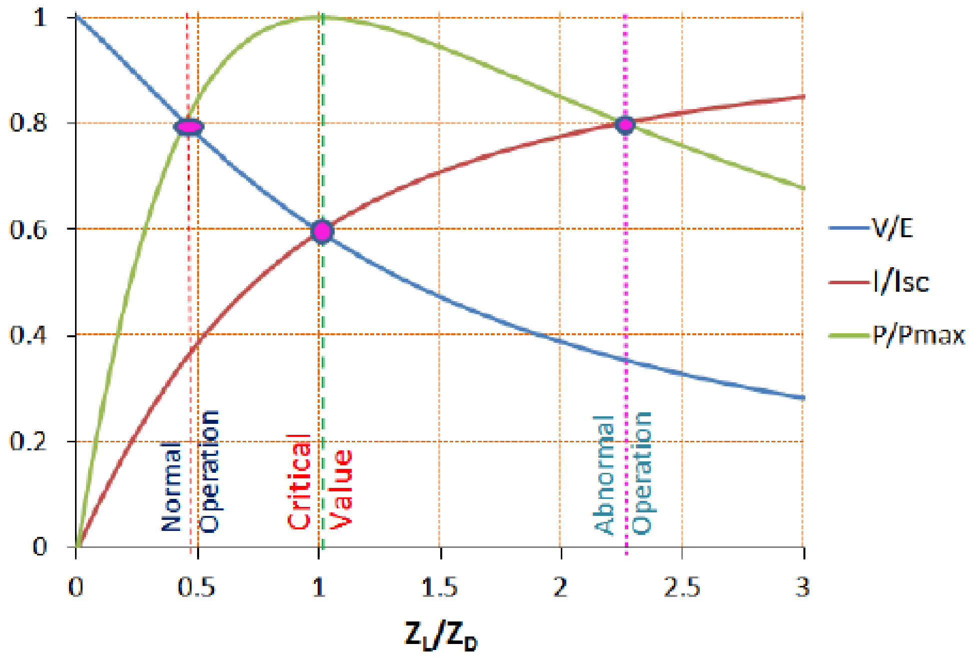


Figure 5.2: Receiving end voltage, current and power (Eskom, 2013)

Conceptual analysis of voltage stability is also shown through traditional P-V curves in figure 5.3.The various values of power factor are plotted where higher voltage solution indicates stable scenario while the lower voltage solutions indicates unstable operation. The locus of critical point is observed and shown through dotted line. This is the point where the system experiences the maximum power and critical voltage. All the points above critical points represent the system’s satisfactory operating condition

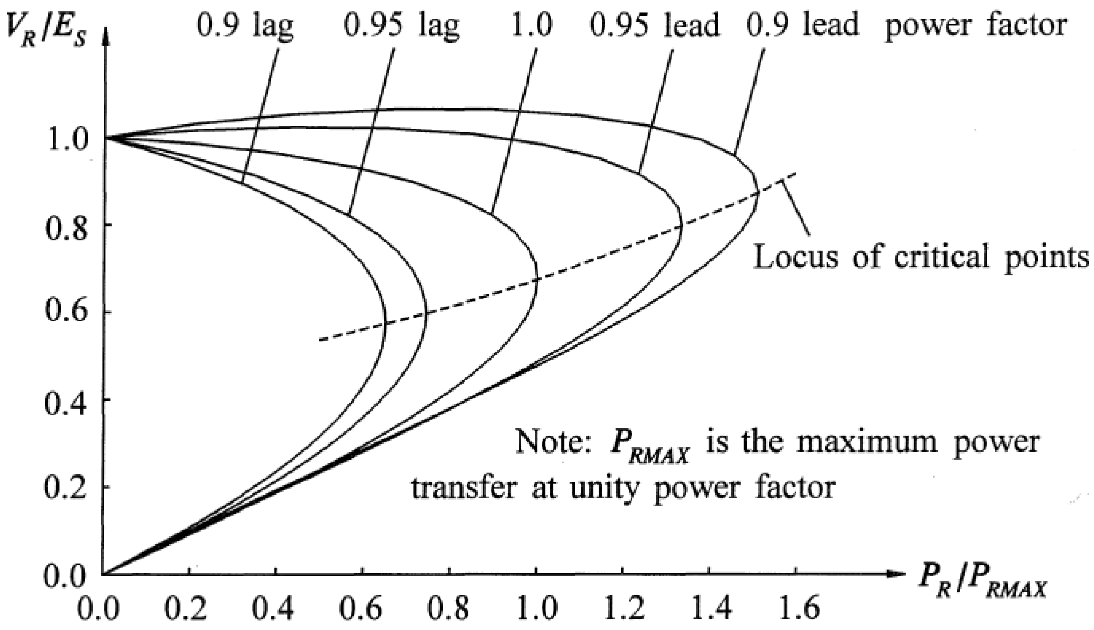


Figure 5.3: P-V curve for the analysis of voltage stability (Kundur, 1994)

5.2 Classification of Voltage Stability

Voltage stability is classified into four categories namely: large disturbance voltage stability, small disturbance voltage stability, Short term and long term voltage stabilities. The literature defines voltage stability according to sizes of disturbances, system states and time frames. A short outline of the groupings is shown in figure 5.4

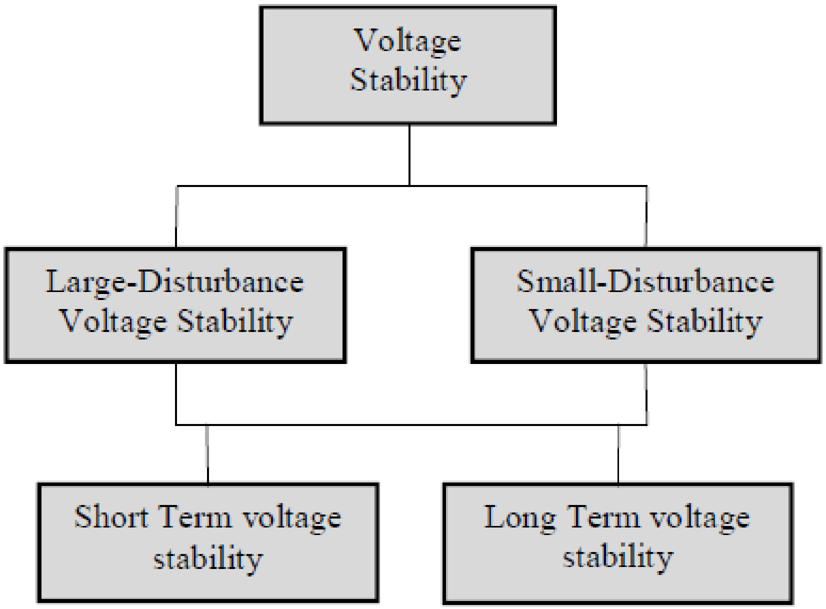


Figure 5.4: Groupings of Voltage instability (Taylor, 1994)

5.2.1 Large disturbance Voltage Stability

A power system that undergoes a larger disturbance is considered stable if the voltages approach post disturbance equilibrium values.

5.2.2 small disturbance voltage stability

A power system that undergoes a small disturbance at a given operating state is considered stable if the voltages are identical to or close to pre-disturbance equilibrium values.

5.2.3 Short voltage stability

Kundur states that this category was introduced following the need to resolve problems associated with dynamic response of power system to severe upsets. This involves fast acting load components such as HVDC converters, induction motors and electronically controlled loads. System differential equations are normally used to solve such stability problems and it may take several seconds to minutes.

5.2.4 Long term voltage stability

The long term voltage stability deals with slower and longer duration phenomena. These disturbances are usually accompanied by large scale system upsets which result in sustained mismatch between generation and consumption of active and reactive power (Kundur, 1994).some of the slower acting components are generator current limiters, thermostatically controlled loads and tap changing transformers. This study may take many minutes and long term dynamic system simulation is used as a solution.

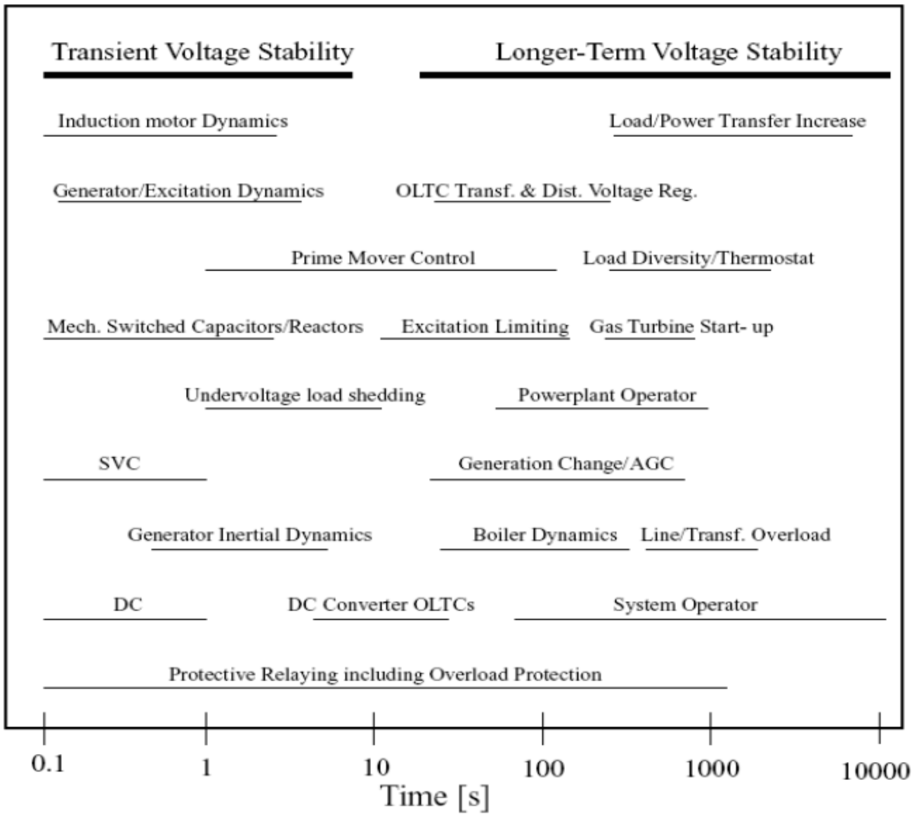


Figure 5.5: Time Span of Components and controls affecting voltage stability (Taylor, 1994)

5.3 Parameters affecting voltage stability

Voltage instability may emerge because of numerous reasons; some significant contributors are listed below.

- Increase in Load
- Switching of heavy loads
- Long transmission lines and line tripping
- Action of tap changing transformers
- Loss of synchronism (generator related parameters)
- Changes in speed prime mover
-

5.4 Mitigations of voltage stability

According to (Kothari & Nagrath, 20011), Voltage stability can be enhanced by the accompanying means.

- Erecting an additional transmission line
- Compensating the line length
- Enhancing the reactive power support by installing SCV and C-banks
- Enhancing excitation generators
- Introduction of HVDC tie between regional grids
- Last resort should be strategic load shedding

5.5 Stability concerns posed by DG in Distribution Network

Chapter five addresses system stability for Master sub-transmission network. Markus, 2015: IV notes that the Europeans simulation studies have shown network stability improvements when VSC HVDC link is incorporated into the sub-transmission network. He further says the improvement is noticeable even with small transmission capacity networks. However South Africa is the late adopter of the distributed generation and conversion of AC to DC lines and therefore had some stability concerns with regards to application of HVDC systems on sub-transmission and distribution networks.

The power system was designed through a top down approach with the synchronous generators connected at the transmission network and operated to transport large amount of active and reactive power from generation, through transmission, to the distribution network and eventually the load. The control of voltage and frequency thus was done on the transmission network by the system operator. Through the introduction of DG, the distribution network will be having generators connected on the high voltage (HV), medium voltage (MV) and low voltage (LV) system. This creates the previously passive network into an active network, with bidirectional power flow.

5.5.1 Voltage Stability Concern

Concerns were raised where voltage stability with embedded generation and sub synchronous resonance with wind turbines on series compensated lines were the most worrying aspects. The distribution network's reactive power supplying elements are lines, shunt capacitors, voltage regulators and On-load Tap Changers. Now with distributed generators of varying generator technologies such as photovoltaic systems (PV), wind turbines (WT), gas turbines, concentrated solar plants (CSP), and hydro power plants integrating into the network, the implications of inefficient control will have an impact on voltage regulation and losses. A typical distribution network with power flow of the feeder using standard control of the on-line tap changers (OLTCs) and voltage regulators (VRs) is shown if figure 5.6.

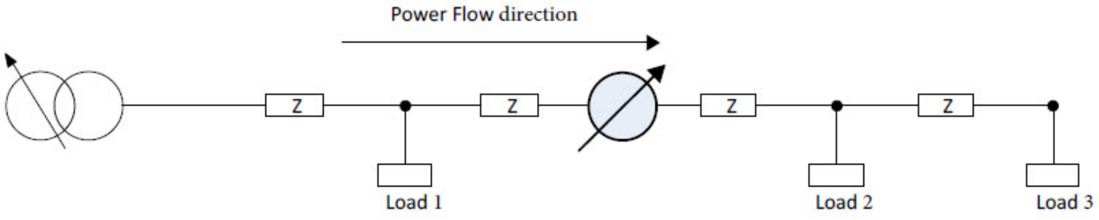


Figure 5.6: Distribution feeder with Voltage regulator (Eskom, 2013)

Figure 5.7. below shows the power flow for a feeder with varying size DG. The reverse power flow will impact the network and the control of the combination of the existing equipment and the newly connected DG brings uncertainties.

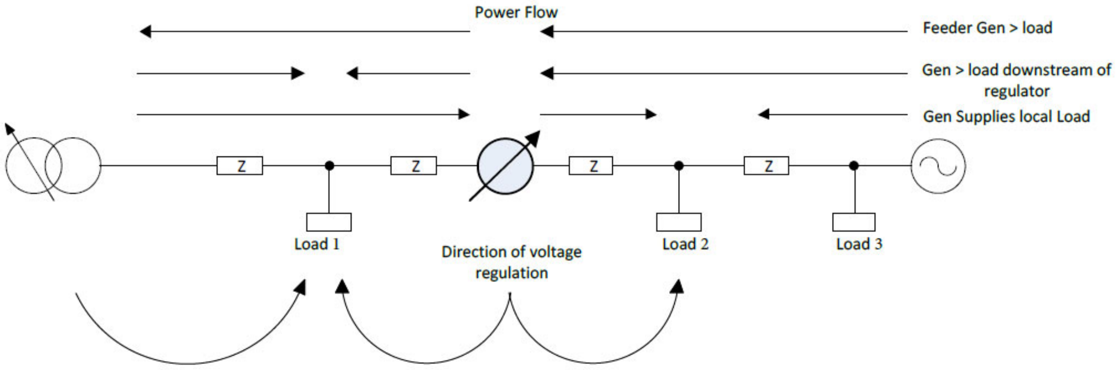


Figure 5.7: Distribution feeder with Power flow for varying levels of DG penetration (Eskom, 2013)

A number of factors to be considered when integrating DG were brought forward namely:

- I_{max} = current carrying capacity of the line at given temperature
- ΔV = change in voltage caused by DG integration
- Rapid voltage change(RVC) limits as specified on South African Grid Code (SAGC)
- (V_{max} and V_{min}) Maximum and minimum operational voltages.

Theoretical values were used to roughly assess the impact of DG while trying to conform to SAGC and voltage apportionment limit standards. The maximum DG penetration based on the above factors is shown in figure 5.8. The installable size is shown based upon the voltage change that a certain amount of DG would cause, when operating at unity power factor, along the entire feeder over the base voltage profile. For example, if DG of a size which causes a 3% ∆V is installed at a point, the voltage along the entire feeder will rise by 3% from the values without DG and with no additional changes to the network control.

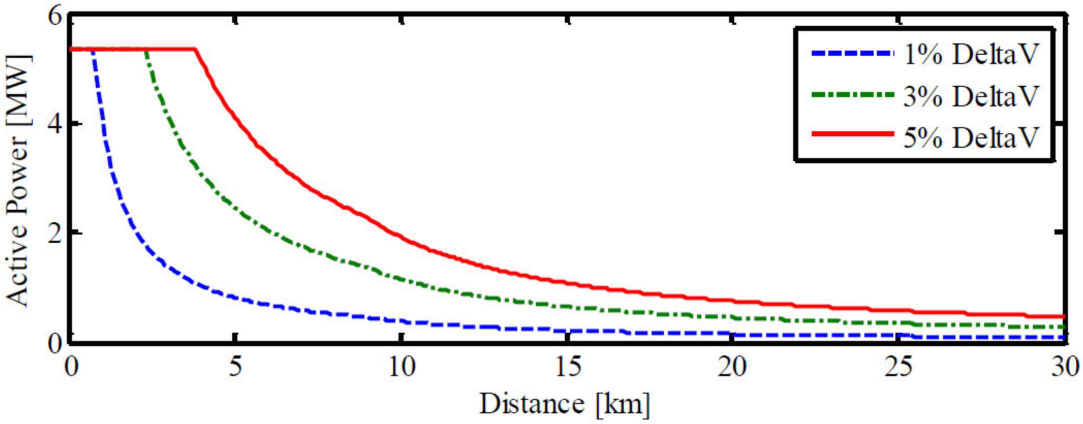


Figure 5.8: Injected MW as a function of Distance to scale ∆V (Eskom, 2013)

The theoretical values and compliance standards were used on the normal distribution network which would result in capacity enhancement in the absence of any previous network abnormalities. This resulted in utilities concluding that the viable option for the DG integration is network upgrade in a form of Voltage upgrade, conductor upgrade or building a dedicated line. The voltage stability posed by DG integration made the distribution planers and designers to be hesitant in the employment of HVDC link in sub-transmission networks, Even though the literature proves it to be possible.

CHAPTER SIX: HVAC Network Modelling, Case studies and Results Analysis

6

6.1 Case Back ground

The HVAC existing network to be modelled is characterised by low voltages and transmission lines overloading. The main contributing factor to voltage instability is usually the voltage drop during the power flow in transmission line. This may limit the capability of power transfer in transmission network. The overview of the affected part of the network is shown in figure 6.1 below. The source is from Master substation feeding the line connecting Willy and Billy to Dilly substation. Tap changing transformers are used to regulate the required output voltage. The network is operating with tap setting number 17 (last tap setting)

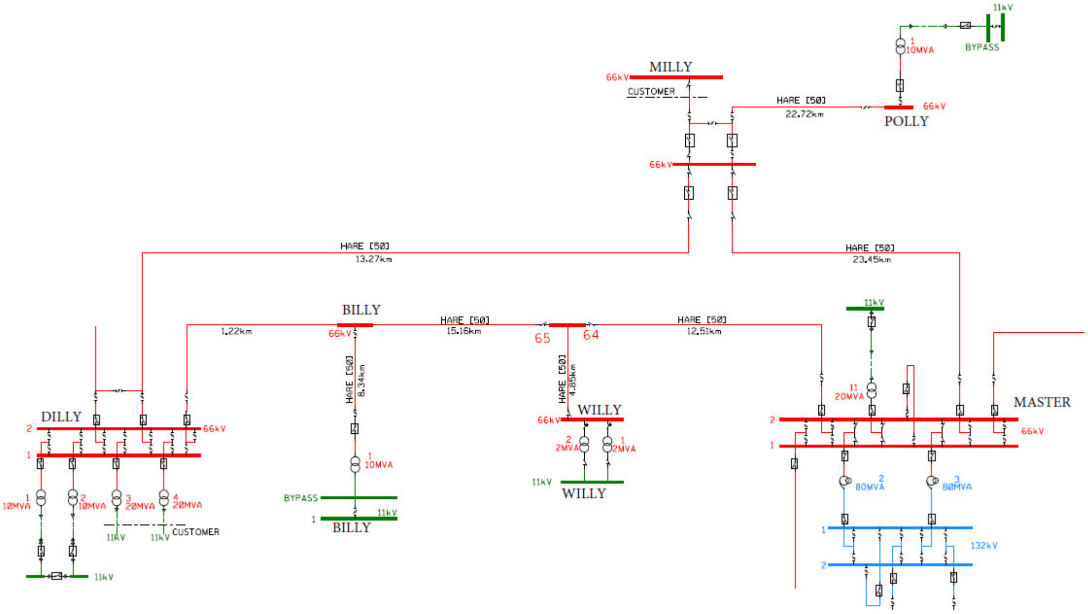


Figure 6.1: Overview of the Network to be studied

The aim of the case studies is to identify the non-conforming section of the network and to investigate which mitigation techniques presented in the literature can stabilize the network. Three scenarios are simulated under short circuit and contingency conditions where voltage is being monitored on the busbars and the capacity together with overloading are monitored on the HV lines of five substations namely Willy, Billy, Dilly, Polly and Milly.

