THE IMPACT OF INVERTER SIDE PV PLANT ON HVDC COMMUTATION FAILURES

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Abstract

The high-voltage direct current (HVDC) system is a crucial technology in transmission; however, this system suffers from commutation failure. Commutation failure is defined as an adverse dynamic event that occurs when a converter valve that is supposed to turn off continues to conduct without transferring its current to the next valve in the firing sequence. Commutation failure disturbs the power transfer, yields a large overcurrent in the converter, and causes a voltage drop in an alternating current (AC) network.

Although commutation failure in HVDC systems has been studied using many other compensating devices, academic researchers have not given enough attention to evaluating the impact of distributed generation (DG) on the power system. Within this gap and based on the publications researched, no published material could be found regarding the impact of a photovoltaic (PV) plant on HVDC commutation failures. This research project seeks to focus on the impact of an inverter side PV plant on HVDC commutation failures.

In this dissertation, the objective is to evaluate the impact of the inverter side PV plant on HVDC commutation failures. The case studies are done by considering the commutation failure severity, the magnitudes of the remaining voltages after different types of faults occurring, and the recovery time required to clear a fault. Case studies are performed in a network with a PV plant and also without a PV plant.

The network was set up in Power System Computer-Aided Design (PSCAD) software to find the critical voltages. Further simulations were done in this study using Power System Simulator for Engineering (PSS/E) software. A network by *Conférence Internationale des grandes réseaux* *électriques* (CIGRE), which is the international council for large electric systems, was used for the studies. The results are represented in a table form using the data from the simulations.

The simulations showed that the presence of a PV plant in the network resulted in less severe commutation failures – even for more severe faults. The magnitudes of the remaining voltages were improved and the recovery time was shorter. In a network without a PV plant, commutation failures started earlier – even for less severe faults.

The probability of commutation failures was reduced when a PV plant was incorporated in the network. The magnitudes of the remaining voltages improved and the time taken by the system to recover from the fault was observed to be shorter than without a PV plant. The simulations yielded good results when there was a PV plant in the network, which is a positive impact on HVDC commutation failures.

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Chapter 1: Introduction

1.1 Background

Direct current (DC) power was the first commercial electricity in the history of the electricity industry. Thomas Alva Edison was the first person to generate DC power. In 1954, the first high-voltage direct current (HVDC) transmission system (100 kV and 20 MW DC link) was installed between the Swedish mainland and the island of Gotland, which led to the installation of a substantial number of HVDC transmission systems [1]. Globally, the HVDC transmission market is expected to double within the next five years.

In the last 40 years, HVDC transmission links with a total capacity of 100 GW have been installed. It is expected that another 250 GW will be added in the current decade [2]. The HVDC market has become an important part of many transmission grids; not least because it can connect remote sources of electrical generation [often emission-free renewable sources such as hydro, wind and PV plants] to load centres where it is needed hundreds or even thousands of kilometres away [3].

The first functional, intentionally made PV device was by Fritts in 1883 [4]. PV systems are becoming more distributed geographically with annual PV installations growing by more than 20% in 45 countries. It has been predicted that 123 GW of solar PV installations are expected globally in 2019 [5]. Renewables are a key component for decarbonising economies. Under the Paris Agreement, countries have pledged to reduce carbon emissions from fossil fuels. Decarbonising the energy sector by moving to renewable energy thus supports efforts to achieve climate objectives, including nationally determined contributions [6].

Increased energy security is supported through energy savings, a decline in investment requirements for capacity additions, dependence on energy imports, and susceptibility to variations in energy prices [6]. A PV system has a high power capability per unit of weight, has a longer life with little maintenance because of no moving parts, and it is highly mobile and portable because of its light weight. Electricity generated by PV systems is highly modular; therefore, the plant economy is not strongly reliant on size. PV energy has the ability to provide energy solutions for residential, commercial, industrial and rooftop configurations and applications [7].

1.2 Problem Statement

The HVDC system is a crucial technology in transmission, but suffers from commutation failure. Commutation failure is defined as an adverse dynamic event that occurs when a converter valve that is supposed to turn off continues to conduct without transferring its current to the next valve in the firing sequence. For a thyristor to turn off, a negative voltage must be applied for a long enough time to drain the stored charge [8].

In a DC system, commutation failure leads to a sharp increase of current and the extensive voltage decrease. In an AC system, continuous commutation failure greatly reduces the active power transmitted by the DC system, thus rendering an enormous change of flows at the receiving inverter station nearby [9].

Several studies relating to commutation failure have been published. The coordination between a static synchronous compensator (STATCOM) and an HVDC classic link feeding a weak AC network was evaluated in order to mitigate the commutation failure phenomenon [10]. In [11], the smallest size of an inductor bank whose connection does not cause commutation failure was evaluated. In [12], a method to mitigate commutation failure in an HVDC system was presented. The method was tested and implemented for the first time in the Three Gorges–Changzhou ±500 kV HVDC project. Another study was conducted to explore the effect of controlling the inverter DC with an aim of assisting the recovery of LCC HVDC inverter from commutation failures caused by AC system faults [13].

The publications researched revealed that no investigation has been done regarding the capability of a PV plant to mitigate commutation failure. Therefore, this study focuses on evaluating the impact of inverter side PV plant on HVDC commutation failures. A case with a PV plant is compared with a case when there is no PV plant in the network.

1.3 Aims and Objectives of the Study

The objective of this study is to evaluate the impact of an inverter side PV plant on HVDC commutation failures. The evaluation is done by considering the commutation failure severity, the magnitudes of the remaining voltages after different types of faults occurring, and the recovery time required to clear a fault.

1.4 Contribution to Knowledge

The study gives insight and contributes knowledge regarding the impact that a PV plant in an HVDC system has on commutation failures. A PV plant has the capability to inject and absorb reactive power in the grid.

1.5 Publications

While undertaking this research, the following journal paper was submitted for review:

N. Mbuli, N. P. Simelane, and J. H. C. Pretorius, “The Impact of Inverter Side PV Plant on HVDC Commutation Failures”.

1.6 Structure of the Dissertation

Chapter 2 discusses various fundamental aspects of HVDC and commutation failure mitigation techniques. A review of the existing knowledge including applicable findings, as well as theoretical and practical contributions to the topic of commutation failures in an HVDC inverter feeding a weak AC system, is discussed.

Chapter 3 reviews the fundamentals of PV systems and discusses the components of a PV system, including the solar cells, panels and inverter. The chapter further explains the development of the PV systems around the world, integration of PV plants into the grid, and the cost of PV system.

Chapter 4 focuses on the publications that discuss the benefits of distributed generation when incorporated into the grid. The impact of DGs on voltage sags caused by faults, power quality and voltage instability when using different DGs is also explained. The studies reviewed in Chapter 4 highlight the importance of renewable energy in the grid.

Chapter 5 discusses the theory of capability of the PV plant to inject and absorb reactive power in the grid. Equations and curves have been used to explain the theory. Three inverter control modes are explained, namely, voltage control mode, power factor control mode and reactive power control mode. The current inverter limit, voltage inverter limit and the PV active power are three PV inverter operating limits also discussed in detail.

Chapter 6 presents all information of the case studies done to assess the impact of a PV plant on commutation failures in an HVDC inverter feeding a weak AC system. A CIGRE HVDC network was used for the studies. PSS/E and (PSCAD) software programs were used for the simulations.

Chapter 7 presents the results obtained from the simulations. The two case studies were evaluated for the phase-to-phase-to-ground fault and the three-phases-to-ground faults. The results are presented in tabular form. The tables show the results for the case with PV plant in the network and a case without PV plant.

Chapter 8 presents the study's conclusions and recommendations regarding the impact of inverter side PV plant on HVDC commutation failures. Findings are discussed for each case and an overall conclusion is made. The chapter further makes recommendations for future studies around the topic.

Chapter 2: Basics of Commutation Failure and Review on Mitigation Techniques

2.1 Introduction

The previous chapter discussed the background of HVDC and PV systems, literature on commutation failures, literature on integrating PV systems into the grid, research gap, study objective, study's contribution to current knowledge, as well as the structure of the dissertation.

This chapter explains the various fundamental aspects of commutation failure. The chapter reviews the current knowledge on mitigation techniques, including substantive findings, as well as theoretical and practical contributions to the topic of commutation failures in an HVDC inverter feeding a weak AC system.

HVDC systems transmit bulk power over longer distances. This chapter reviews the publications on commutation failures, mitigation techniques, commutation process, and the various means used for configuring HVDC systems. A Graetz bridge is a circuit that is widely used for the basic configuration of an HVDC converter. The circuit operation is explained in this chapter.

2.2 Normal Commutation Process

Commutation is the switching of current conduction from one thyristor valve to another in the same row in an HVDC system. The commutation process cannot be rapid and it takes a certain time, which is called the overlap time; also known as angle of overlap (μ). The firing time is represented by the angle (α). The current is related to voltage time area. If the current is higher, the voltage-time area, which is represented by angle (γ), becomes larger. Figure 1 shows the occurrence of commutation amongst Valve 1 and Valve 3 [10].

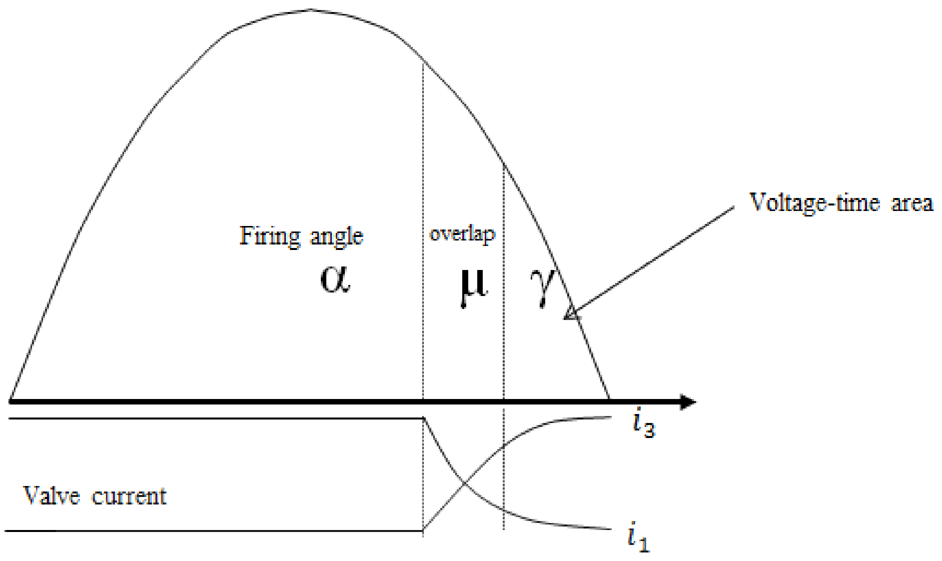

Figure 1: Commutation process between Valve 1 and Valve 3 [10]

2.3 Commutation Failure

Failing to switch current from one valve to the next in a row in an HVDC system results in commutation failure. As a result, the current increases and the voltage decrease. Continuous commutation failure on an AC system reduces the active power transmitted by a DC system, which is undesirable. A short circuit across the valves may be observed due to commutation failure [12] , [13], [14].