6.2 Short Circuit Conditions

Short Circuit events were simulated to identify the critical part of the network where VSC-HVDC can be installed. The fault was applied in four major lines of the electrical network at study off which two had no significant effect on the voltage. The remaining two (Master-willy and Master-Milly line) showed voltage violation limits.

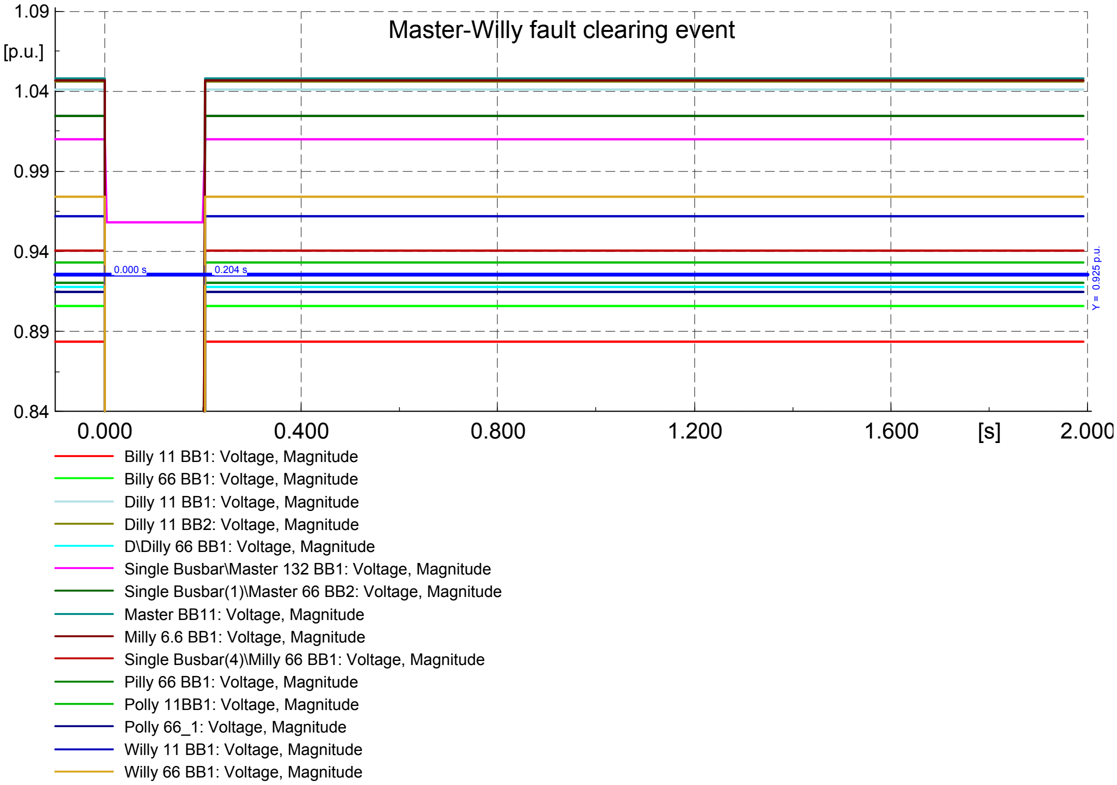


Figure 6.2: Master-willy fault clearing event

From figure 6.2 above, the blue thick line has been set as minimum operational constant of 0.925 per unit. Any busbar voltage that goes below this minimum set point is in violation of voltage regulation standards. The fault was applied for two seconds and cleared. Out of fifteen bubars being monitored, five busbars do not meet the minimum operational voltage of 0.925 per unit. This means that under fault conditions, thirty three percent of the customers are adversely affected by fault occurrences.

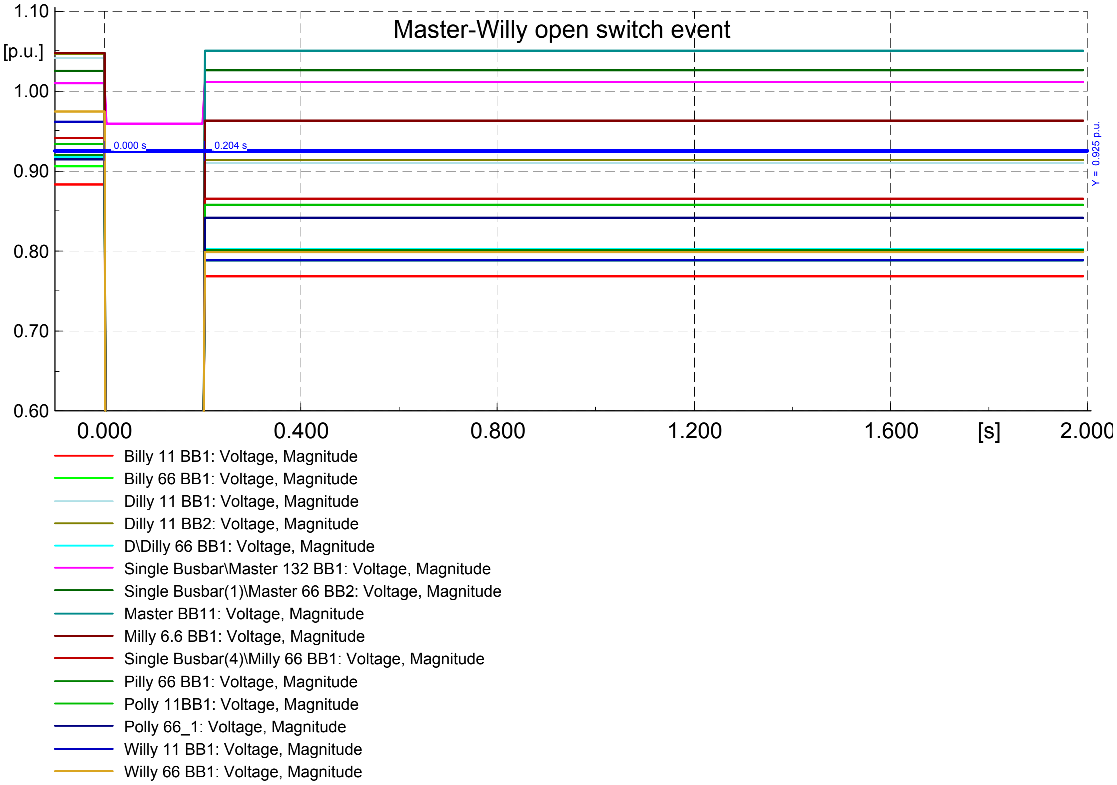


Figure 6.3: Master-willy open switch event

Figure 6.3 above shows an event where a fault occurred at Master –Willy overhead line and the switch remained open. It can be seen that seventy three percent of the network cannot deliver power to the customers as the bus voltages are below the minimum operating point of 0.925 per unit. If one takes a closer look on the colour coding of the busbars, it is mostly Masters Substation busbars (the source) that meets voltage regulation standards beyond minimum operational level.

The same principle was applied on master-Milly overhead line where a fault clearing and open switch events were monitored. Figure 6.4 and 6.5 show the results of such events. The network behaviour is more or less the same as that of Master-Willy events.

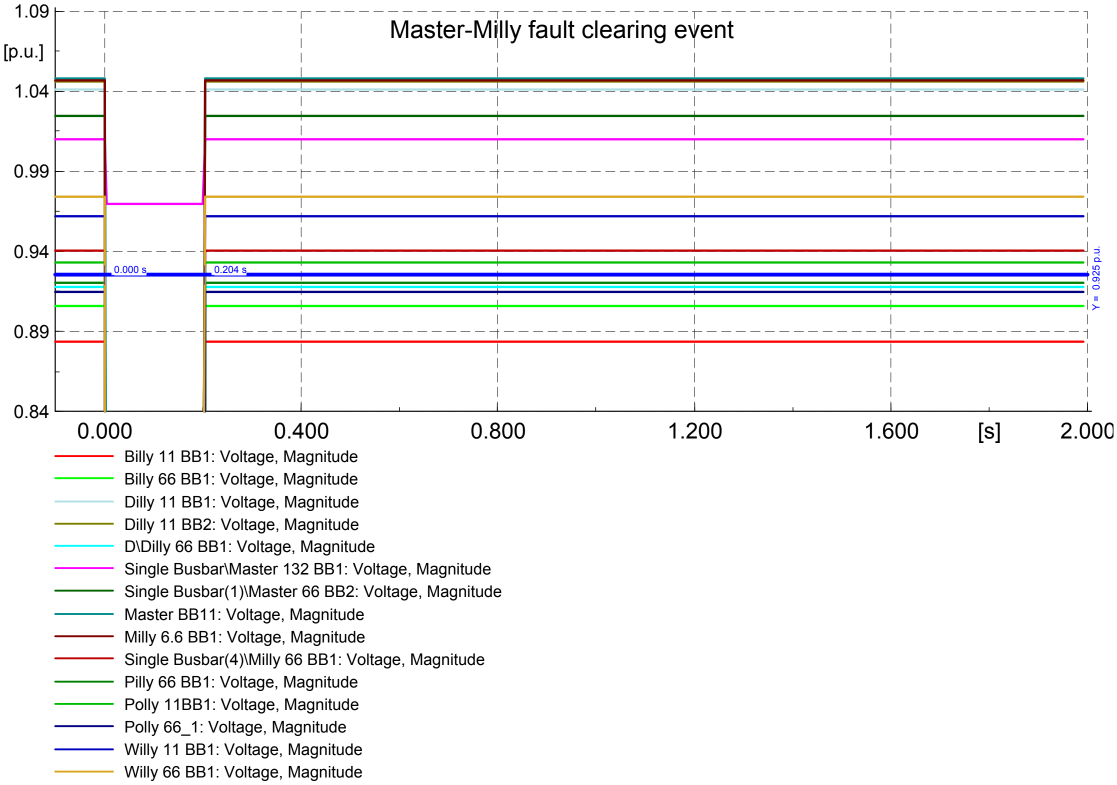


Figure 6.4: Master-Milly fault clearing event

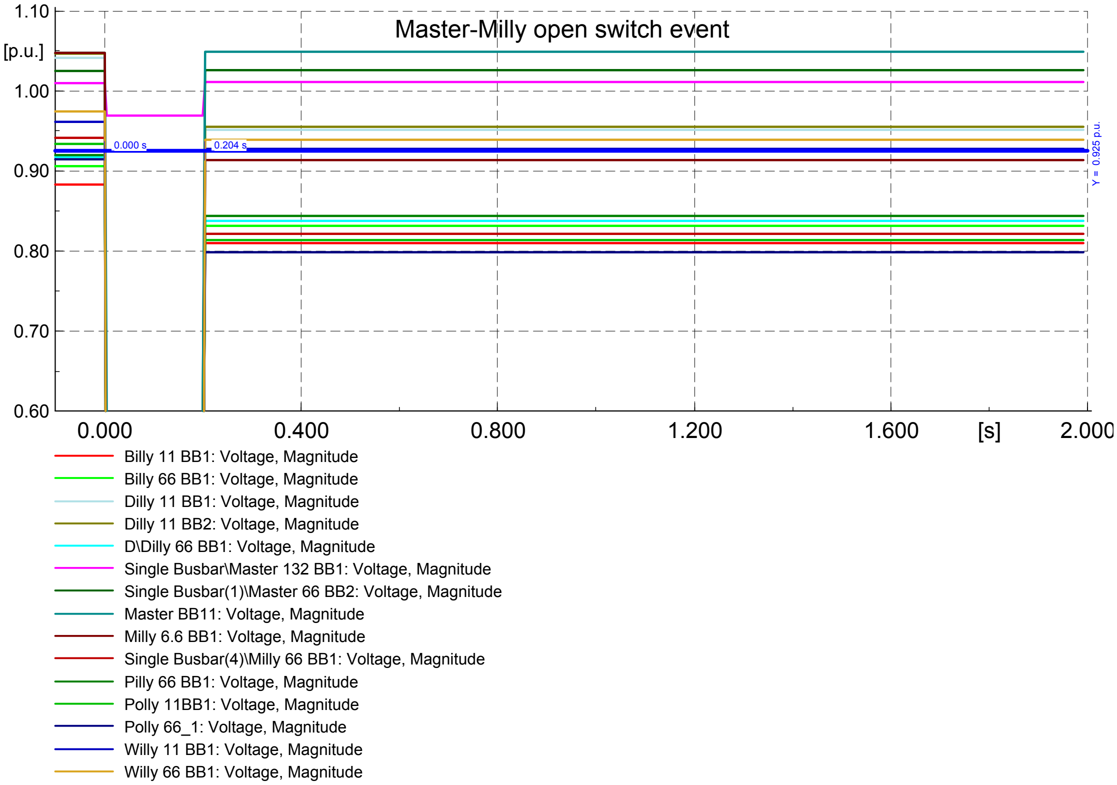


Figure 6.5: Master-Milly open switch event

6.3 Contingency Conditions

An emergency restoration plan was set out in order to manage the network during emergency conditions and minimise the supply interruption time. The network at study was monitored under three scenarios namely normal operation, N-1 with loss of Master-Willy 66kV overhead power line and N-1 with loss of Master-Milly 66kV overhead power line. Of the three scenarios, busbar voltage, percentage loading of the line as well as power carrying capacity in megawatts were monitored.

6.3.1 The normal operation network problem scenario 1

Simulation were done, the calculations converges. However the network does not deliver the required voltage in some of the substations on the interconnected power system. Zooming in onto figure 6.6 below, the 66kV busbar voltage at Dilly substation is 0.91 per unit. This value is below the minimum requirement of 0.925 per unit as set out on voltage apportionment limits for HV networks. It must be borne in mind that this is a load substation hence the prohibition of adding new loads to this network. On the other hand the backbone transmission lines are overloading close to 100% capacity and beyond while the maximum power transfer capacity is only 31 megawatts, see figure 6.7 and 6.8. This network behaviour raises voltage stability concerns as outlined in chapter five of this thesis.