Repeated commutation failure may lead to overcurrent in the valves and the time to restart the HVDC system when the fault is cleared may be delayed. Severe commutation failure can result in valve blockages. Commutation failure occurs easily if there is a short-circuit fault in the AC lines close to the inverter station. HVDC inverter stations experience frequent commutation failures [12], [13], [14].

If the characteristics of some electrical quantities of an AC system and a DC system become complex in the transient process and the working environment of the neighbouring relay protection equipment is not in a good condition, AC protection could fail, which negatively influences the security and stability of the power grid [12] , [14].

2.4 Line Commutated Converter

A Graetz bridge is a circuit used to show the basic configuration of an HVDC converter. The circuit is a three-phase, full-wave bridge, which has the advantage of providing better utilisation of the converter transformer and a lower voltage when the valve is in an off state. The circuit is composed of six thyristors that are arranged in the form of three-phase legs. Each phase leg contains two thyristors; a three-phase power supply is connected to the centre points. A thyristor is a three-terminal, semi-controllable semi-conductor device: it can be turned on through control [12], [15]. The circuit diagram is shown in Figure 2.

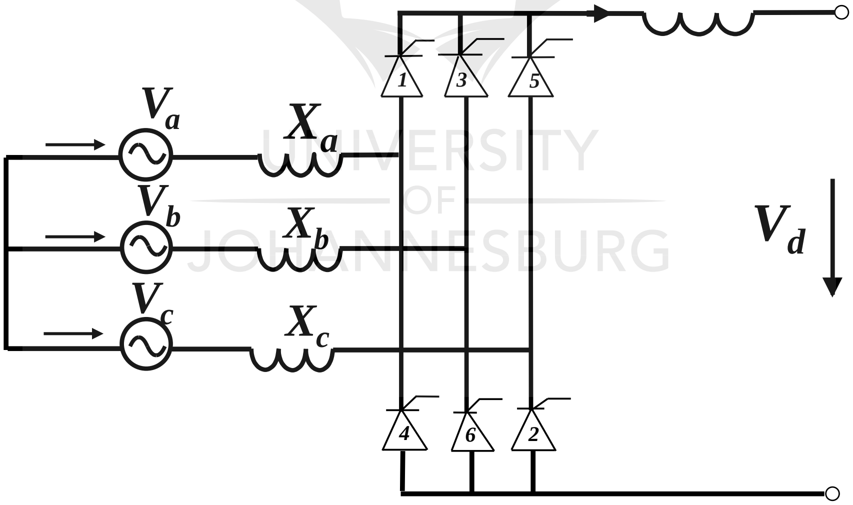

Figure 2: Equivalent circuit for a three-phase full-wave bridge converter [15]

A Graetz bridge can be employed for power transmission in two directions by applying different ring angles to its thyristor valves. When the angle α is less than 90 degrees, the DC flows from the positive polarity of the circuit, so that power flows from the AC side to the DC side. When the angle α is greater than 90 degrees, the voltage changes polarity, so that the DC flows from the negative polarity of the DC circuit, and the power flows from the DC side to the AC side [12], [15].

2.5 Review of Publications on Mitigation Techniques

An HVDC system comprises two Graetz bridges that are joined at the DC side. One Graetz bridge operates in rectifier mode and the other in inverter mode. Commutation failure is one of the eminent faults that occur on the inverter side of an HVDC system during operation, which reduces DC transmission power [16], [17]. Several studies have been done to identify the source and magnitude of commutation failure.

In [18], the concept of an HVDC system and the status of research on commutation failure fault analysis were firstly presented, which pointed out the inadequacies of the current diagnosis methods. Secondly, by analysing the features and their effects, the risks and pre-control measures of commutation failure were identified. Lastly, the study proposed a new method that could be used to diagnose commutation failure based on the wavelet energy spectrum and grey comprehensive relationship degree. The results proved the efficiency and accurateness of the method for commutation failure.

In [19], the performance of a line and capacitor commutated converter based on an HVDC system in a Simulink environment was assessed. The protection of an inverter against commutation failure can be improved by placing a series capacitor between the converter transformer and the thyristor valves, namely, a capacitor commutated converter (CCC). The conventional and the CCC inverters were connected to weak AC systems. Matrix Laboratory (MATLAB) and Simulink were used for the simulations.

A new analysis of commutation failure risk in a multi-infeed HVDC system is presented in [20]. The study compared the variance of the commutation angle of the relevant inverter after constructing a new HVDC system. PSCAD and EMTDC were used for simulations. The results showed that the equivalent commutation impedance of the relevant inverter has been proven to increase.

In [21], the difference between the ABB and the Siemens strategy in addressing the inverter side AC fault was analysed. It was identified that commutation failure with the Siemens strategy lasts longer than with the ABB strategy. The simulation results showed that using a compound phase-shifting control reduces the duration of the fault and improves the power retrieval and system reaction after the fault has cleared.

A novel commutation failure prediction based on DC and voltages was introduced in [22]. The study proved by simulation that correct predictions are possible for two distinct cases, namely, a sudden increase in rectifier AC voltage and during the recovery after a DC line fault in a bipolar transmission. A simulation for time domain showed the success of the proposed commutation failure likelihood.

A study on the application of a flux-coupling type superconducting fault current limiter for decreasing HVDC commutation failure was conducted in [23]. The results showed that installing superconducting fault current limiters could efficiently reduce the duration of a commutation failure and assist in the fault recovery process. Sometimes, a possible sequential commutation failure is eluded as a result of improving the power transmission characteristics.

A study was conducted on how the power flow settings of the HVDC links could be controlled to increase transient stability margins. Four control strategies were considered. Simulation results showed that HVDC modulation significantly increases the stability of the system [24].

In [25], a new commutation failure mitigation method for HVDC thyristor-based inverters was presented. Case studies were performed under both symmetrical and asymmetrical faults. The results showed that the strategy could successfully alleviate commutation failures and improve the dynamic performance of the HVDC system.

In [26], an individual-phase-control static var compensator (SVC) compensation strategy for HVDC link with a weak receiving AC side was presented. The results showed that using uniform-phase-control SVC compensation would lead to continuous commutation failure when an AC system is weak. However, using individual-phase-control SVC compensation would inhibit commutation failure effectively.

A novel additional control strategy was proposed in [27]. The strategy entails reducing the probability of commutation failure and increasing the recovery speed of the DC system, especially when connected to a weak AC system. It was found that this method both reduced commutation failure and improved the recovery speed of a DC system.

2.6 Conclusion

This chapter discussed various fundamental aspects of HVDC systems and commutation failure. The current knowledge, including substantive findings, and theoretical and methodological contributions to the topic of commutation failures in an HVDC inverter feeding a weak AC system were discussed.

The literature review in this chapter revealed that substantial work has been done to find a method for mitigating commutation failure in an HVDC network with weak AC systems. MATLAB and PSCAD software programs have been used for these studies. An HVDC system is becoming an increasingly popular choice for bulk power transmission.

The next chapter reviews the fundamentals of PV systems. The components of PV systems including solar cells, panels and inverters are discussed. The chapter further discusses the development of PV plants around the world, integration of these PV plants into the grid, and the cost of PV systems.

Chapter 3: Fundamentals of Photovoltaic Systems

3.1 Introduction

The previous chapter discussed various fundamental aspects of HVDC systems and commutation failure in HVDC systems. The current knowledge, including substantive findings, and theoretical and methodological contributions to the topic of commutation failures in an HVDC inverter feeding a weak AC system were reviewed.

In this chapter, a literature review of the fundamentals of PV systems is conducted. The components of PV systems including solar cells, panels and inverters are discussed. The chapter further discusses the development of PV plants around the world, integration of PV plants into the grid, as well as the cost of PV systems.

There is a significant need for additional electrical capacity due to the growth in electricity demand. PV power is a renewable energy that requires no maintenance. The environmental factors affecting the performance of PV systems are discussed in this chapter. Although it is costly to install a PV system, it is a good investment.

3.2 Photovoltaic System

The PV cell is the mechanism that converts solar light into electric energy. PV energy conversion works on the principle of a P–N junction. A P–N junction is a border line or boundary between two types of semi-conductor materials, namely, p-type and n-type, that are inside a single crystal of a semi-conductor [28]. The ‘p’ (positive) side has an excess of holes, while the ‘n’ (negative) side has an excess of electrons. The potential barrier selectively divides light-generated electrons and holes, directing more electrons to one side of the cell and more holes to the other. Figure 3 shows the circuit symbol for a P–N junction.

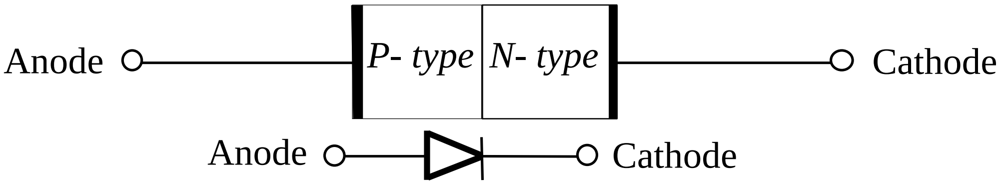

Figure 3: A P–N junction [28]

The triangle in Figure 3 corresponds to the p side. Electrons flow into the p-region where they become excess minority carriers; holes flow into the n-region where they too become excess minority carriers. The chemical potential, including the potential energy due to electric fields of the electrons, is usually called the Fermi level [28].

In general, the PV system consists of a PV generator, which is a set of series–parallel electrically interconnected solar panels. PV panels are rated in terms of the nominal peak power of the panel at standard test conditions. The PV generator delivers the total power, which is the sum of nominal peak power of each solar panel present in the PV installation. The PV generator is connected to an inverter that is connected to the load or grid [29].

3.3 Components of a Photovoltaic System

The core components of a PV panel are the solar cells that absorb sunlight and convert it into electricity, a solar inverter that converts DC to AC, as well as the mounting, cabling and other electrical accessories needed to set up a working system. The power conditioning and control system comprise an inverter that converts DC to AC and that controls the quality of the output power to be supplied to the grid, also by means of an L–C filter inside the inverter itself [30],

[31]. The basic PV device is the PV cell. A set of coupled cells form a panel. Panels are composed of series cells in order to obtain large output voltages.

3.3.1 Solar Cells

Solar cells absorb and convert optical power into electric power. In general, a system powered by solar cells requires a large area solar cell array to generate the required power. The three types of PV cells, namely, monocrystalline, polycrystalline and amorphous cells, depend on the nature of the semi-conductor material used in the production process [30], [31].

3.3.2 Photovoltaic Solar Panels

PV panels comprise one or more PV modules. Numerous PV cells make a module, and a number of modules make an array. Solar panels are interconnected with other electrical components of a PV system by means of solar cables. The PV arrays produce DC, which must be converted to AC through an inverter, an electrical filter, and be connected with the grid at the point of common coupling through an isolation transformer. A PV panel converts the light from the sun directly into electric energy [31].

3.3.3 Modelling of PV Arrays

A solar cell performs best when its surface is perpendicular to the sun’s rays, which change constantly over the course of the day and season [32]. It is important to understand the mathematical model of a cell, which is given by Equation 1 to Equation 11. The PV cell equivalent circuit is shown in Figure 4.