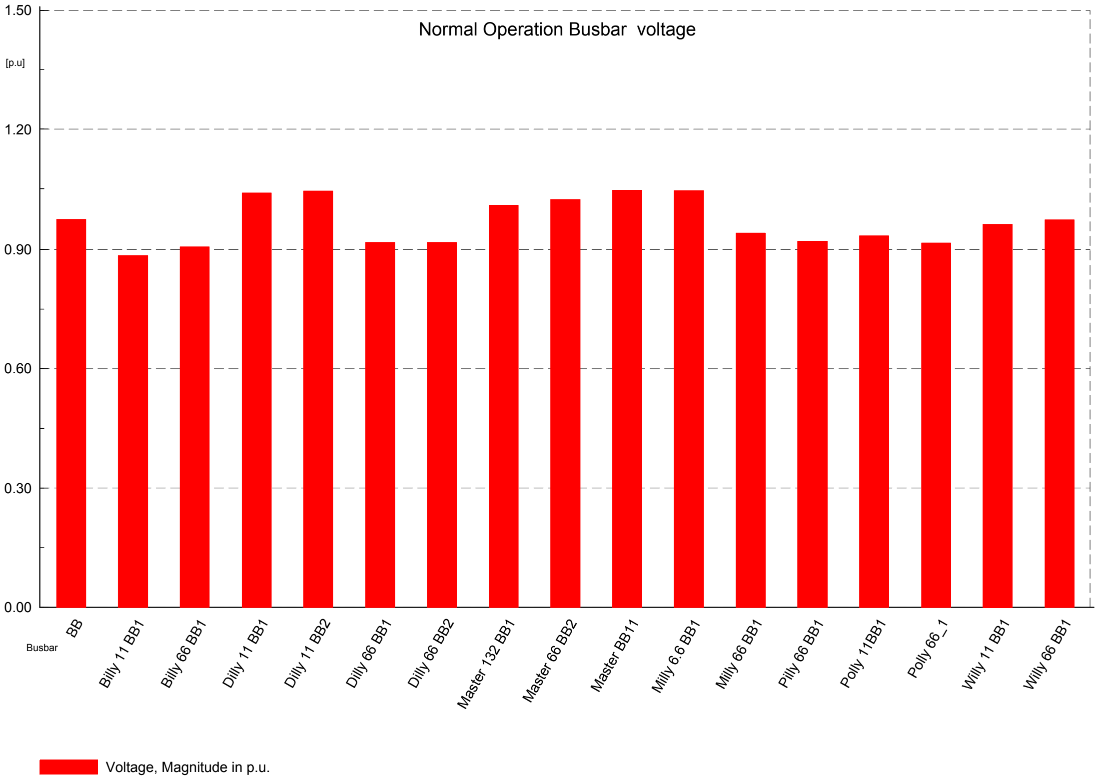


Figure 6.6: Busbar voltage normal operation

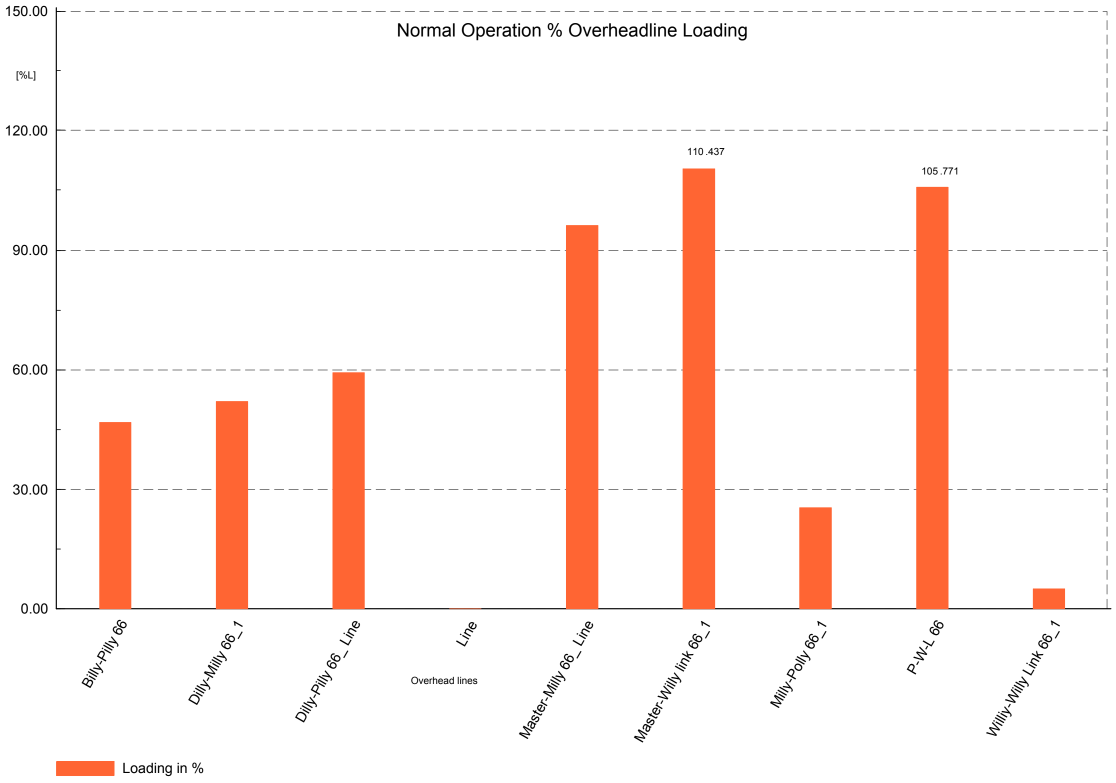


Figure 6.7: Normal Operation % Overheadline Loading

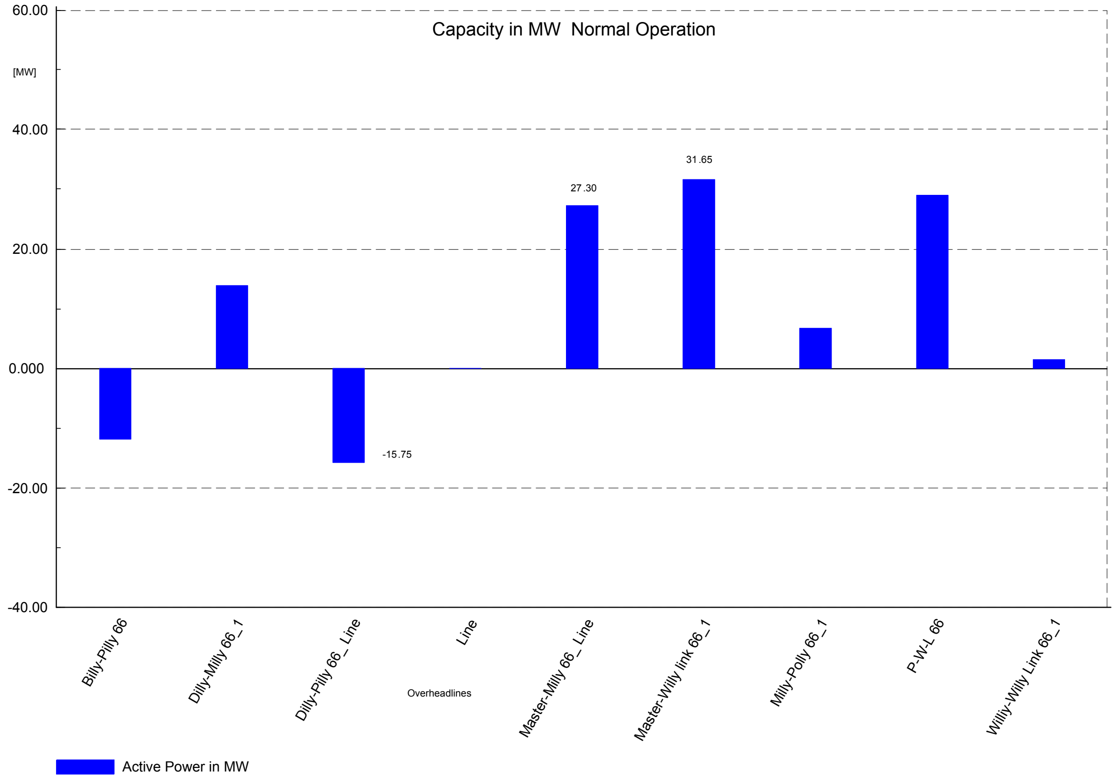


Figure 6.8: Line capacity normal operation

6.3.2 The Master-Willy leg off network problem scenario 2

If Master-Willy 66kV line is out of service, Willy, Billy and Dilly 66kV busbars voltage drops to minimum of 0.8 p.u respectively. This implies that under no circumstances will this line be out of service. On the other hand, the Master-Milly 66kV line get to be overloaded to 187% of Rate A rating and 102% of rate B rating of the conductor. Therefore Willy substation cannot be supplied due to low voltages and overloading (Thermal limits).Under this scenario three isolation points were opened along the line so as to verify this drastic voltage drop. Figure 6.9, 6.10 and 6.11 below shows the measured values at all affected busbars with their respective % line loading and power values.

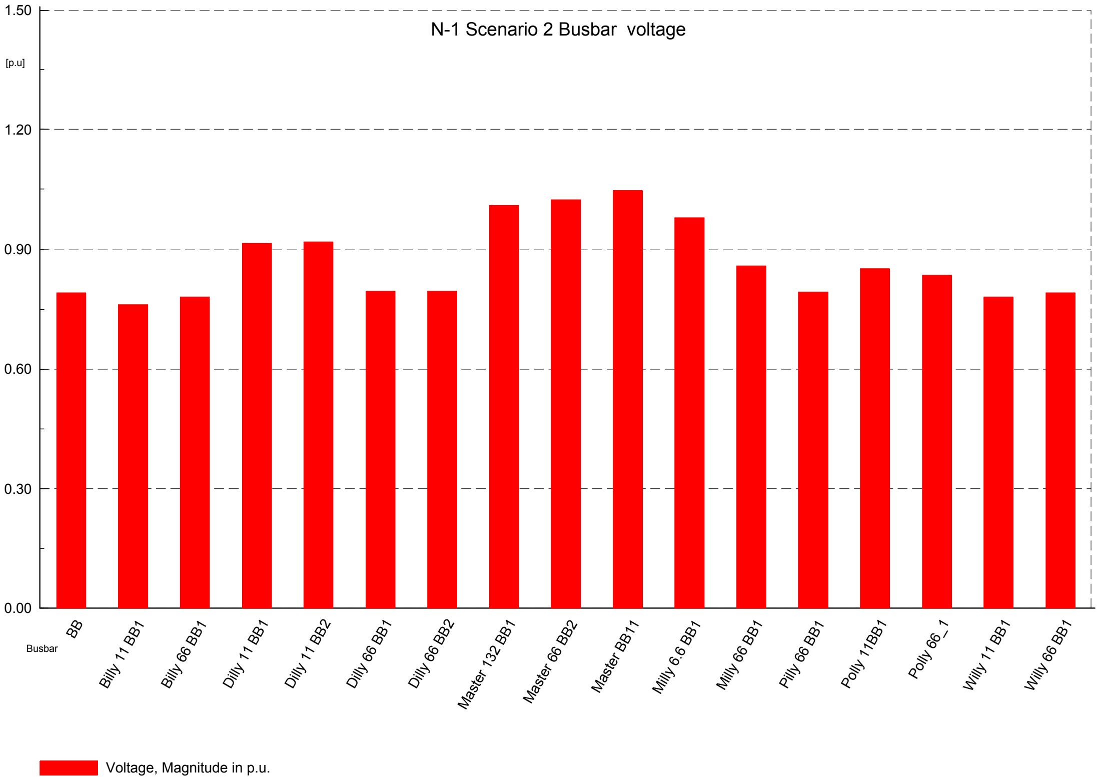


Figure 6.9: N-1 Master-Willy Busbar Voltage

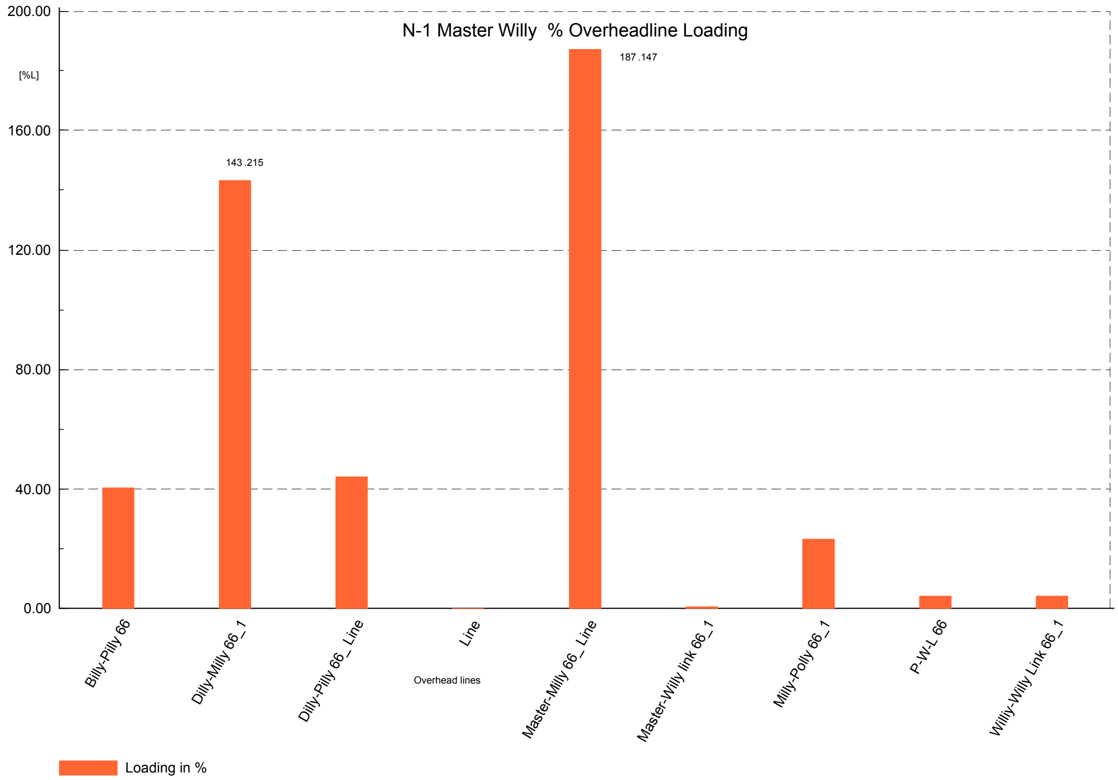


Figure 6.10: N-1 Master-Willy % Overhead line loading

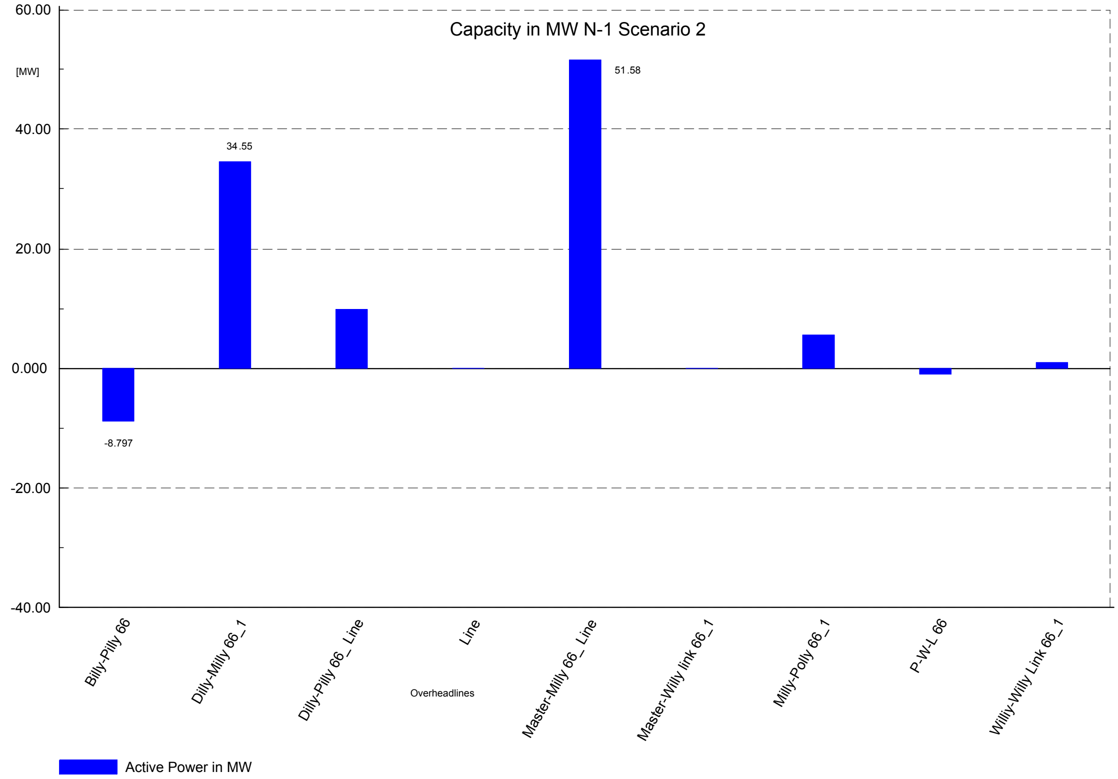


Figure 6.11: Line capacity N-1 Master-Willy

6.3.3 The Master-Milly leg off network problem scenario 3

If Master –Milly 66kV line is out of service, Willy 66kV busbar voltage drops to 0.93 pu. Billy and Dilly 66kV busbar voltage drops to 0.82 p.u respectively. Milly busbar voltage drops to 0.81 followed by Polly, the most severely affected busbar at 0.78 p.u. On the other hand, the Master-willy 66kV line get to be overloaded to 45MVA at 193.83% of Rate A rating and 100% of rate B rating of the conductor. Therefore Billy cannot be supplied due to low voltages and overloading (Thermal limits). Figure 6.12, 6.13 and 6.14 below shows the measured values at all affected busbars with their respective % line loading and power values.

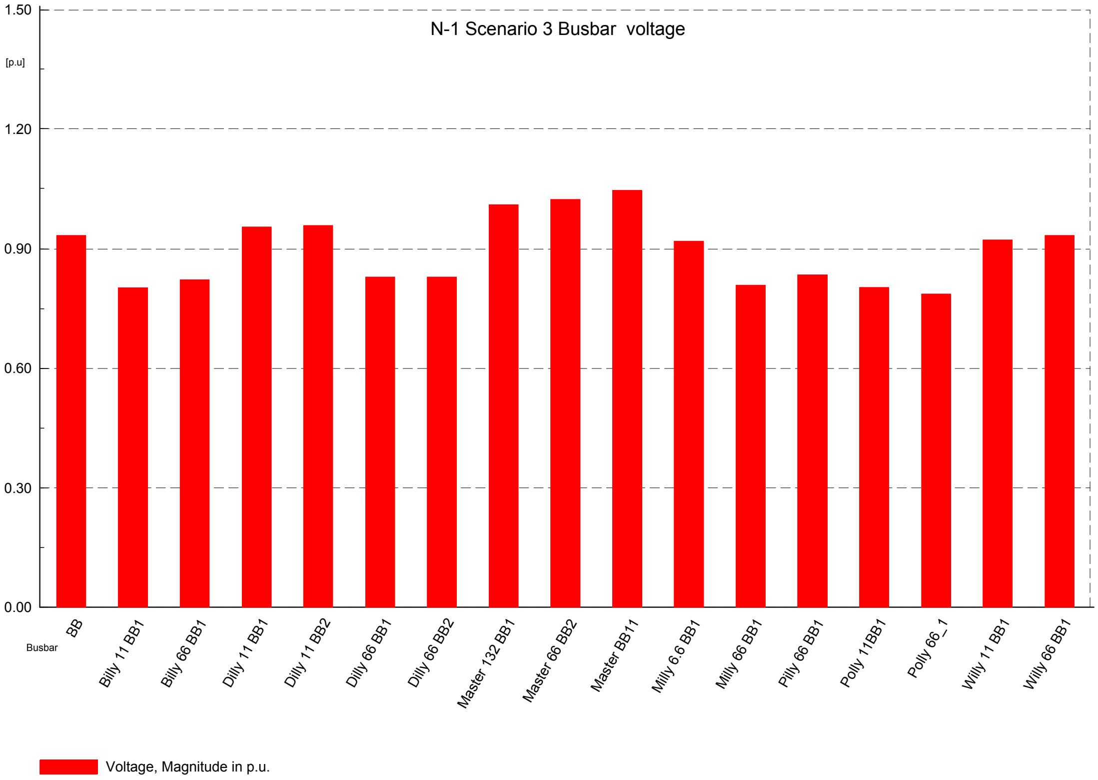


Figure 6.12: N-1 Master-Milly Scenario 3 busbar voltage

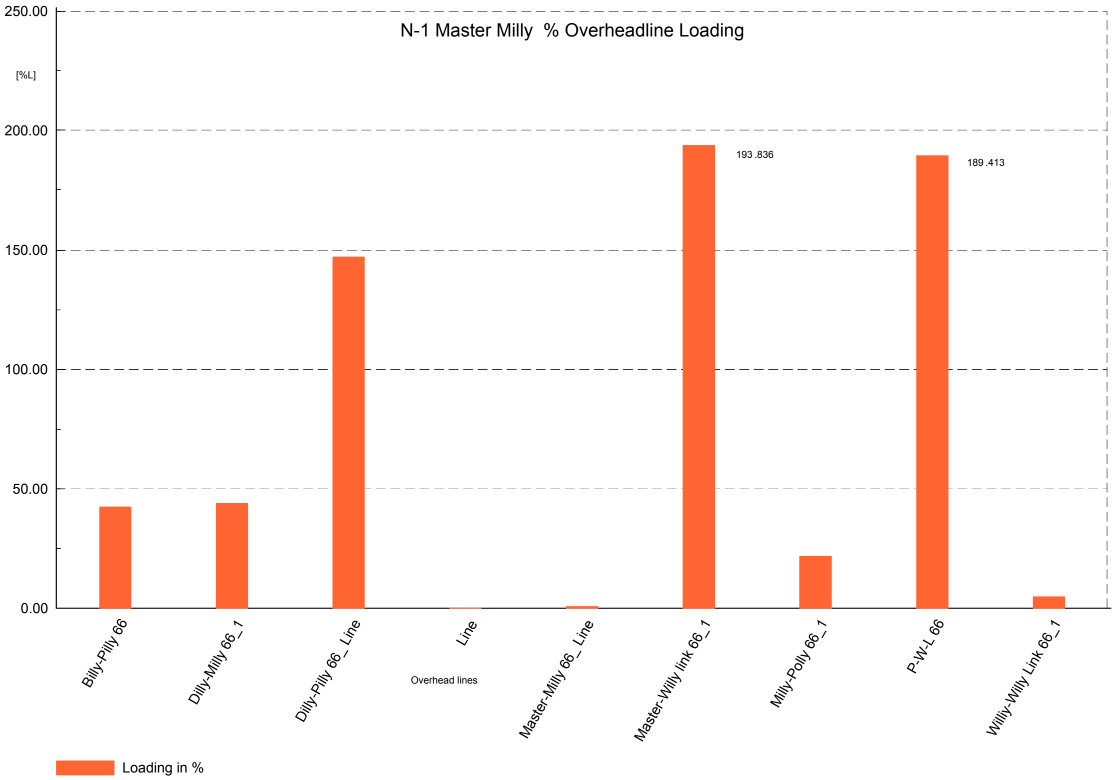


Figure 6.13: N-1 Master-Milly % Overhead line loading

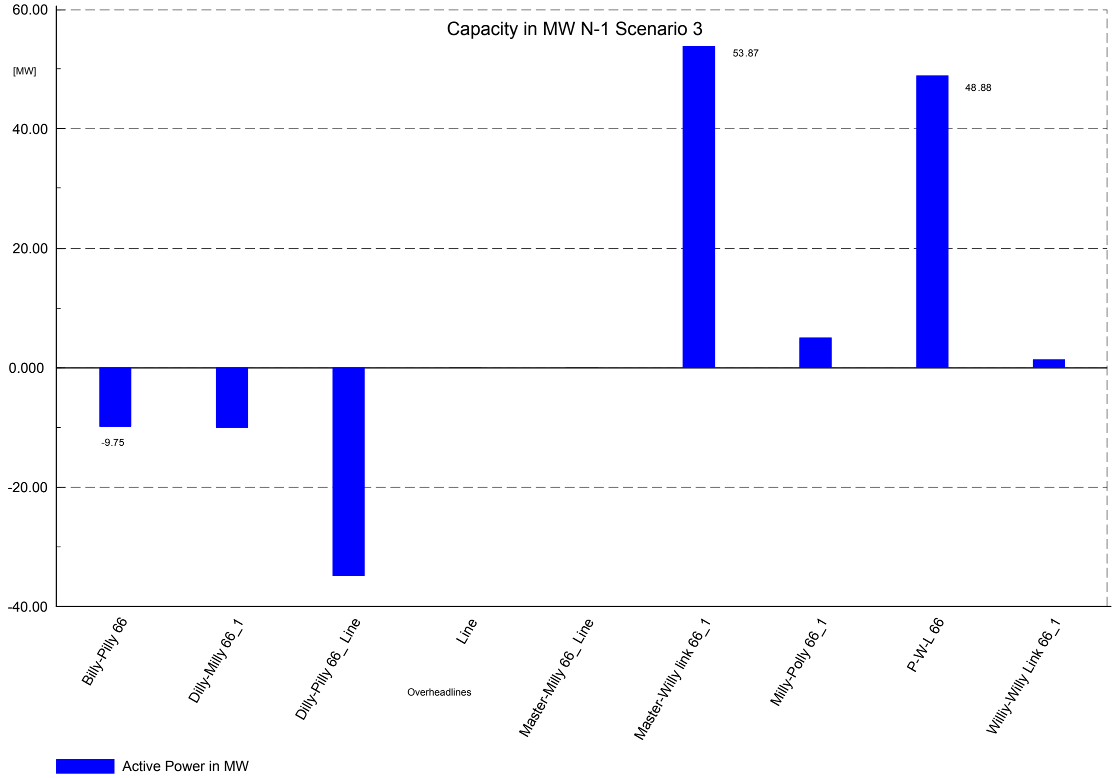
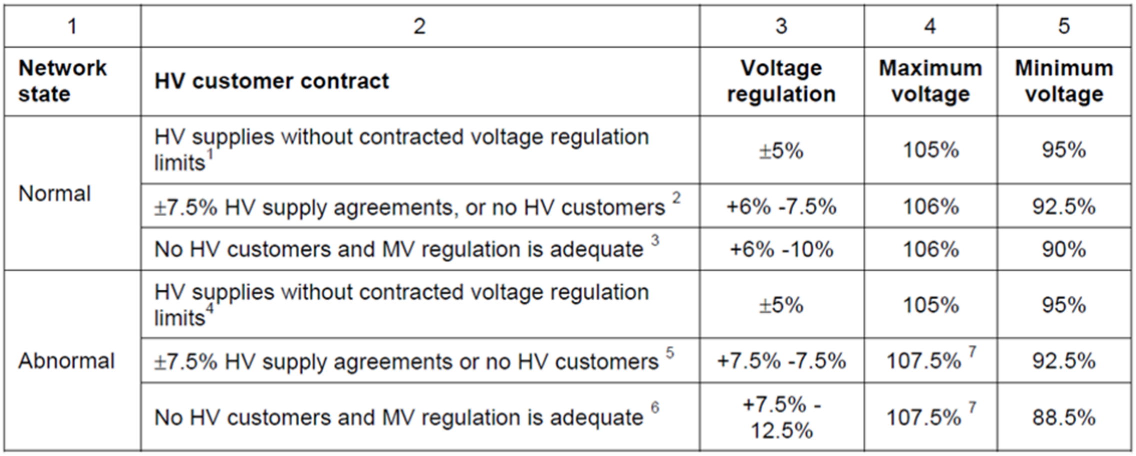