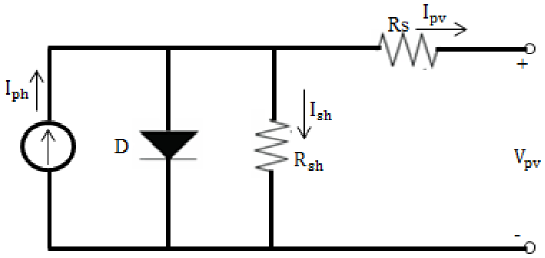

Figure 4: Equivalent circuit of a PV cell [32]

$$I_{ph} - I_d = I_L \tag{1}$$

$$I_d = I_o(e^{\frac{qVd}{rkT}} - 1) \tag{2}$$

$$I = I_{ph} - I_o \left(\frac{q(V+R_SI}{e\;nKT\;-1}\right) - \frac{V+R_SI}{R_{sh}} \tag{3}$$

ignoring R_{sh} for simplicity,

$$I_{ph} - I_0 \left(e^{\frac{qV_d}{rKT}} - 1\right) = I_L \tag{4}$$

but

$$V_d = V_L + R_sI_L \tag{5}$$

$$I_{ph} - I_o\left(e^{\frac{q\left(V_L+R_{SI_L}\right)}{rkT}} - 1\right) = I_L \tag{6}$$

$$I_{ph} - I_L = I_o(e^{\frac{q(V_L+R_SI_L)}{rkT}} - 1) \tag{7}$$

$$\frac{I_{ph}-I_L}{I_o}+1=q\left(\frac{V_L+R_sI_L}{rkT}\right) \qquad (8)$$

$$V_L+R_sI_L=\frac{rkT}{q}In\left(\frac{I_{ph}-I_L}{I_o}-1\right) \qquad (9)$$

$$V_L=\frac{rkT}{q}In\left(\frac{I_{ph}-I_L}{I_o}-1\right)-I_LR_s \qquad (10)$$

$$V_{oc}=\frac{rkT}{q}In\left(\frac{I_{ph}}{I_o}+1\right) \qquad (11)$$

if $I_L = 0$, then I_{ph} is variable, and V_{oc} will not reduce;

V_{oc}	is the output voltage of the cell;
Iph	is the generated current from PV action;
Io	is the reverse saturation current;
γ	is the value between 1 and 3; it differs according to type of diode;
K	is the Boltzmann's constant;
R_{sh}	is the recombination of the electron and hole pair before it reaches the load;
Q	is the electron charge;
V_d	is the diode voltage;
T	is the ambient temperature; and
n	is the ideality factor.

3.3.4 Inverter

Distributed PV generation systems use switching inverters to introduce sinusoidal current into the grid [33]. The different PV inverter categories include module integrated inverters, string inverters, multistring inverters, mini-central inverters and central inverters [34]. An inverter is needed to intensify the low voltage produced by the module to high AC level in the grid. The inverter further incorporates a function for tracking the maximum power point [35].

3.4 Cost of a PV System

According to literature, the most expensive component in a PV power system is the PV module, which accounts for 65% of the total cost [32]. The inverter forms 15% of the total cost of the system. Labour and other components cost 10% of the total cost each. Figure 5 shows the component cost breakdown in PV power systems.

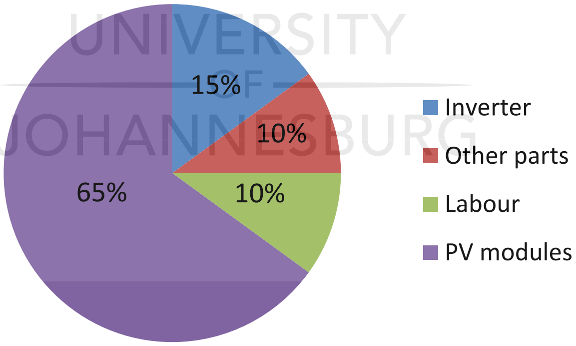

Figure 5: PV system component cost breakdown [32]

3.5 Operating Conditions and Field Factors Affecting the PV System

A solar PV array performance is intensely dependent on operational conditions and field factors, such as the geometric location of the sun, irradiation levels of the sun, and ambient temperature. Temperature has an effect on the efficiency and maximum PV output of a solar panel [36].

In [37], a study was conducted on the PV array modelling under uniform irradiation and partial shading conditions. It was discovered that the insolation received by the PV array is not uniform at all times due to the possibility of some parts of the PV array being shaded. Shaded modules behave as a load instead of as a generator. A hot spot is created due to the shading. In order to avoid the hot spot, the current of non-shaded PV modules should be driven through the bypass diode.

3.5.1 Temperature

The radiant intensity and the temperature of the cell are taken into consideration when analysing the temperature effect on the PV module. Temperature influences the output of a PV cell. An increase in temperature at high voltages may result in a voltage drop. If the cell is operating in the high-voltage, high-temperature region of the curve, it will lead to significant power reductions in the output [38].

3.5.2 Solar Irradiance

The power per unit area received from the sun in the form of electromagnetic radiation in the wavelength range of the measuring instrument is called solar irradiance. The irradiation consists of three different terms, namely, direct irradiance, indirect irradiance from the sun, and indirect irradiance from the earth. The SI unit for irradiance is watt per square metre (W/m^2) [39].

Solar irradiance is a measure of the irradiance (power per unit area on the earth's surface) produced by the sun in the form of electromagnetic radiation. Solar irradiance is seen by humans as sunlight. The output of the PV system is mainly influenced by the amount of solar radiation that arrives at the surface of the PV module of the system [39].

3.6 Photovoltaic System Developments

In current years, PV generation technology has considerably reduced its cost to profitable levels. As a result, the number of PV-based self-consumption installations is increasing. In [40], two different approaches regarding reactive power control of PV inverters have been compared. The first approach was a PV operating with a unity power factor and the second approach was a PV operating with reactive power control. This study discovered that implementing a reactive power control could improve voltage levels.