Figure 6.14: Line capacity N-1 Master-Milly

6.4 Analysis of results

The results recoded in figures 6.2-6.14 are for voltage magnitude in per unit, percentage loading of the backbone overhead transmission lines and power carrying capacity when Existing AC network is subjected to disturbances of various types and magnitudes .HV Network abnormalities affects a bigger number of consumers and therefore maintenance needs to be preventative and condition based. The power system security is a worrying factor as the network cannot withstand the effects of contingency and short circuit disturbances. This system is operated in heavily stressed conditions and is becoming more complicated to manage. According to Eskom distribution voltage and apportionment limits standard (DST_34-542) the recommended sub-transmission HV limits to be used are listed in figure 6.15 below. It can be seen from figures 6.2-6.14 that this portion of the network barely conforms to the minimum operating voltage as set out in HV standards in figure 6.15.



1	2	3	4	5
Network state	**HV customer contract**	**Voltage regulation**	**Maximum voltage**	**Minimum voltage**
Normal	HV supplies without contracted voltage regulation limits[1]	±5%	105%	95%
	±7.5% HV supply agreements, or no HV customers [2]	+6% -7.5%	106%	92.5%
	No HV customers and MV regulation is adequate [3]	+6% -10%	106%	90%
Abnormal	HV supplies without contracted voltage regulation limits[4]	±5%	105%	95%
	±7.5% HV supply agreements or no HV customers [5]	+7.5% -7.5%	107.5% [7]	92.5%
	No HV customers and MV regulation is adequate [6]	+7.5% -12.5%	107.5% [7]	88.5%

Figure 6.15: Standard operating Voltage limits for HV network

Looking at the ‘normal operation network” results, the operation is under severely stressed condition. Voltages of the system are partly below the accepted range; low voltage transformers as well as overhead transmission lines are showing the signs of being overloaded .furthermore there are no guarantees that the system can maintain stability during disturbances because the power system planning design is no longer compatible to today’s electricity demand.

The “Master-Willy leg off” results shows the system has been weakened to a level where a contingency violates the voltage regulation limits.as per figure 6.15, the minimum voltage is 88.5% provided that there are no HV customers and MV regulation is adequate.in all five substations the HV busbar is below the minimum limit.at this state the system transits into emergency state where control actions need to be applied to restore the system back to normal state. More or less the same behaviour was observed when master-Milly leg was out of service and therefore the third scenario will not be further elaborated.

Figure 6.16 shows the voltage profile of HV network under peak loading conditions. The sending end voltage is controlled by on-load tap changer transformer situated at Master substation. The transformer has reached the last tap setting and therefore no compensation method can be further applied by the component. From the planning perspective the operational voltage should be any value between 95% and 105% as shown in figure 6.15. However for operational purposes which are inclusive of contingency simulation studies allows the minimum of 92, 5% and maximum of 107, 5 % of abnormal voltage. It can be seen that the voltage decreases with distance away from source substation, which should be the case on distribution feeder. However it must range within allowable limits, which is not the case with figure 6.16.the voltage regulations limits are way violated. Also the red colour shows the overloaded transmission line thus another limiting factor on the capacity of the line.

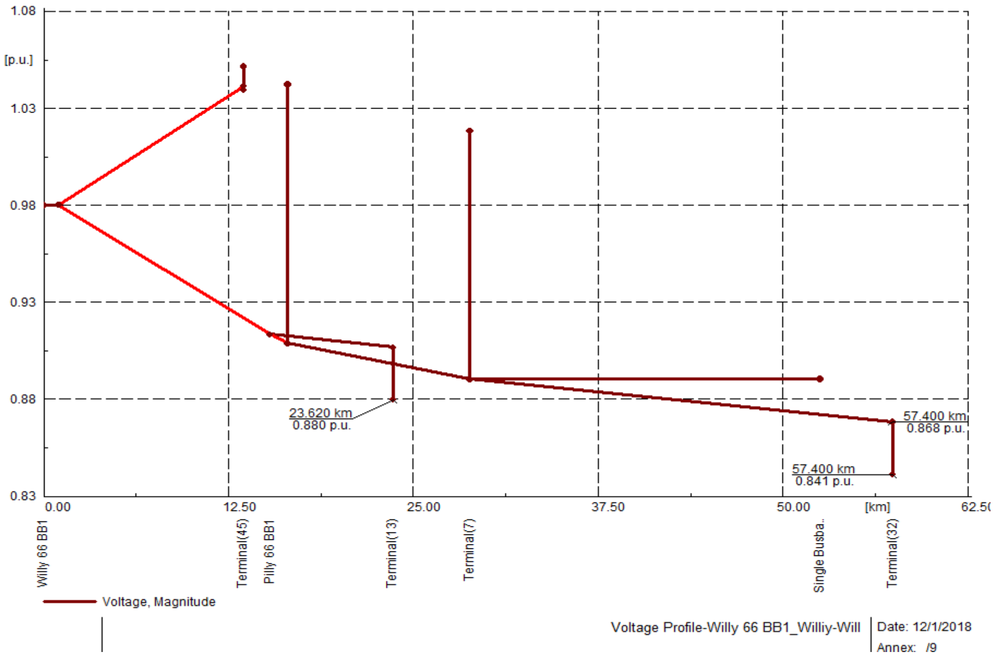


Figure 6.16: Voltage Profile

From the base case scenarios, 66kV bursars reactive power was also monitored.at Willy and Billy substations, a very small change that is an increase in reactive power is observed when the volt drop of 15% occurs. This is more evident at Dilly substation, where a significant change in voltage causes a noticeable change in reactive power. Under normal operation the reactive power is 5.99 MVARs. Under case B the voltage drops about 14% and the corresponding reactive power is 9.35MVARs. This implies that Dilly is a load substation and any rise in reactive power causes undesirable voltage drops and thermal loading.

It can be observed that the existing AC network is facing problem of low supply voltage tied with shortage of electrical energy. This is due to utilization of low current carrying capacity conductors that are overloaded and ultimately lead to volt drop and energy/power loses. This used to be a low voltage distribution network problem. However developing countries are faced with financial problems which prohibit them from upgrading the existing HV networks.

Network development plans would be focused on assessing the network requirements to meet additional loads and address issues that cannot be solved by optimisation of the existing network ensure that Distribution networks meet the minimum quality of supply, reliability and operational requirements as specified in the Distribution Network Code. The focus should be on improving power quality on constrained networks first, then reliability.

CHAPTER SEVEN: VSC-HVDC network modelling

7

7.1 Guideline for incorporating VSC-HVDC link in to weak AC system

This section details the power system analysis guideline followed in this thesis. The flow chart in figure 7.1 shows the outlined procedure followed when incorporating VSC-based HVDC link on the base case network studied in chapter 6. This is a high level procedure adopted by utilities. The VSC-HVDC system capabilities will be applied to see if there is a need for any network upgrade. Furthermore, is there any network capacity enhancement realized.

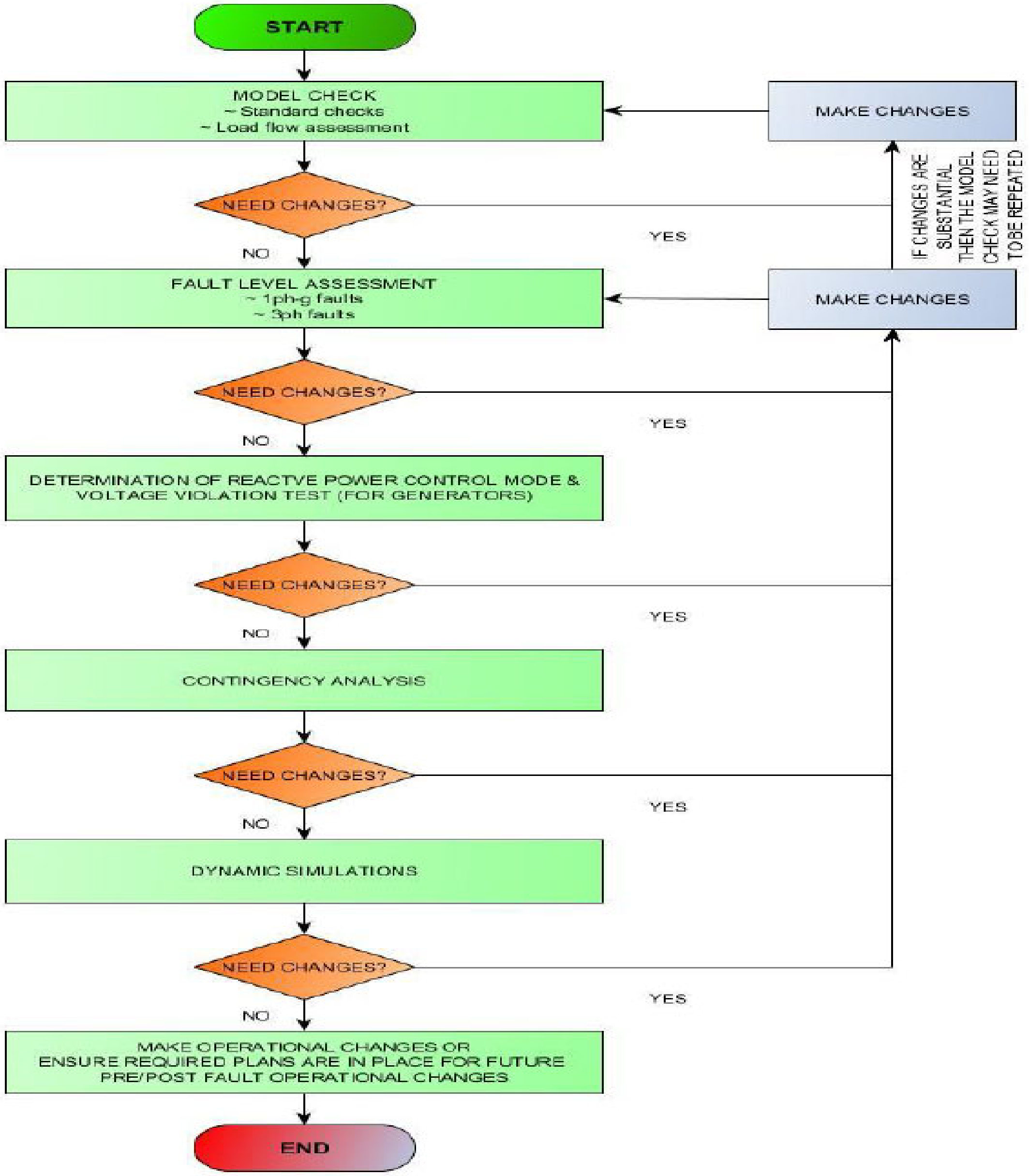


Figure 7.1: Flow diagram for VSC-HVDC link incorporation procedure (DNOP_240-82534300)

7.2 Modelling of a VSC-HVDC link

Figure 7.2 shows the single line diagram of a VSC-HVDC link as modelled on Digsilent power factory. For the purpose of this study, a simplified modelling approach was adopted where two converters are connected to one another by the HVDC transmission line. This VSC grid model is a replacement of existing HVAC link. The maximum increase in power transfer capability and voltage control will be based on a simplified transmission line model for short transmission lines.

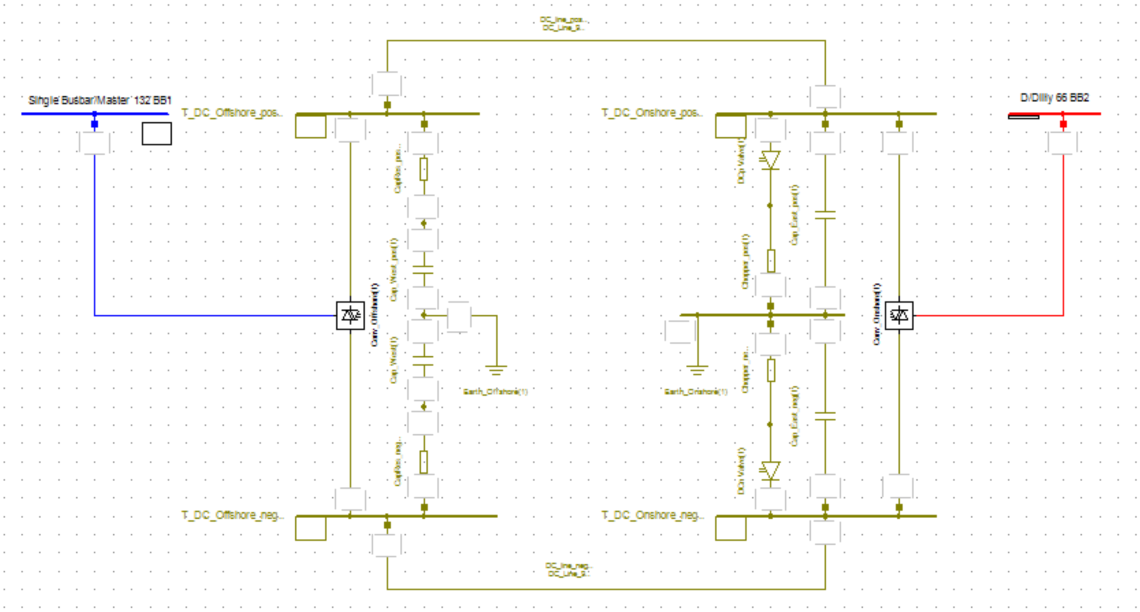


Figure 7.2: VSC-HVDC link single line diagram

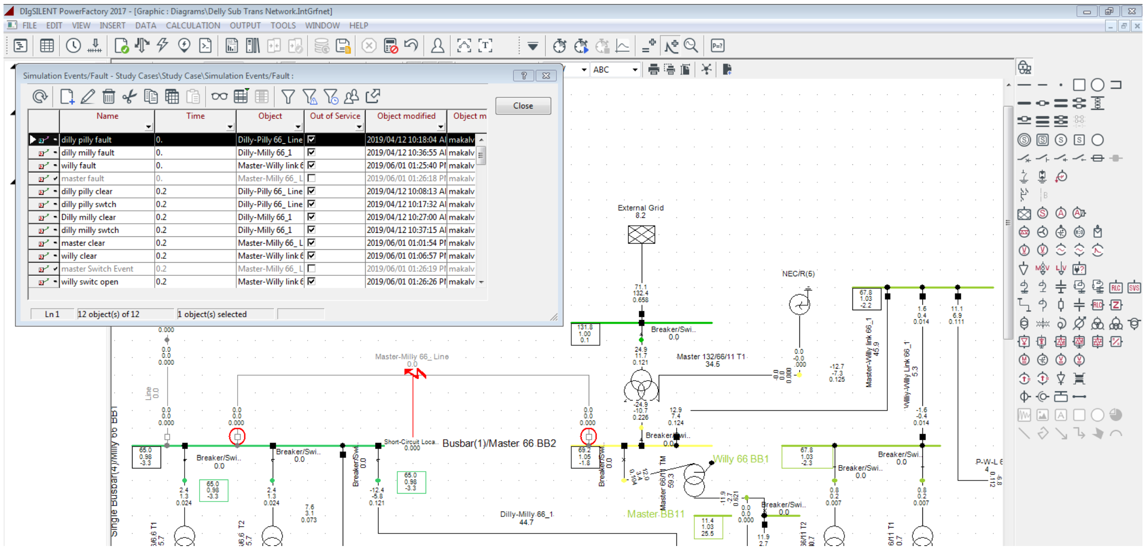
Power factory network reduction tool was used to provide a simplified representation of the AC network that contains the interface points. The two connection nodes are 132kV busbar with blue colour coding and 66kV busbar with red colour coding. The two converters were modelled as voltage source converters where an offs-sure converter was connected at 132 kV busbar on the source side of AC the network (see figure 7.4 rated AC-voltage).An on-sure converter was connected to 66kV busbar on the load side of the AC network (see figure 7.5 rated AC-voltage).

This type of arrangement also proves the phenomena highlighted by (Andersen , 2013:4) in chapter three of this thesis where he mentions that VSC-technology is not only limited to long distance transmission. Secondly it can be observe that it fulfils a situation where HVDC systems can be applied and expanded in a manner similar to AC substations. Initial step of the adopted flow chart presented in figure 7.1 is implemented at this stage of the simulation procedure. Standard network check and load flow studies were successfully executed.

7.3 Fault level assessment after VSC-HVDC link incorporation

Following the steps as set out on the guideline and using the reduced network representation in figure 7.2, the fault level assessment was carried out in a form of short circuit analysis to ascertain the system's adequate handling of short circuit. The outcome of the fault assessment may be to change the VSC-HVDC link control set-points or network configuration as the goal is to isolate the short circuit safely with minimal damage on the equipment and system interruption.

Recalling the short circuit results that failed the short circuit test in chapter 6, it was imperative to conduct the short circuit analysis so as to verify the admissible thermal limits of transmission lines and voltage tolerance of the system. Figure 7.3 is a demonstration of how the study could be simulated on power factory. It was then identified that the suitable position for VSC-HVDC link is between Master and Dilly substations.