Another study investigated the significant growth of PV systems that has occurred around the world over the years [41]. The study indicated that PV systems could both be used for large power generation facilities and also for small-scale generation systems. The study proved the economic viability for residential and building applications. The installed capacity of PV power generation systems is rapidly growing worldwide, which enables sustainable electric power systems to be constructed.

Recently, it has become crucial to integrate distributed generation into electrical distribution systems, specifically PV systems [42]. The number of PV plants installations is growing exponentially worldwide. PV systems provide clean energy and can be used to produce adequate supply to meet energy demand. The amount of electricity generated by PV systems generally varies with climate change. The increase in the number of PV systems has created a demand for more storage devices to store the surplus electric power and dispatch it when required [43].

3.7 Grid-connected Photovoltaic Plants

Grid-connected PV power systems are energised by PV panels that are connected to the utility grid. According to literature, the first grid-connected PV plants were introduced in the 1980s as thyristor-based central inverters. A grid-connected PV power system consists of PV panels, maximum power point tracking, solar inverters, power conditioning units and grid connection equipment [44].

The importance of grid-connected PV systems regarding the intermittence of renewable generation and the characterisation of PV generation concerning grid code compliance was investigated and emphasised in [45]. The distribution network impact of the high penetration of distributed PV systems was presented in [46]. The study further discussed the mitigation of negative aspects, and the challenges and benefits of integrating large scale distributed PV power plant.

In [47], a study was conducted to identify the boundary constraint for PV distributed generation capacity in IEEE 13 bus, IEEE 69 bus and IEEE 30 bus distribution test systems. The study identified that PV distributed generation has a positive impact on the system.

The electric energy produced by PV panels and systems was analysed, optimised and modelled in [48]. The optimal operation of PV panels as a function of weather conditions was analysed. The results obtained showed that the optimal electrical properties of PV panels depended on solar irradiation and the panel’s connection (parallel or series).

An assessment of the control methods for a PV-fed three-phase voltage source inverter and its application to various loads are presented in [49]. This study compared different control strategies used in a three-phase PV inverter feeding loads at different power factors. Each control strategy offered different characteristics towards the operation. The voltage total harmonic distortion was observed to be decreasing as there was an increase in the power factor of the resistor-inductor (R–L) load.

The development of a high gain and high efficiency power conditioning system for a grid-connected PV module is proposed in [50]. The study further suggested an accurate PV cell model that considers the environmental conditions such as temperature and shadow effects. Physical security information management and MATLAB software applications were used for the simulations. It was found that the proposed system could be operated at higher efficiency because it avoided the shadow effects.

In [51], the integration impact on system stability was studied using a custom model of PV arrays integrated with PSS/E. The focus was on the impact of large solar plants on power systems due to the rapid variation in power injection. The results showed that the vulnerability of the system increased.

A method for three-phase probabilistic power flow in an unbalanced radial distribution system with single-phase and three-phase grid-connected PV systems was analysed in [52] using sequential Monte Carlo techniques. The output power of a grid-connected PV system was simulated to evaluate the efficiency of the PV inverter and the reliability of the overall PV system. The study yielded good results when more PV plants were connected to the grid.

The impact of a grid-connected PV system on the low-voltage system was evaluated in terms of voltage profile and the effect of unbalanced PV connection. Three different studies were performed to investigate the impact PV plant could have on a low-voltage distribution network. It was observed that the impact of PV plant was highly location and network dependent [53].

3.8 Conclusion

This chapter explained the fundamentals of PV systems. The studies that have been conducted on the integration of PV power into the grid were discussed. The numbers of PV systems that have been installed around the world over the years have increased.

It was further found that a PV system has the ability to improve the voltage profile. Studies showed that PV systems could be deployed in different configurations. However, the work covered in these studies did not incorporate the PV system in an HVDC system with the aim of mitigating commutation failure.

The next chapter focuses on publications that describe the benefits of DGs when incorporated into the grid. The status of the integration of DGs in the network is explained. The impact of different DGs on voltage sags caused by faults, power quality and voltage stability is described.

Chapter 4: The Impact of Distributed Generation on Voltage Dips

4.1 Introduction

The previous chapter conducted a literature review about the fundamentals of PV systems. The components of PV systems, including solar cells, panels and inverters, were discussed. The developments of PV system around the world, integration of PV plants into the grid, as well as the cost of PV system were described.

This chapter focuses on publications that discuss the benefits of DG when incorporated into the grid. The impact of different DGs on voltage sags caused by faults, power quality and voltage stability is explained. The studies highlight the importance of renewable energy in the grid.

Environmental and economic factors give an opportunity for the DGs to be deployed in the most remote areas around the world. The focus is on having more renewable energy to meet the increasing energy demand. Different types of DG systems have different effects on the grid. According to literature, DGs have a positive influence on the voltage dips in the system.

4.2 Review on the Impact of Distributed Generation

Distributed energy incorporation into the grid is growing as it offers more environmental and economic benefits than conventional systems. PV energy grew by an enormous 32% in 2017, followed by wind energy, which grew by 10%. Underlying this growth are considerable cost reductions, with the level cost of electricity from solar PV plants declining by 73%, and onshore wind by almost 25% between 2010 and 2017. Both technologies cost around the same than power generated by fossil fuels [54]. Using renewable energy resources has several advantages for both the final utility grid and the consumer.

Renewable energy is used to meet the higher energy demand and to moderate primary resource requirements such as fossil fuels [55]. Various studies have been done to evaluate the impact of DGs in the network. In [56], a comprehensive fault ride through scheme based on computation of positive and negative sequence voltage and current complex amplitudes that apply to most conventional PV power systems without increasing the system complexity and additional cost. The results showed that the scheme is functional for mitigating voltage dips.

The impact of transmission faults on the voltage dip performance of a weak Upington distribution network with a concentrating solar power plant (CSP) is investigated in [57]. The study simulated a three-phase transmission fault recorded historically. The first step in this study was to tune the simulation to match the recorded fault, which was followed by two cases where there was base case and a case with the CSP plant. The results for the two cases were compared. The comparison showed that the severity of recorded voltage sags improved when a CSP plant was introduced in the network.

A study on the power quality and voltage stability with different DG technologies was done in [58]. A Belgian medium-voltage distribution network was used. The results showed that DG could generally contribute to the improvement of the voltage profile of a distribution system. This study further found that DG is capable of supporting the voltage stability at nearby nodes and has less impact on distant nodes.

In [59], an experiment was done to observe the impact of DG when modelled as a local generator connected to a distribution network. The generator increased the fault levels at the bus of interest, which reduced the severity of voltage sags in the entire system.

DG for alleviating voltage dips in low-voltage distribution grids is investigated in [60]. This study analysed the impact of three different forms of DG systems on the remaining voltage during voltage dips in low-voltage distribution networks. The voltage dips improved when DG was incorporated in the network.

In [61], a small test distribution network was used to explore the impact of DG on voltage sag characteristics. The study presented a simple method for comparing and ranking the performance of a protection system. A synchronous generator showed a positive effect on the voltage sags characteristics, and an improvement was observed on the voltage sags.

The study in [62] explored the impact of DG on voltage sag in distribution systems. A voltage sag assessment was performed on Thailand's distribution systems. The fault positioning method was used for analysis and the voltage sag frequency was investigated. The impact of DG regarding voltage sag improvement was satisfactory.

A study was conducted in [63] to evaluate the impact of DG units on the sensitivity of customers to voltage sags. The statistical method of Monte Carlo was used. The Monte Carlo simulation method was executed for a case without a DG unit and a case with a DG unit. It was observed that DG units generally improve voltage sag severity.

In [64], a stochastic evaluation of the impact of distributed synchronous generation on voltage sag performance was done. Stochastic prediction of voltage sag performance based on the fault positioning method was utilised. PSS/E was used for simulations. A case with and without DG were compared. It was found that the severity of voltage sags decreased when DG was present in the network.

The impact of a synchronous generator on the characteristics of voltage sags caused by faults in a small distribution network was analysed in [65]. The results indicated that DG could have a positive outcome on the voltage sag performance of distribution networks. Another study was conducted where the mitigation of voltage dips through DG systems was evaluated using series compensation and transfer to a micro-grid during the voltage dip. Simulations were done to analyse the transient performance of both solutions. It was concluded that the solutions were able to alleviate voltage dips [66].

Different schemes used to mitigate voltage dips through DG deployment were reviewed in [67]. The benefits and drawbacks of each scheme were highlighted in the study. Most schemes were able to recover the grid voltage quickly after voltage dips. In [68], a study was conducted regarding the use of renewable distributed generation with the aim of lessening voltage dips that arise from both external grid faults and within the micro-grid. The results showed that voltage levels throughout and after faults were sustained more when renewable DG was connected.

4.3 Conclusion

This chapter discussed the impact of DGs on voltage dips. The impact of various types of DG systems was investigated on different types of networks. The software programs used in the studies include Monte Carlo, PSCAD and MATLAB. The studies showed that DG systems have a positive impact on the voltage profile and reactive power compensation.

The studies demonstrated that DG has a positive impact on voltage sags caused by faults. The power quality could be improved by incorporating DG. Voltage stability could be improved when using different DG systems because of their capability to supply reactive power when there is a voltage dip.

The next chapter discusses the theory of the capability of a PV plant to inject and absorb reactive power in the grid. Equations and curves are used to explain the theory. Three converter control modes are explained in detail, namely, voltage control mode, power factor control mode and reactive power control mode. The current inverter limit, voltage inverter limit and the PV active power are three PV inverter operating limits also discussed in detail.

Chapter 5: Photovoltaic Impact on Commutation Failure

5.1 Introduction

The previous chapter focused on the publications that discussed the benefits of DG when incorporated into the grid. The impact of different DG systems on voltage sags caused by faults, power quality and voltage stability was also described. The studies highlighted the importance of renewable energy in the grid.

This chapter discusses the theory of capability of the PV plant to inject and absorb reactive power in the grid. Equations and curves are used to explain the theory. Three converter control modes are explained in detail, namely, voltage control mode, power factor control mode and reactive power control mode. The current inverter limit, voltage inverter limit and the PV active power are three PV inverter operating limits also discussed in detail.

A reactive power supply to the power system is essential for maintaining voltage stability. It is ideal that all DG should contribute to the voltage control by supplying reactive power. PV inverters have the same technological design than full-converter wind generators; hence, their reactive power capabilities are similar.

5.2 Capacity of Reactive Power in a PV Source

The reactive power output of PV power plants rely on the ability of inverters and the internal transmission loss when the inverters are used as reactive power sources. Figure 6 shows the equivalent circuit of a single inverter within a PV plant connected to the grid. U_g is the voltage of the inverter output, U_s the voltage of the internal bus bar, δ_i is the phase angle of the inverter output, X_i is the reactance of the line, P_{Ii} is the active power of the inverter, S_i is the apparent power of the inverter, P_i is the active power gathered in the bus bar, and jQ_i is the reactive power gathered in the bus bar [69].