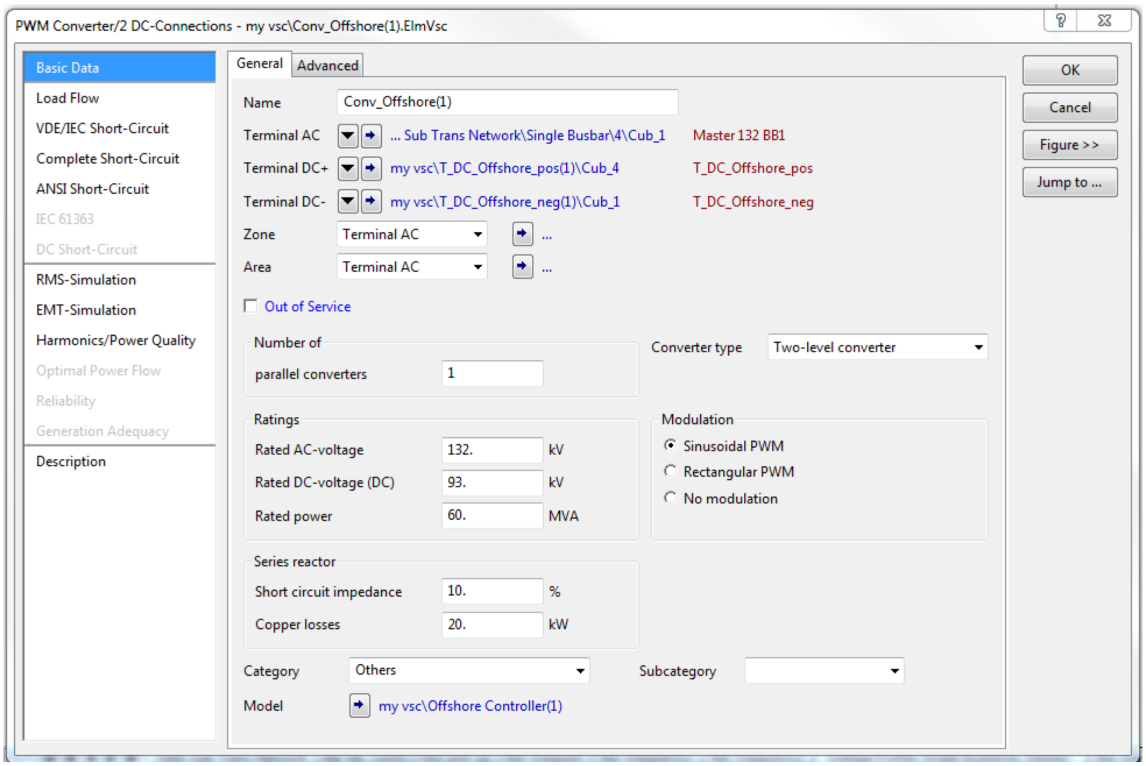
Name	Time	Object	Out of Service	Object modified	Object m
dilly pilly fault	0.	Dilly-Pilly 66_ Line	☑	2019/04/12 10:18:04 AI	makalv
dilly milly fault	0.	Dilly-Milly 66_1	☑	2019/04/12 10:36:55 AI	makalv
willy fault	0.	Master-Willy link 6	☑	2019/06/01 01:25:40 PI	makalv
master fault	0.	Master-Milly 66_ L	☐	2019/06/01 01:26:18 PI	makalv
dilly pilly clear	0.2	Dilly-Pilly 66_ Line	☑	2019/04/12 10:08:13 AI	makalv
dilly pilly swtch	0.2	Dilly-Pilly 66_ Line	☑	2019/04/12 10:17:32 AI	makalv
Dilly milly clear	0.2	Dilly-Milly 66_1	☑	2019/04/12 10:27:00 AI	makalv
dilly milly swtch	0.2	Dilly-Milly 66_1	☑	2019/04/12 10:37:15 AI	makalv
master clear	0.2	Master-Milly 66_ L	☑	2019/06/01 01:01:54 PI	makalv
willy clear	0.2	Master-Willy link 6	☑	2019/06/01 01:06:57 PI	makalv
master Switch Event	0.2	Master-Milly 66_ L	☐	2019/06/01 01:26:19 PI	makalv
willy switc open	0.2	Master-Willy link 6	☑	2019/06/01 01:26:26 PI	makalv

Ln 1 | 12 object(s) of 12 | 1 object(s) selected

Figure 1.3: Fault level assessment

7.4 Determination of VSC-HVDC control modes

It has been mentioned on the literature review in chapter three section 3.8 that VSC-HVDC has got the capability to control the system. Different control strategies were highlighted but the most documented one is a vector current control system, as a consequence the vector current control has been used on this thesis. The following basic data shown in Figure 7.4 and 7.5 was entered for the off-sure and on-sure converters respectively.



PWM Converter/2 DC-Connections - my vsc\Conv_Offshore(1).ElmVsc

Name: Conv_Offshore(1)

Terminal AC: ... Sub Trans Network\Single Busbar\4\Cub_1 — Master 132 BB1

Terminal DC+: my vsc\T_DC_Offshore_pos(1)\Cub_4 — T_DC_Offshore_pos

Terminal DC-: my vsc\T_DC_Offshore_neg(1)\Cub_1 — T_DC_Offshore_neg

Zone: Terminal AC ...

Area: Terminal AC ...

☐ Out of Service

Number of parallel converters: 1

Converter type: Two-level converter

Ratings

Rated AC-voltage	132.	kV
Rated DC-voltage (DC)	93.	kV
Rated power	60.	MVA

Modulation

● Sinusoidal PWM
○ Rectangular PWM
○ No modulation

Series reactor

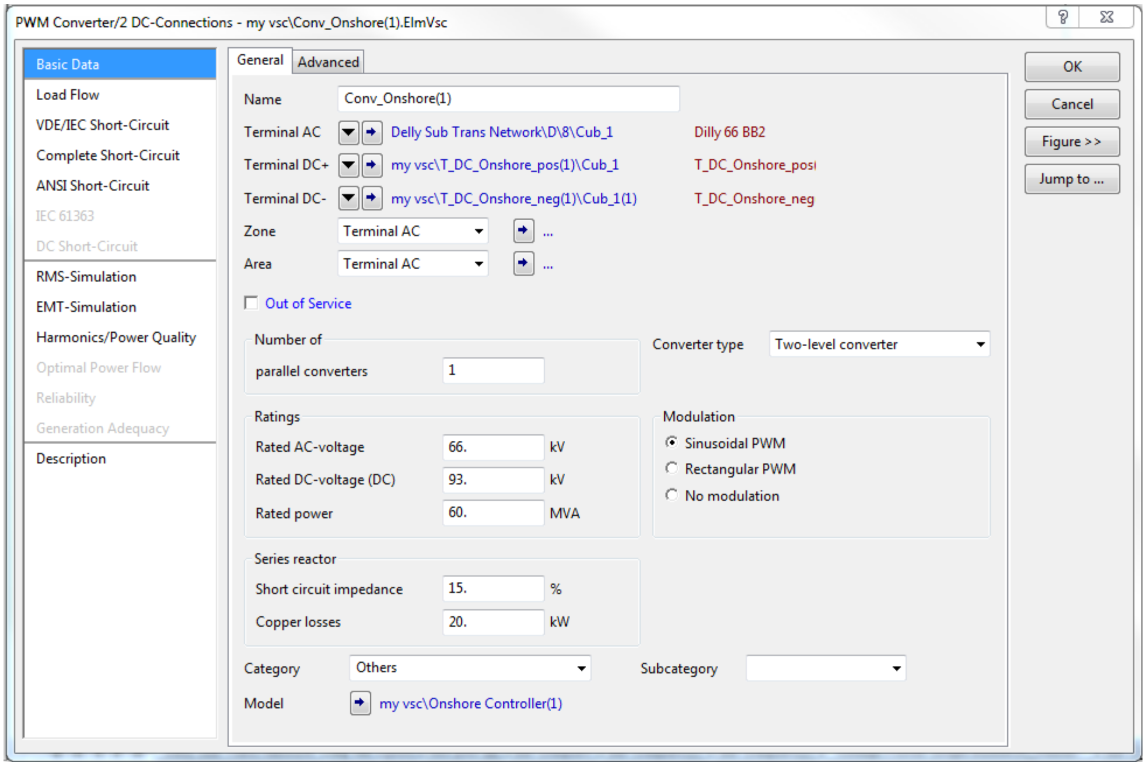
Short circuit impedance	10.	%
Copper losses	20.	kW

Category: Others

Subcategory:

Model: my vsc\Offshore Controller(1)

Figure 7.4: Basic data tab set up for off-sure converter



PWM Converter/2 DC-Connections - my vsc\Conv_Onshore(1).ElmVsc

Name: Conv_Onshore(1)

Terminal AC: Delly Sub Trans Network\D\8\Cub_1 — Dilly 66 BB2

Terminal DC+: my vsc\T_DC_Onshore_pos(1)\Cub_1 — T_DC_Onshore_pos

Terminal DC-: my vsc\T_DC_Onshore_neg(1)\Cub_1(1) — T_DC_Onshore_neg

Zone: Terminal AC ...

Area: Terminal AC ...

☐ Out of Service

Number of parallel converters: 1

Converter type: Two-level converter

Ratings

Rated AC-voltage	66.	kV
Rated DC-voltage (DC)	93.	kV
Rated power	60.	MVA

Modulation

● Sinusoidal PWM
○ Rectangular PWM
○ No modulation

Series reactor

Short circuit impedance	15.	%
Copper losses	20.	kW

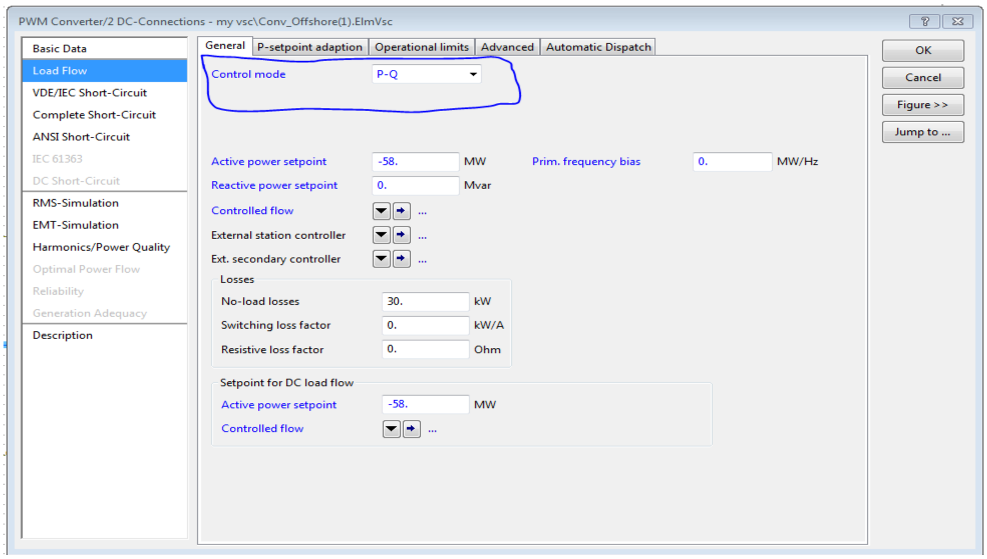
Category: Others

Subcategory:

Model: my vsc\Onshore Controller(1)

Figure 7.5: Basic data tab set up for on-sure converter

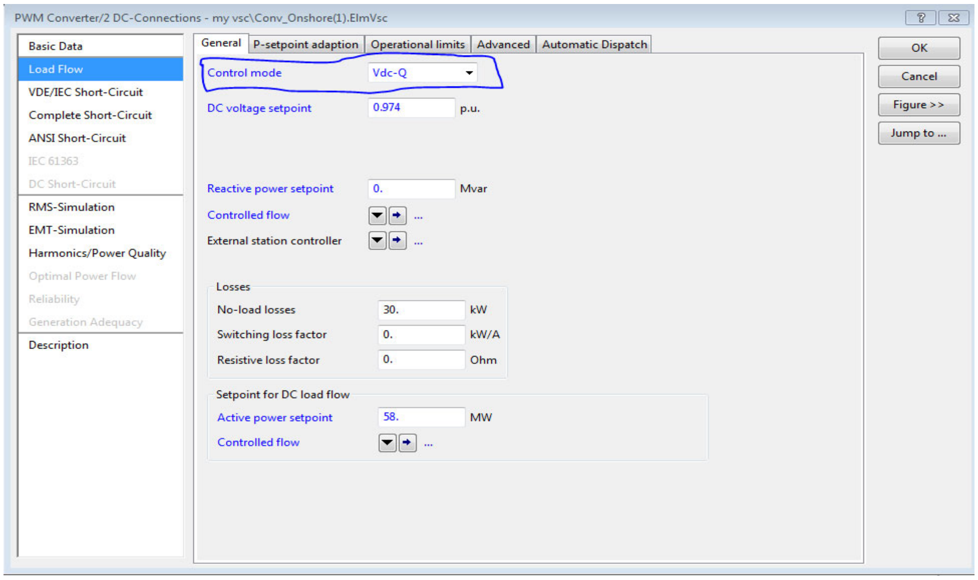
The voltage source converters come with station controller where a set point needs to be selected according the desired needs of the intended operation. Here a voltage control, power factor control and reactive power control mode can be chosen.in figure 7.6 below, P-Q control mode was selected for an off-sure converter to control the power of the system at study.



Control mode: P-Q
Active power setpoint: -58. MW
Prim. frequency bias: 0. MW/Hz
Reactive power setpoint: 0. Mvar
Controlled flow
External station controller
Ext. secondary controller
Losses
No-load losses: 30. kW
Switching loss factor: 0. kW/A
Resistive loss factor: 0. Ohm
Setpoint for DC load flow
Active power setpoint: -58. MW
Controlled flow

Figure 7.6: Power control mode

Therefore, on the on-sure converter the Vdc-Q mode was selected, this where the DC voltage is being controlled as the conversion from DC-to-AC takes place.



Control mode: Vdc-Q
DC voltage setpoint: 0.974 p.u.
Reactive power setpoint: 0. Mvar
Controlled flow
External station controller
Losses
No-load losses: 30. kW
Switching loss factor: 0. kW/A
Resistive loss factor: 0. Ohm
Setpoint for DC load flow
Active power setpoint: 58. MW
Controlled flow

Figure 7.7: DC voltage control mode

CHAPTER EIGHT: Results, Discussion and Recommendations

8

8.1 Short circuit conditions after Integration of VSC-HVDC link

After following methodology described in Chapter seven and subjecting the network to operation scenarios described in chapter six with VSC-HVDC link incorporated to the system, a variety of results were obtained. The VSC-HVDC link provided power enhancement capabilities and voltage control. A large disturbance was introduced into the system in a form of short circuit to both Willy and Milly 66kV overhead lines. Typically such faults are meant to depress the system voltage, cause synchronous generators to speed up and cause non-synchronous generators to enter FRT mode. Figure 8.1 and 8.2 show the results of the fault occurrence after it was cleared after 200ms.from both figures it can be observed that the minimum bus voltage is 0.972 pu. This is way above the blue thick line that has been set as minimum operational constant of 0.925 per unit. The VSC incorporation to the system improved the system security, quality, stability, reliability and availability thereby keeping bus voltages within acceptable limits even after a fault.

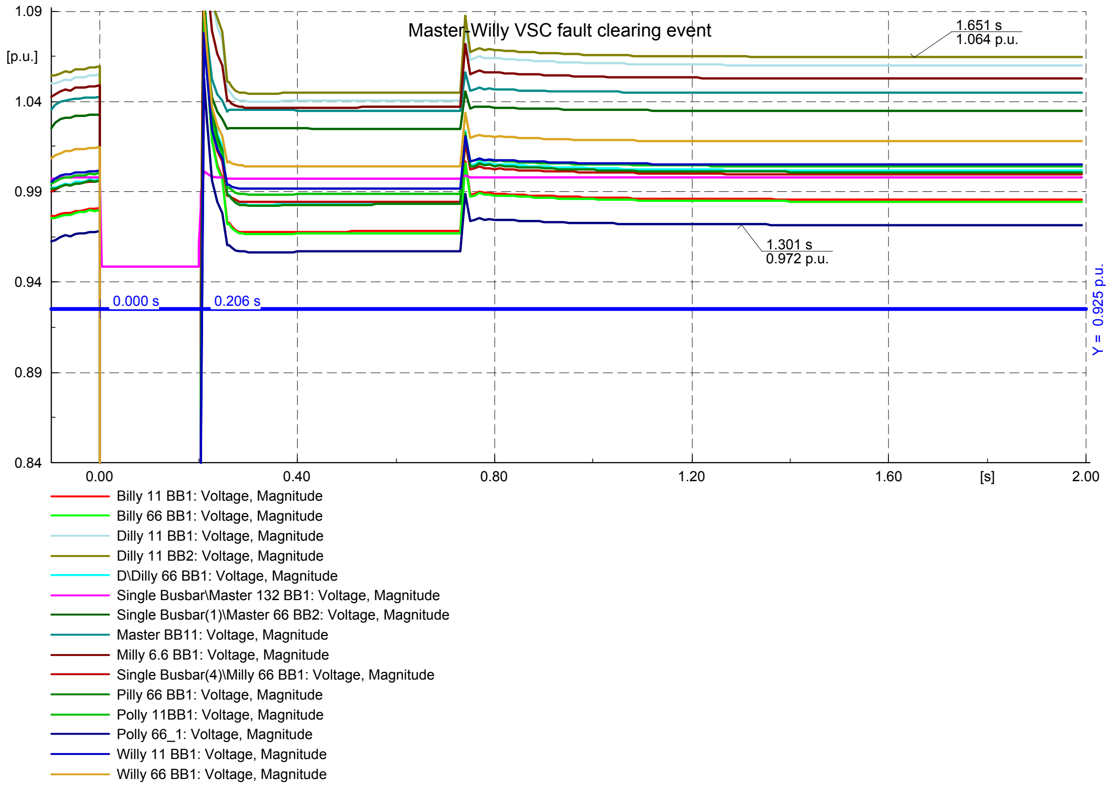


Figure 2.1: Master-willy VSC fault clearing event

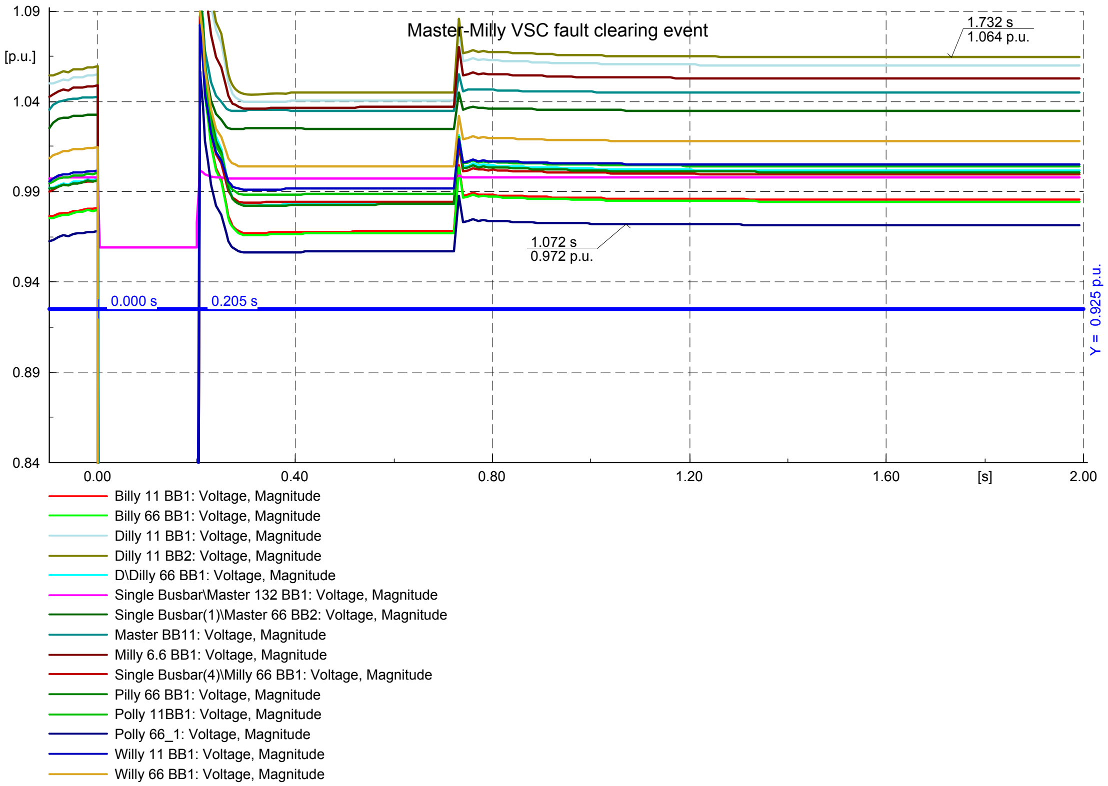


Figure 8.2: Master-Milly VSC fault clearing event

The same network was subjected to a large disturbance and the switch remained open. Once a breaker starts tripping, it easier to reach voltage violation because the system becomes weaker. However from figures 8.3 and 8.4, it can be observed that the minimum bus voltage is 0.972 pu and 0.954 pu respectively. The VSC incorporation improved network low voltages above the minimum acceptable operating voltage of 0.925 pu. None of the busbars are reaching voltage violation therefore. The results of this study clearly show the VSC-HVDC link capability to autonomously modify its active and reactive power output into the distribution and sub-transmission system in response to changes in voltage that was presented on chapter six figures 6.3 and 6.5 respectively.

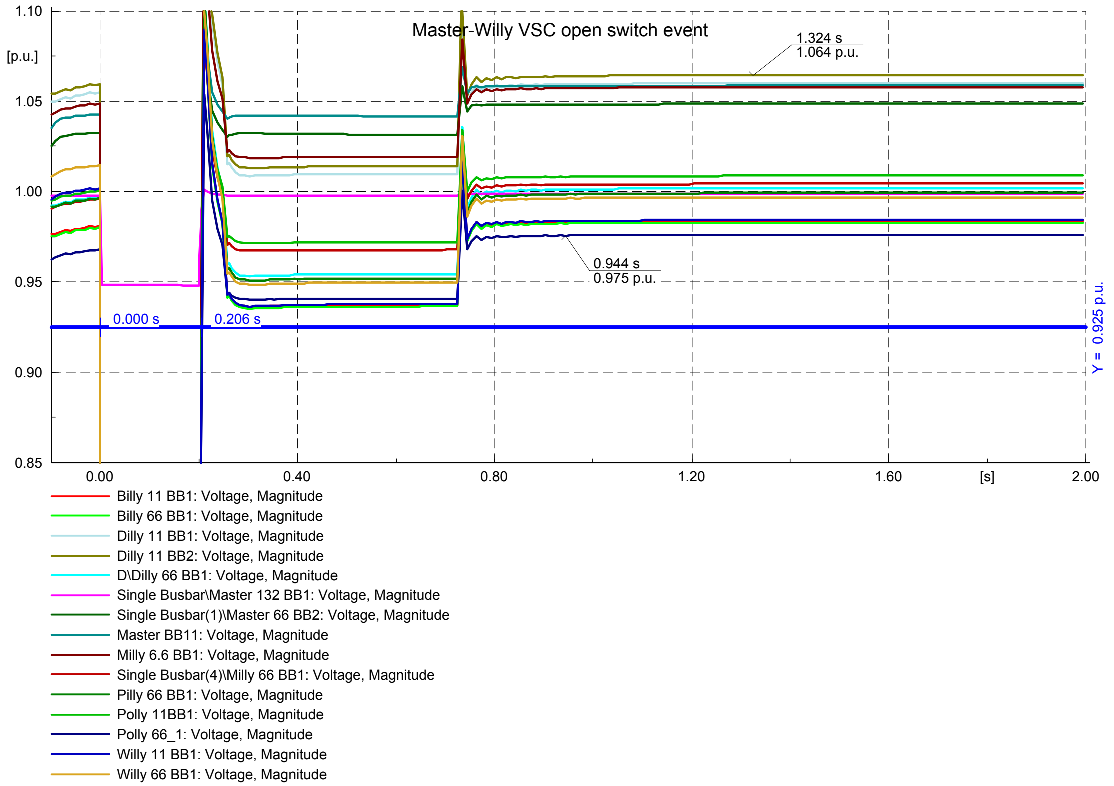


Figure 8.3: Master-Willy VSC open switch event

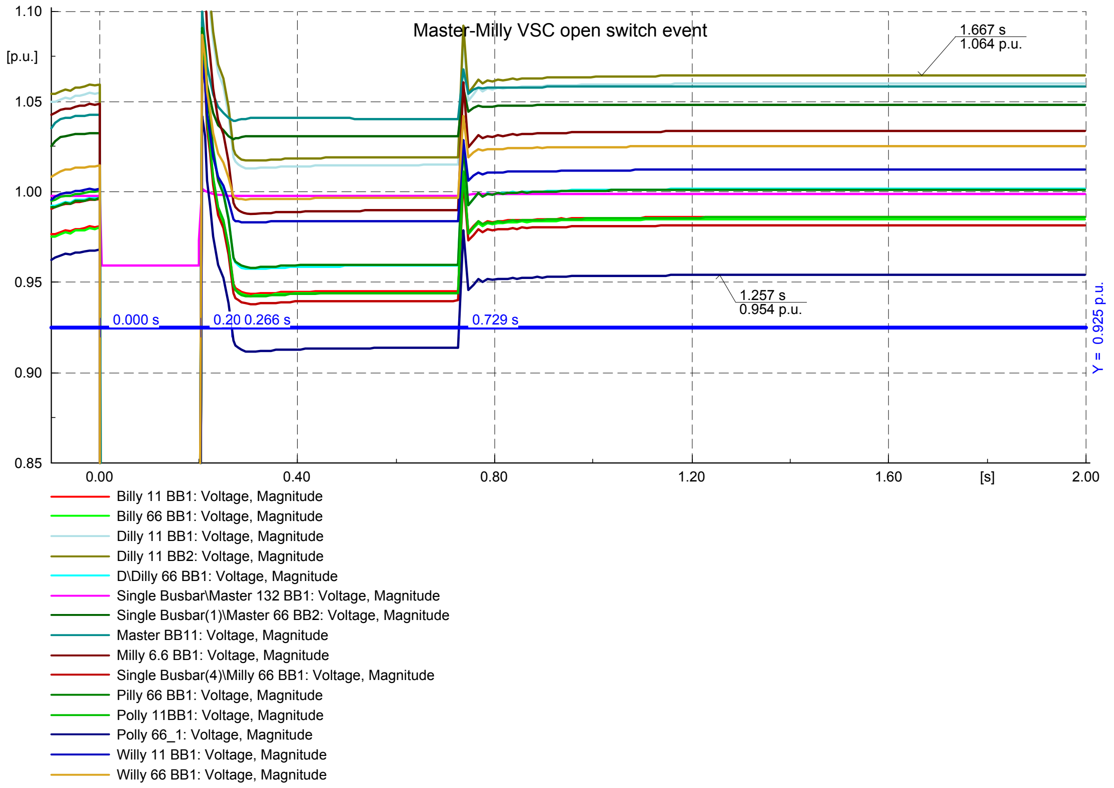


Figure 8.4: Master-Milly VSC open switch event

8.2 Contingency conditions after Integration of VSC-HVDC link

8.2.1 The normal operation network problem scenario 1

The normal operating conditions that are considered are the busbar voltages (above 95%) and the line loadings (below 100% at rate A) that complement the power carrying capacity of the main lines. The normal operation network problem scenario had to be looked at in the abnormal need set or contingency conditions due to the fact that it previously violated the voltage and loading limits. What was deemed as normal was abnormal so it can be assumed that if there was no need under normal operating conditions, no further normal condition studies need to be looked at. The VSC-HVDC link that was imbedded inside the AC network was used to strengthen the weak points of the power system at the same time increase power transmission capacity of the network. The attention is given to busbar voltages of the affected network (figure 8.1), percentage loading of the two overhead transmission lines being Milly and Willy 66kV (figure 8.2) as well as power carrying capacity of these two lines (figure 8.3) .referencing back to chapter 6 figure 6.6, we could see a minimum voltage of 0.91 pu. However with VSC incorporation, the minimum busbar voltage of 0.99 pu at Polly 66_1 is observed. This shows a remarkable improvement as the voltage is almost 1 pu. Voltage stability is said to be the one of the limiting factors for power transfer in the transmission grid. However Simulations studies shows that even with small VSC-HVDC transmission capacity, VSC-HVDC links can significantly improve voltage stability.

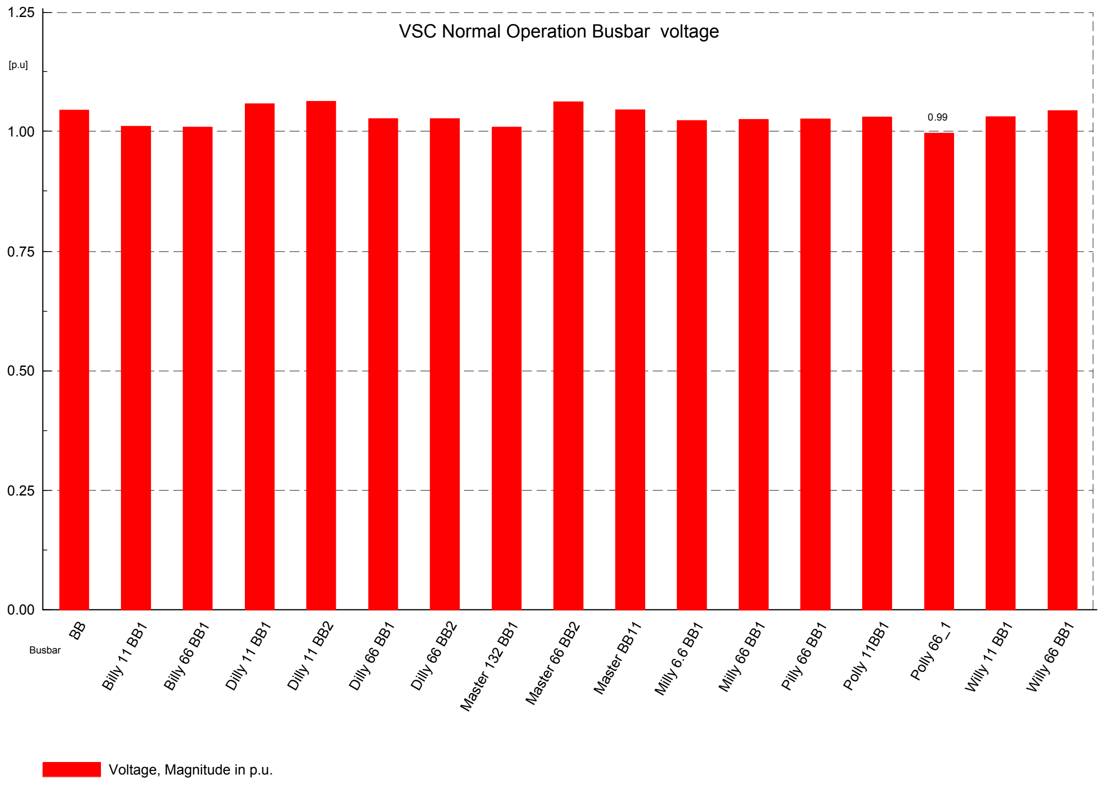


Figure 8.1: VSC Busbar voltage normal operation

Ideally these transmission lines are set to operate at 80% maximum specified loading limit under normal network status. Anything above this rate calls for contingency intervention. Depicted from figure 8.2 percentage line loading for Master-Milly and Master- Willy 66 KV lines are now 38% and 42% respectively. A huge improvement can be witnessed as the lines were previously overloaded at 98% and 110 %. It must be borne in mind that these values are of the same voltage level, same network load and same probabilistic ampacity values. The very same Hare conductor @ 50 degrees template; rated 32 MVA under normal and 45 MVA under emergency was used. Thermal Loading problems and Voltage limits Violations (Normal Conditions)

Normal ratings (Rate A) of the conductors were used for Normal Network Status.

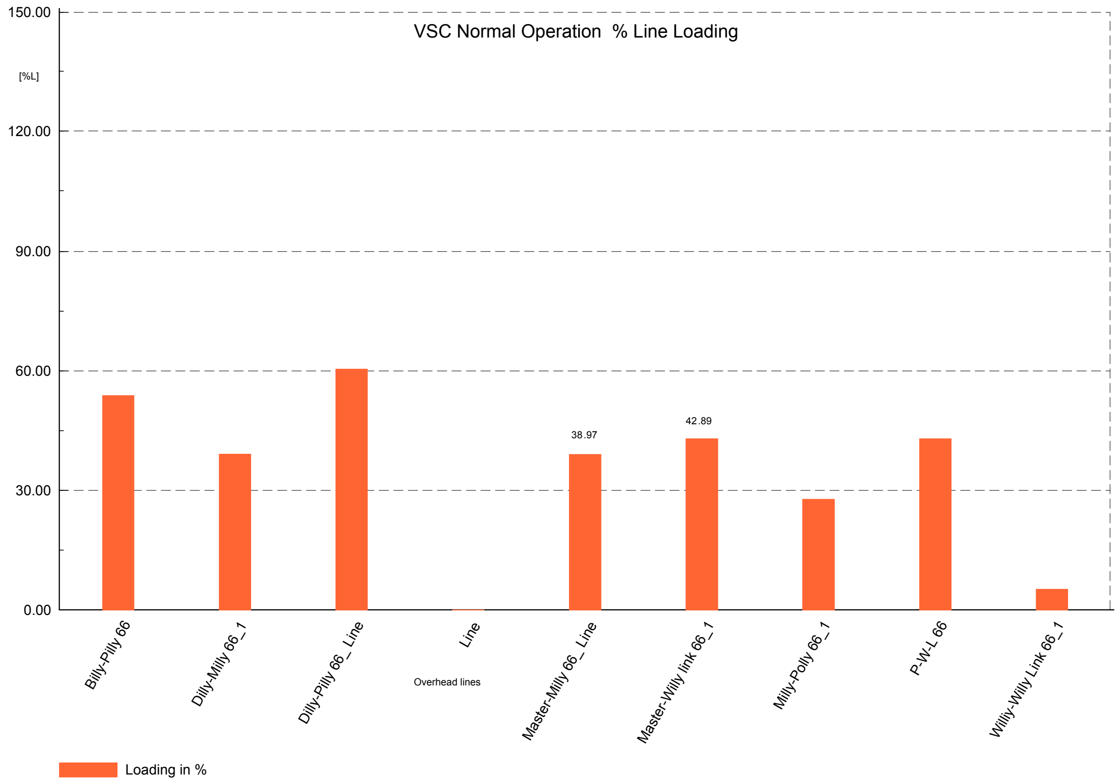


Figure 8.2: VSC Normal Operation % Overheadline Loading

According to ABB, the number of HVDC links in AC systems result in a more controllable and precise power exchange. As can be seen from figure below, The HVDC link was used to control power flow in a weak AC network. Under normal operation, Master-Milly and Master-Willy 66 KV lines were delivering 27.3 and 31.65 MW of power respectively. After VSC-HVDC link it can be observed that the two lines are now delivering 3.67 and 0.488 MW of power respectively. There is a difference of 23 and 31.16 MW meaning the power carrying capacity has been enhanced and optimised through the existing lines, both lines can still push more power at the same voltage level. DC can transmit 2-to-3 times more power without any stability problems

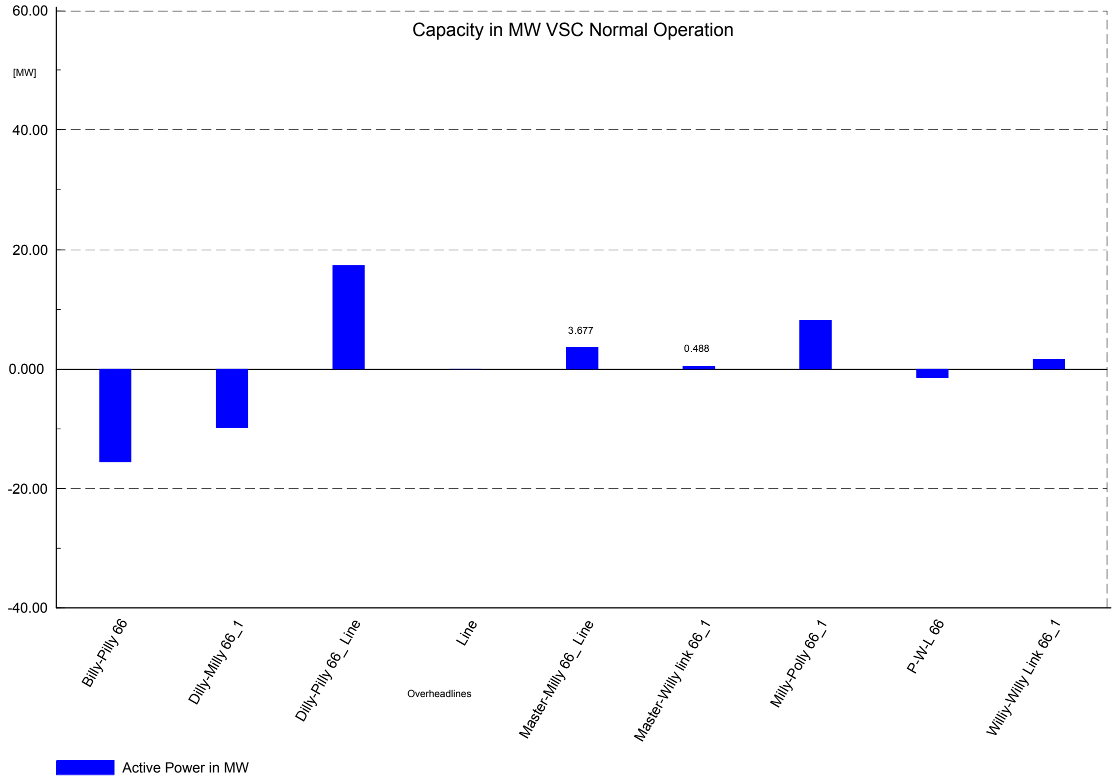


Figure 8.3: VSC Line capacity normal operation

8.2.2 The Master-Willy leg off network problem scenario 2

Abnormal conditions put a lot more stress on the network, as the allowable line loading is increased (100% at rate A to 100% at rate B) and the minimum busbar voltage decreases (95% to 92.5%). As the relationships between these standard limitations are not linear, several needs are expected to arise in the event that an asset performs near the allowable threshold. Abnormal conditions also contain a multitude of different combinations, focusing mainly on Master-Milly 66kV line and the network busbar voltages.

Given that the Master-Willy line failed the contingency analysis to a point where the minimum voltage was 0.8 pu or 80% and the line loading of Master-Milly was 187% at rate-B.The busbar voltage results presented on figure 8.4 show a tremendous improvement as the minimum bus voltage is 0.97 pu or 97 % at Billy 66kV busbar under N-1 conditions. A greater increase of 4.25% above the minimum allowable voltage of 92.5% is observed. This in turn shows a firm and reliable network under N-1 conditions.

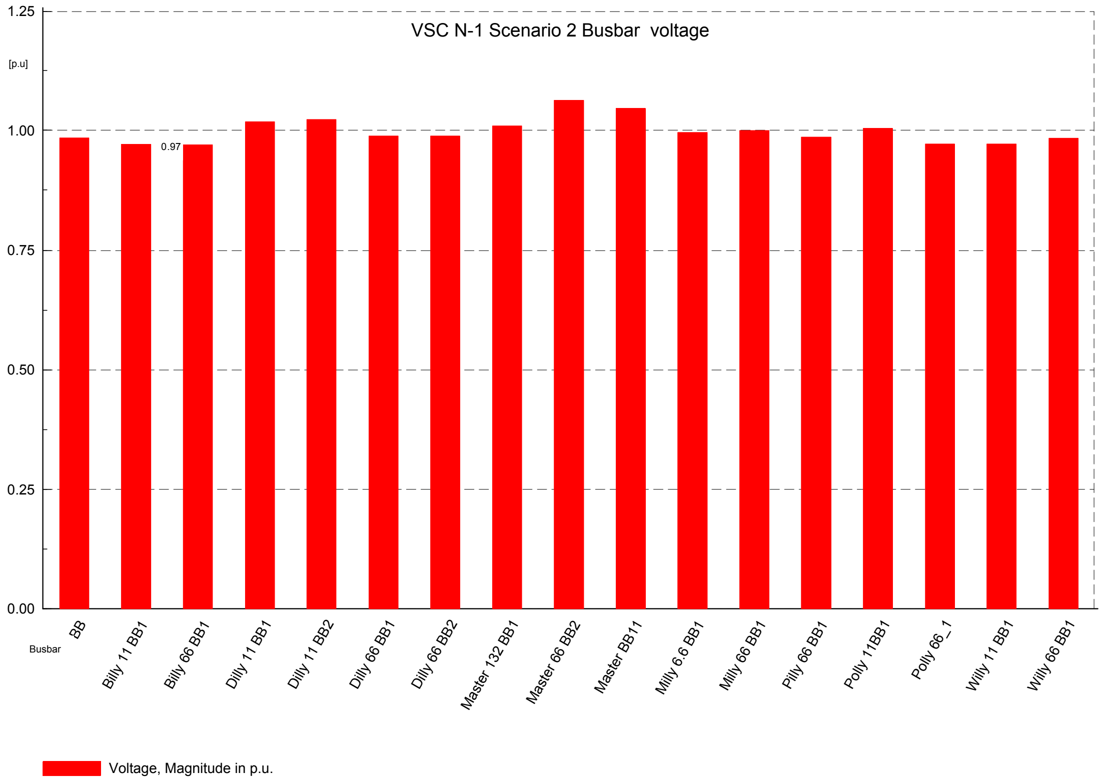


Figure8.4: VSC N-1 Master-Willy Busbar Voltage

As there were both high line loadings and low voltage issues post VSC-HVDC link incorporation, the solution proposed aught to address both of these need scenarios. Apart from low voltage alleviation presented in figure 8.4, it is clear from figure 8.5 and 8.6 below that the VSC incorporation improved the capacity of the lines. Under N-1 condition, the Master-Milly 66kV line loading drops from 187.147% rate-B to 80.1% rate-A of the conductor while there is a spare capacity of 50MW that could be delivered in case of any additional load. VSC-HVDC brought a holistic solution that mitigates all contingency load and voltage violations under N-1 conditions.

This implies that the station is very close to becoming overloaded, and it will be extremely difficult to switch out a transformer to perform maintenance work

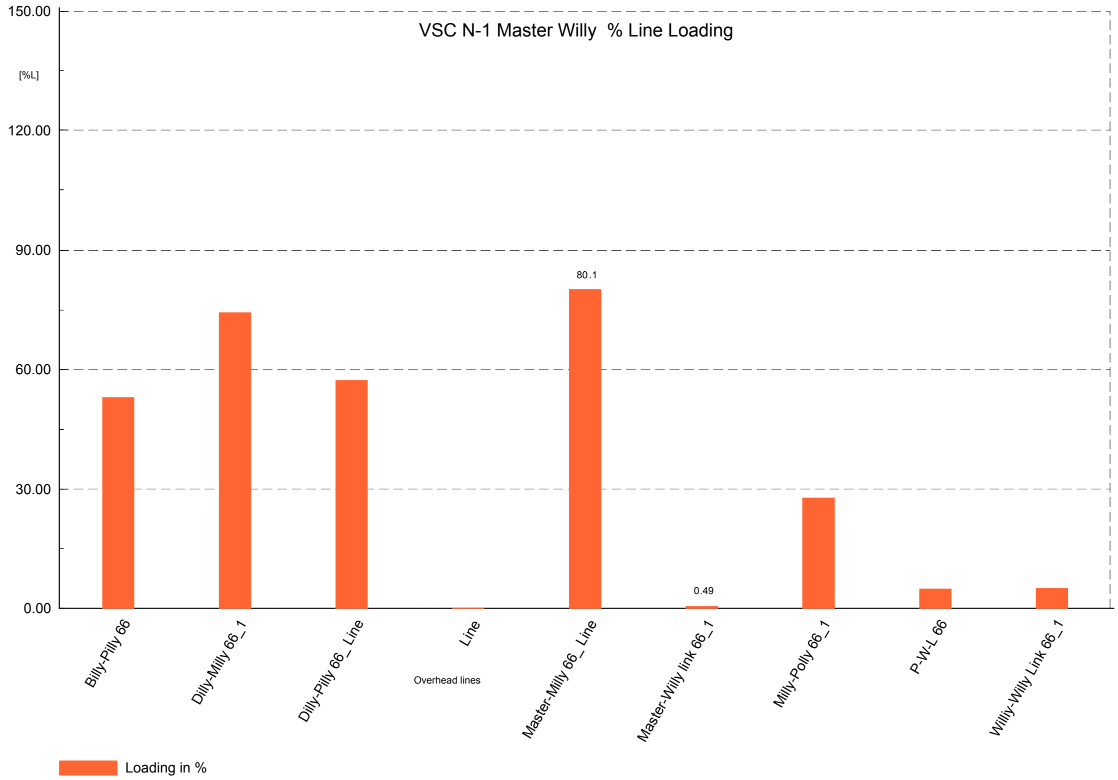


Figure 8.5: VSC N-1 Master-Willy % Overhead line loading

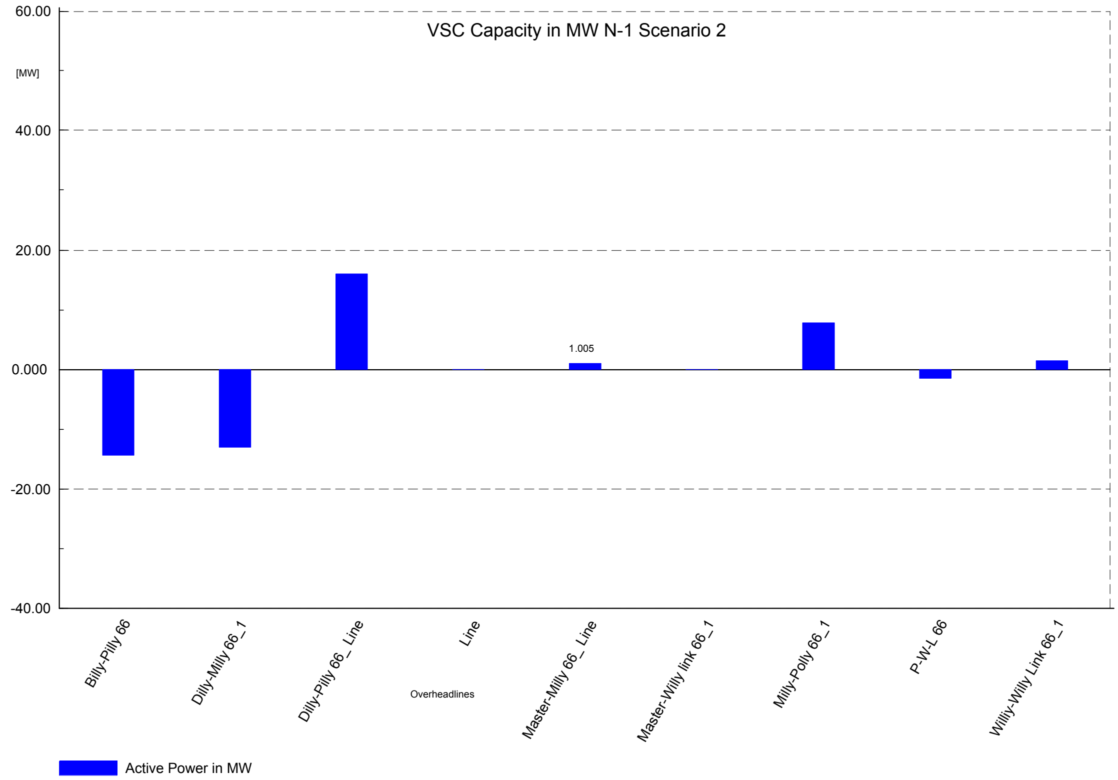


Figure 8.6: VSC Line capacity N-1 Master-Willy

8.2.3 The Master-Milly leg off network problem scenario 3

According to Eskom Standard, (firm substations), distribution substations must be firm at all times. This implies that in the event that a line or transformer is lost, the remaining lines or transformers must be able to carry the entire load without operating past 100%.Due to the configuration of the network at study, The N-1 contingency scenario had to be simulated twice to fulfil the firm substation requirements. From figure 8.7 it can be deduced that the substations busbar voltages improved substantially with the introduction of a VSC-HVDC link. The minimum bus voltage is 0.95 pu or 95% at Polly substation. It should be noted that this is an N-1 contingency scenario (abnormal condition) meeting the requirements of a normal operating condition.

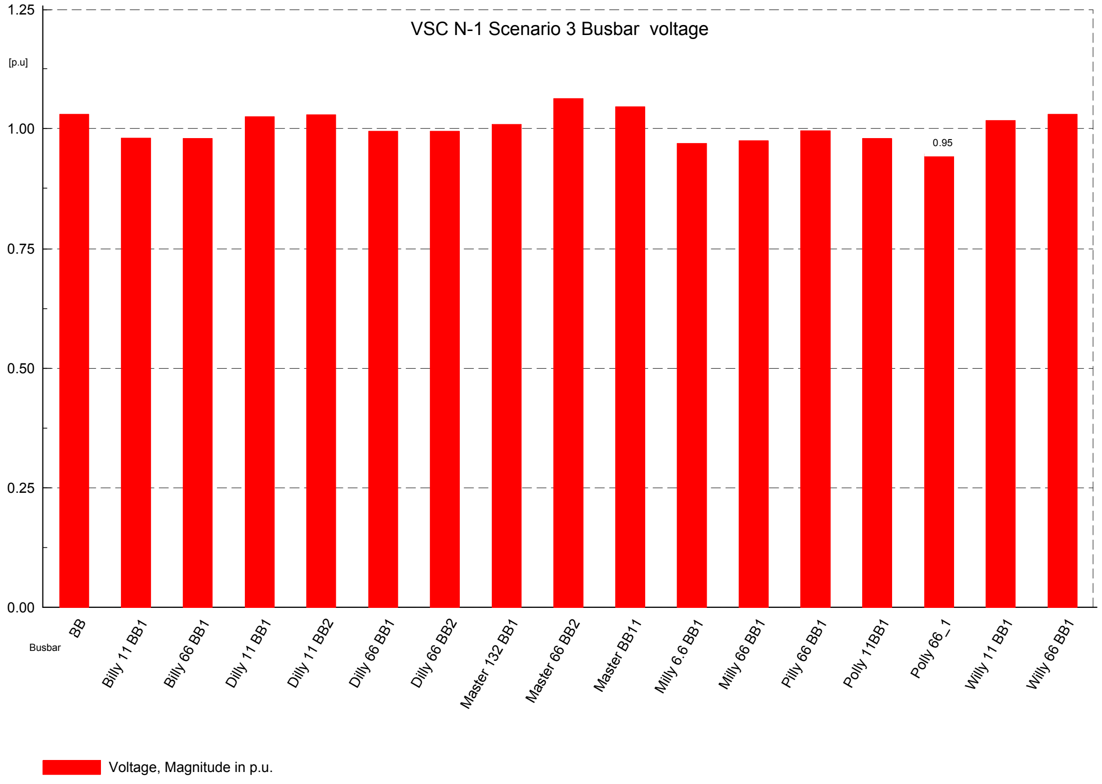


Figure 8.7: VSC N-1 Scenario 3 Busbar Voltage

Furthermore the line loading at Master-Milly 66kV line drops from 193.836% rate-B to 78.9% rate-A of the conductor while there is a spare capacity of 52MW that could be delivered in case of any additional load. The percentage line loading and the capacity in megawatts results are both advocating for the capacity enhancement as the topic of this thesis suggests. It can be seen from Figure 8.8 and 8.9 Simulations results that it was not by a chance that the VSC-HVDC link enhanced the network capacity.it can be concluded that the terminals of VSC can be considered as voltage source.

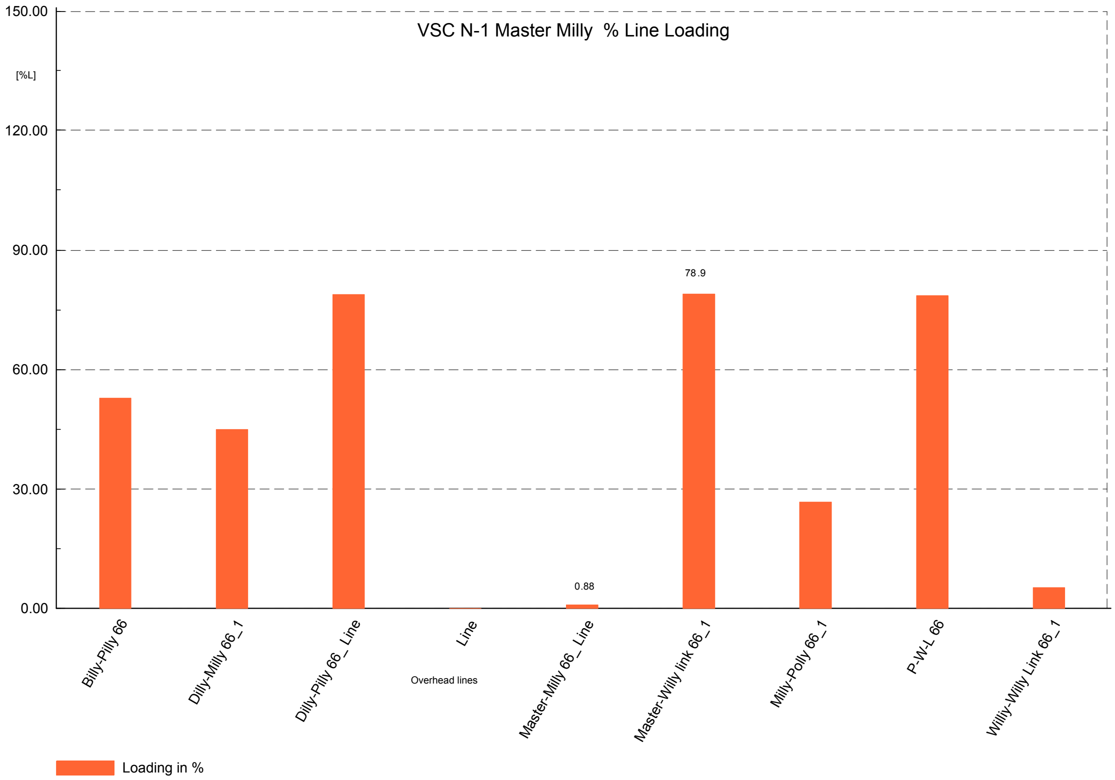


Figure 8.8: VSC N-1 Master Milly % Line Loading

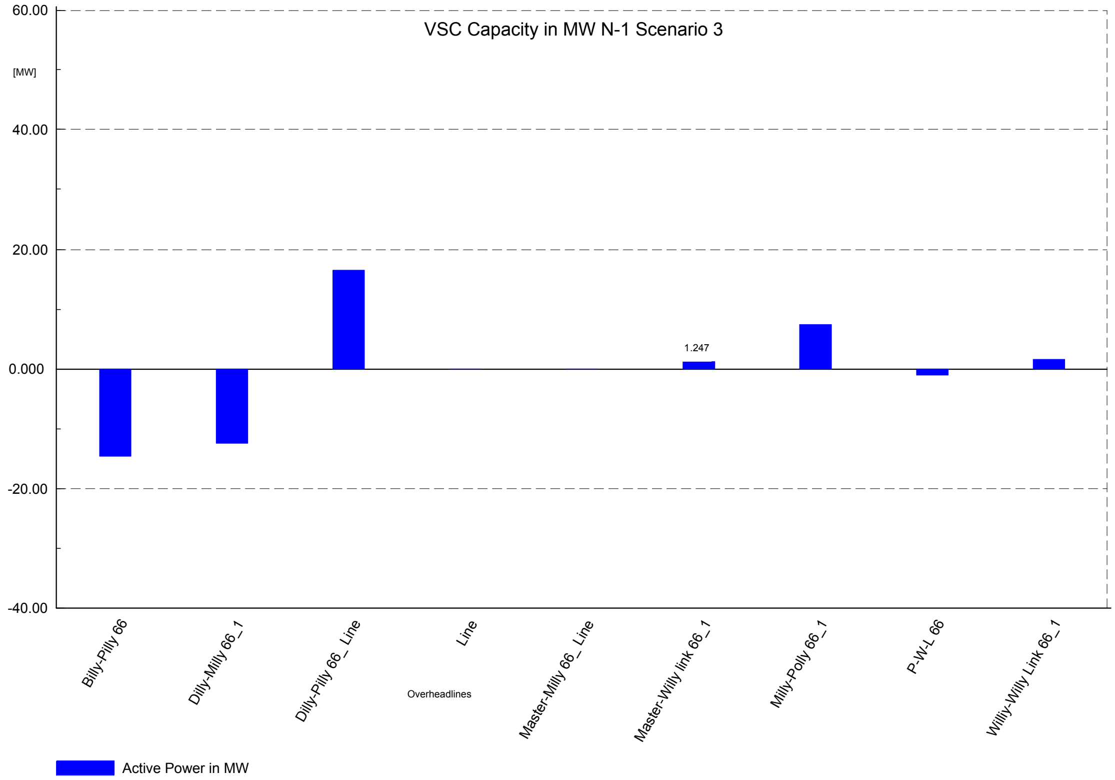


Figure 8.9: VSC N-1 Master Milly % Line Loading

8.3 Conclusion and Recommendations

The main goal of the thesis was to enhance the network capacity through HVDC link. However the network on which the studies were performed did not only present the bottlenecks but low voltage problems as well. The motivation for grid expansion lead to evaluation of possible enhancement methods on HVAC networks as opposed to HVDC networks and thereafter, two study cases each with three operating scenarios were developed and simulation were ran for HVAC and HVDC configurations. The first study case was using the existing HVAC line and the second study case was converting the AC line into DC and replacing the HVAC line with a point-to-point VSC-HVDC link.

Different operating points were considered with respect to voltage and loading violation limits for peak loads and contingency or abnormal conditions to examine the technical economical viable solution. From this thesis, it can be concluded that the reliability, stability and security of the system is a critical issue especially when the system is heavily loaded. This statement is supported by the results presented in chapter six where the performance of the power system decreased with the size and complexity of the network. The literature has been referring to the future which is now, where the loading of the existing power system has increased, leading to bottlenecks and reliability problems. On HVAC networks, if power should be transmitted through interconnected systems, transmission lines needs to be supported along the corridor. With an attempted support, the loading and voltage violations couldn’t be solved simultaneously.

As a consequence, the needed enhancement of the power system was done through VSC-HVDC link. The proposed VSC-HVDC link was able to enhance the capacity of the network by modulating the active and reactive power of the HVDC link. DC interconnection survived the N-1 contingency scenarios and assisted on power supply restoration under short circuit conditions. From this it can be deduced that the incorporation of VSC-HVDC link proved to be effective and it can be used for power system stability enhancement as well.

As far as trends in high voltage transmission systems were concerned, Power enhancement capacity through power electronics was anticipated to happen at transmission, sub-transmission and distribution systems. The VSC-HVDC can clearly strengthen the grid and improve the performance of the system at all levels.

8.4 Limitations and Future work

The limitation of the study was the challenge to model the VSC-HVDC on power factory. Detailed VSC-HVDC models from manufactures where the control structures are elaborated are not available.one can either use the black box models from ABB or the control structure of a generic type from Digsilent Power Factory. There is a lack of documentation corresponding to the model behaviour.

From an academic point of view, the modelling challenges experienced in this thesis present an opportunity for researchers to embark on documenting the VSC-HVDC model behaviour especially on how the controllers of these models are tuned. Furthermore this will eliminate the challenges faced when connecting renewable energies at distribution level particularly in South Africa as the electrical power sector aims at increasing the penetration of renewable resources.

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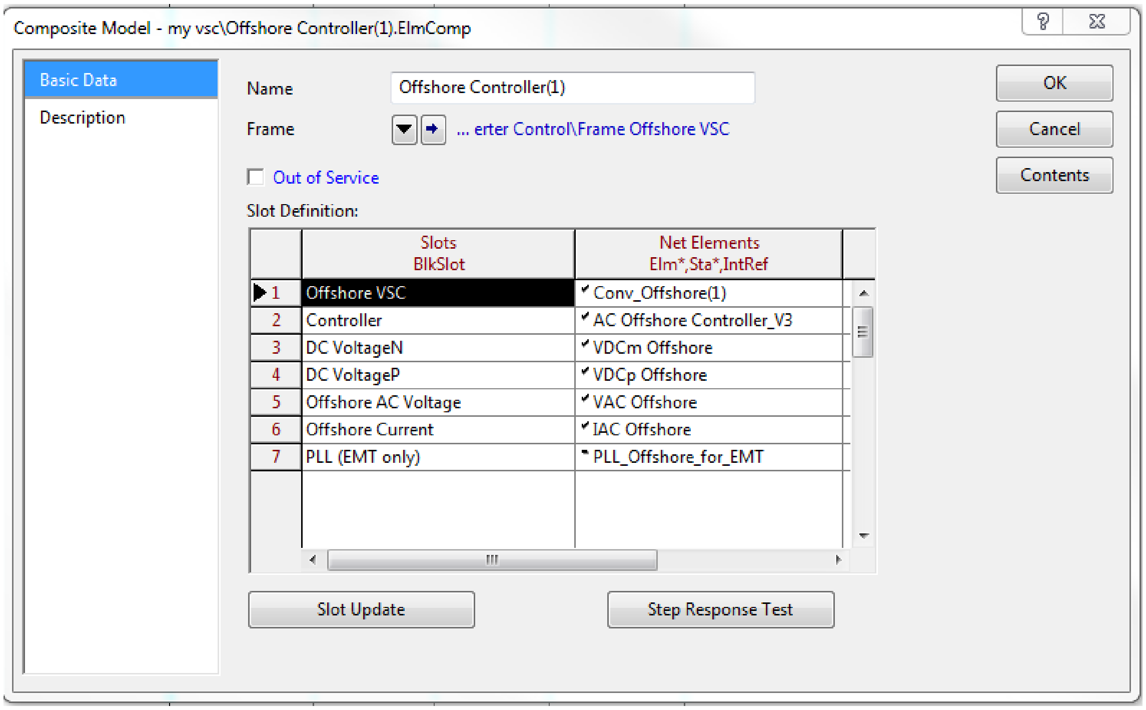
CHAPTER TEN: APPENDICES

Appendix A: VSC Dynamic Models



Name: Offshore Controller(1)

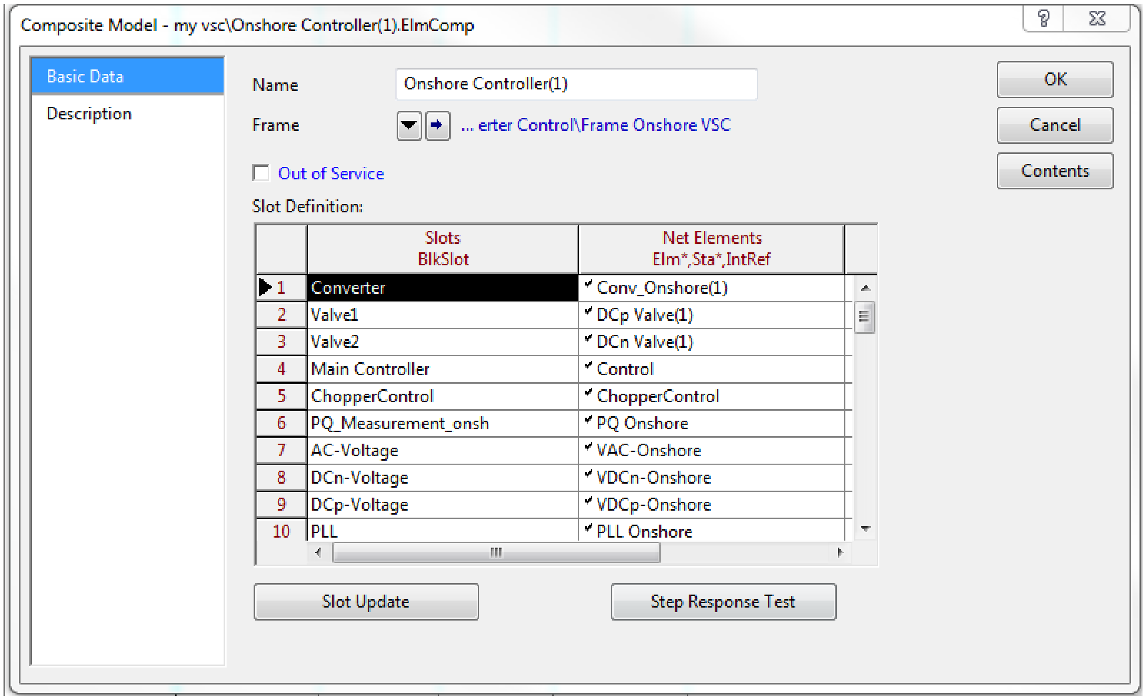
Frame: ... erter Control\Frame Offshore VSC

☐ Out of Service

Slot Definition:

	Slots BlkSlot	Net Elements Elm*,Sta*,IntRef
▶ 1	Offshore VSC	✓ Conv_Offshore(1)
2	Controller	✓ AC Offshore Controller_V3
3	DC VoltageN	✓ VDCm Offshore
4	DC VoltageP	✓ VDCp Offshore
5	Offshore AC Voltage	✓ VAC Offshore
6	Offshore Current	✓ IAC Offshore
7	PLL (EMT only)	- PLL_Offshore_for_EMT

Figure 10.1: VSC-Offsure Composite model



Name: Onshore Controller(1)

Frame: ... erter Control\Frame Onshore VSC

☐ Out of Service

Slot Definition:

	Slots BlkSlot	Net Elements Elm*,Sta*,IntRef
▶ 1	Converter	✓ Conv_Onshore(1)
2	Valve1	✓ DCp Valve(1)
3	Valve2	✓ DCn Valve(1)
4	Main Controller	✓ Control
5	ChopperControl	✓ ChopperControl
6	PQ_Measurement_onsh	✓ PQ Onshore
7	AC-Voltage	✓ VAC-Onshore
8	DCn-Voltage	✓ VDCn-Onshore
9	DCp-Voltage	✓ VDCp-Onshore
10	PLL	✓ PLL Onshore

Figure 10.2: VSC-Onsure Composite model

Appendix A: Continued

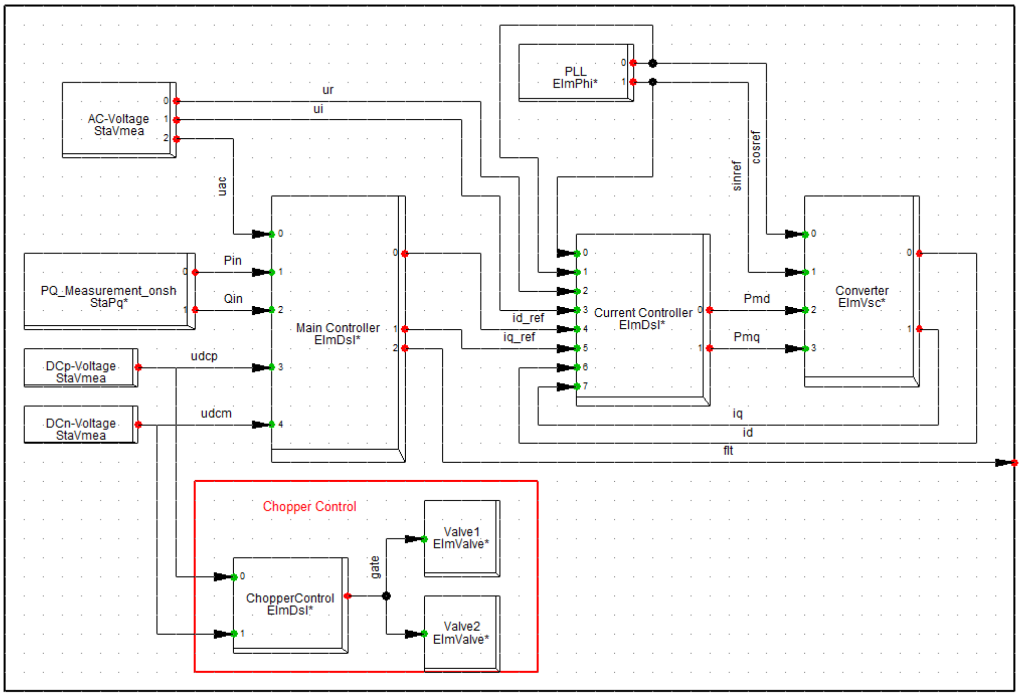


Figure 10.3: Composite frame of a VSC

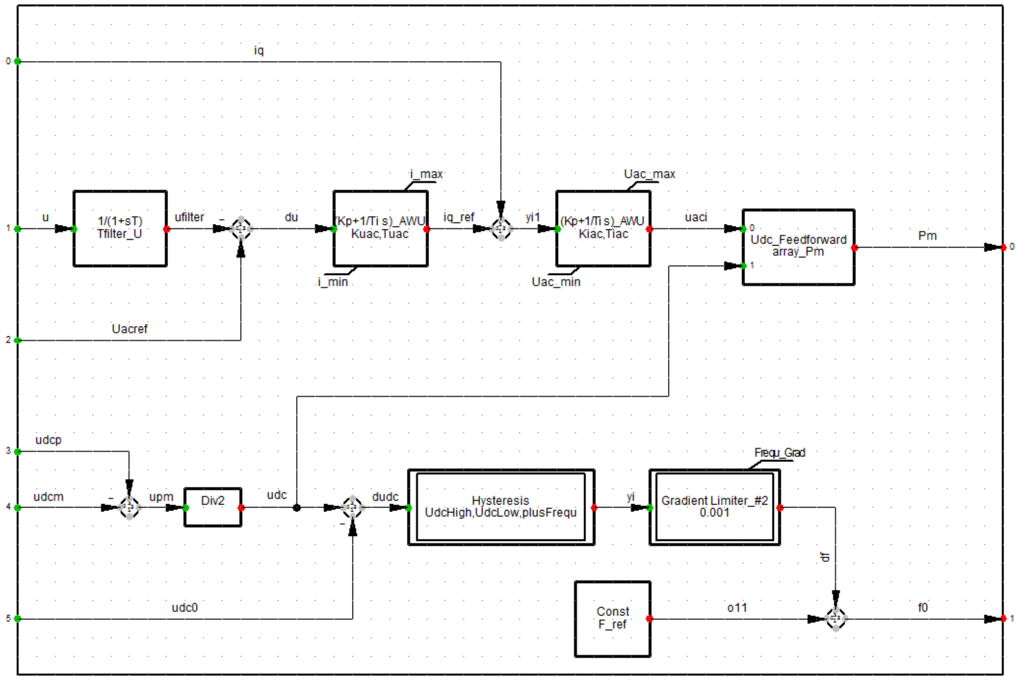


Figure 10.4: VSC controller

APPENDIX B: Master -Dilly Load Profiles

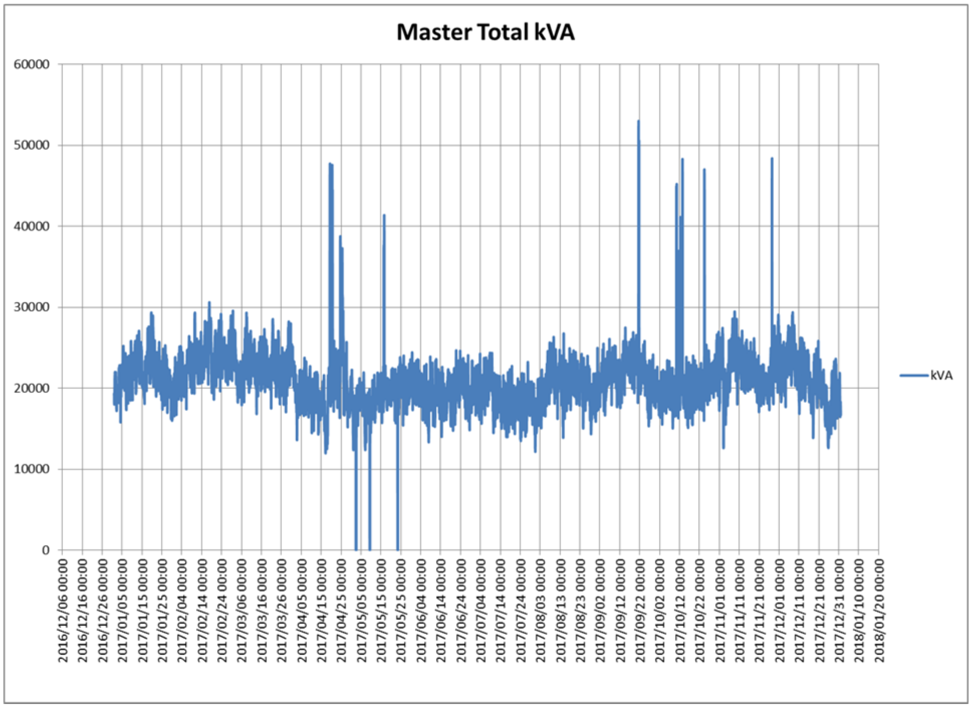


Figure 3.5: Master Substation load profile

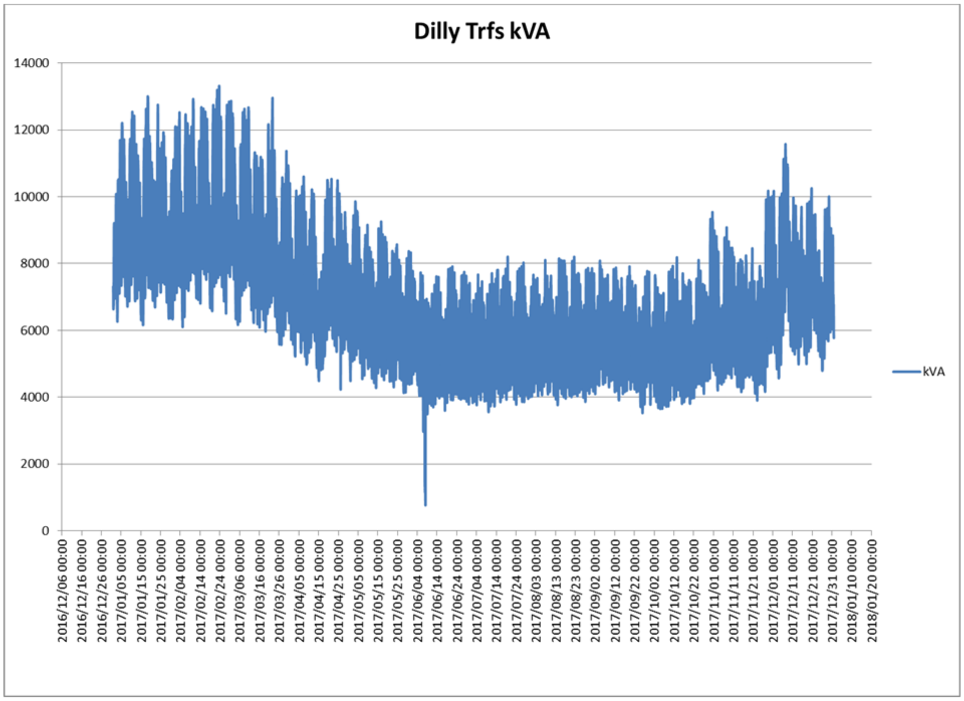


Figure 4: Dilly Substation Load Profile

Appendix B: Continued

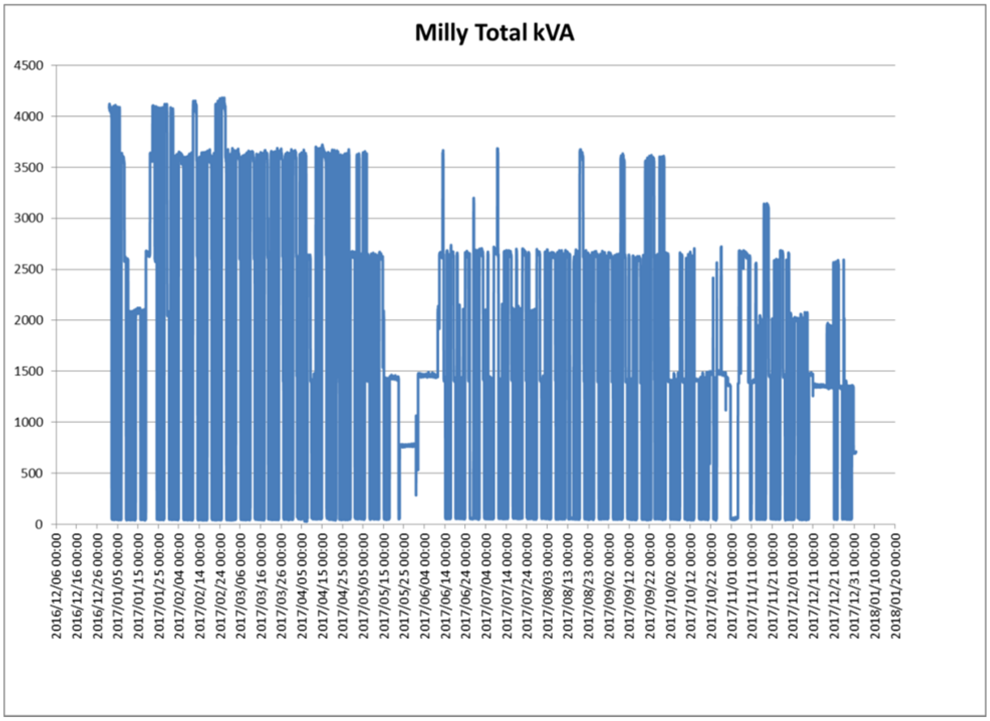


Figure 5: Milly Substation Load Profile

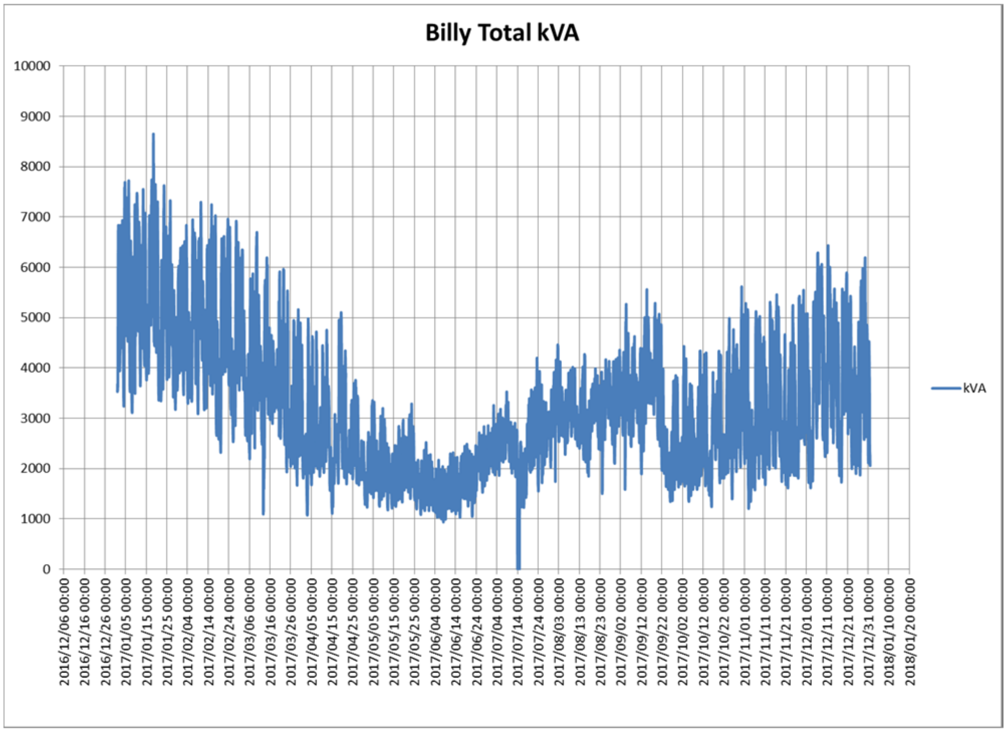


Figure 6: Billy Substation Load Profile