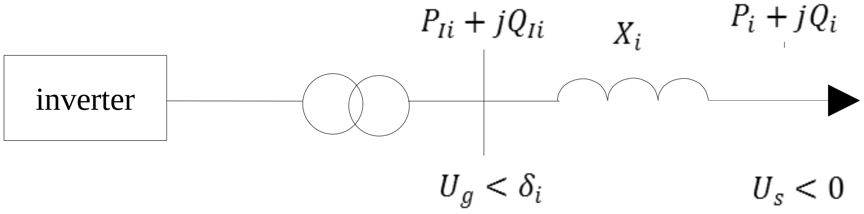

Figure 6: PV plant equivalent circuit [69]

5.3 Current Inverter Limit

The maximum current (I_i) injected by the PV inverter is known as the current inverter limit, which is also known as the maximum permitted heating of the power converter. The maximum current imposes the limit of active power (P) and reactive power (Q) that can be injected by the PV generator. Equation (12) is the equation of the circle that is used to determine the limit of P and Q [69] , [70].

$$P^2 + Q^2 = (U_g I_i)^2 \qquad (12)$$

where U_g is the one-phase voltage in the grid;

I_i is the single-phase current in PV converter;

P is the active power; and

Q is the reactive power.

$$I_i = \frac{\sqrt{P^2+Q^2}}{U_g} \qquad (13)$$

From Equation (13), the current limit has c_2 and $r_{2} = U_g I_i$, which represent the centre and radius.

5.4 Voltage Inverter Limit

The maximum PV inverter voltage (U_i) is the inverter limit, which is determined by the maximum DC link voltage in the power converter. The U_i depends on the continuous voltage from the inverter input, the modulation technique, and the rate of amplitude modulation. The additional capacity limits of P and Q are defined by the maximum PV inverter voltage as described by Equation (14) below [69], [70].

$$P^2 + \left(Q + \frac{U_g^2}{X}\right)^2 = \left(\frac{U_g U_i}{X}\right)^2 \tag{14}$$

where U_i is the single-phase voltage; and

X represents the reactance seen from the inverter terminals.

The voltage inverter limit is represented by the following equation:

$$U_i = \sqrt{\left(P_i^2 + \left(Q + \frac{U_g^2}{X}\right)^2\right)\left(\frac{X}{U_g}\right)^2} \tag{15}$$

The voltage inverter limit is an ellipse with the following characteristics:

a – semi-major axis; *b* – semi-minor axis; *c* – focal semi-distance; *ecc* – eccentricity; C_1 – centre; *K* – constant of the ellipse.

$$a = b = \frac{U_g U_i}{X} \tag{16}$$

$$c = \sqrt{a^2 - b^2} = 0 \tag{17}$$

$$ecc = \frac{c}{a} = 0 \; 0 < ecc < 1 \qquad (18)$$

$$C_1 = (0, -\frac{{U_g}^2}{X}) \qquad (19)$$

5.5 Photovoltaic Active Power Limit

The maximum active power obtained from the PV field is defined as the PV active power limit. Figure 7 illustrates the operational limits of the PV inverter. The viable inverter operation area is marked in grey. In Quadrant 1, the inverter can inject both active and reactive power. In Quadrant 4, an inverter is capable of injecting active power and absorbing reactive power [70].

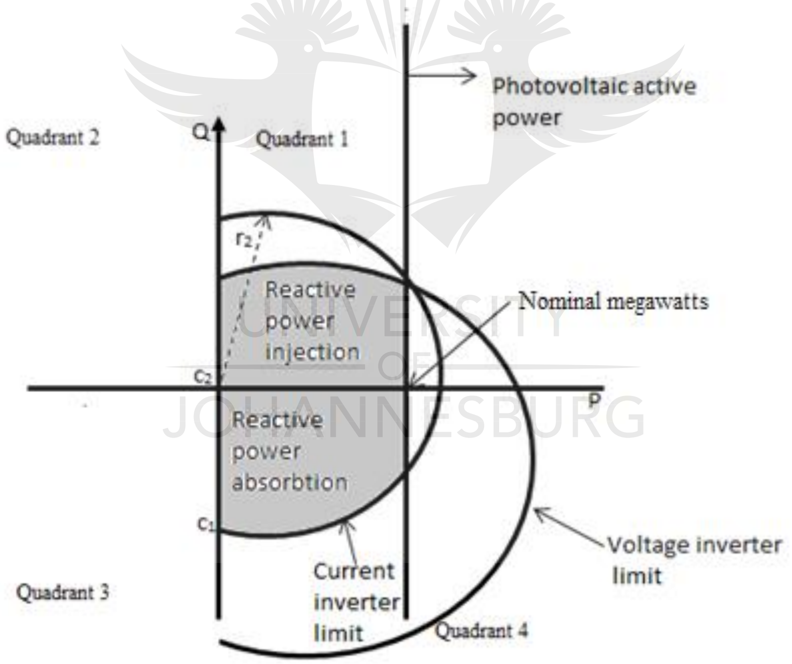

Figure 7: Active and reactive power capacity of PV generator [70]

5.6 Converter Control Modes

The first generation of the converter electrical control system determines the active and reactive power to be delivered to the system. When a centralised plant controller is present in an actual solar

PV plant, it is possible to regulate the voltage at a remote bus within the plant or at an inverter terminal voltage. There are three control modes, namely, voltage control mode, power factor control mode, and reactive power control mode [71].

5.6.1 Voltage Control Mode

In the voltage control mode, the system monitors the voltage and regulates voltages that exceed the range by adjusting the reactive outputs. Terminal voltage is controlled with a faster control loop, which provides a good system response during fault events. In this mode, *Varflag* is set to 1, which means that the reactive power command (*Qcmd*) is derived from the Var emulator and that *Kvi* is not set to 0. Figure 8 shows the block diagram for the voltage control mode [71].

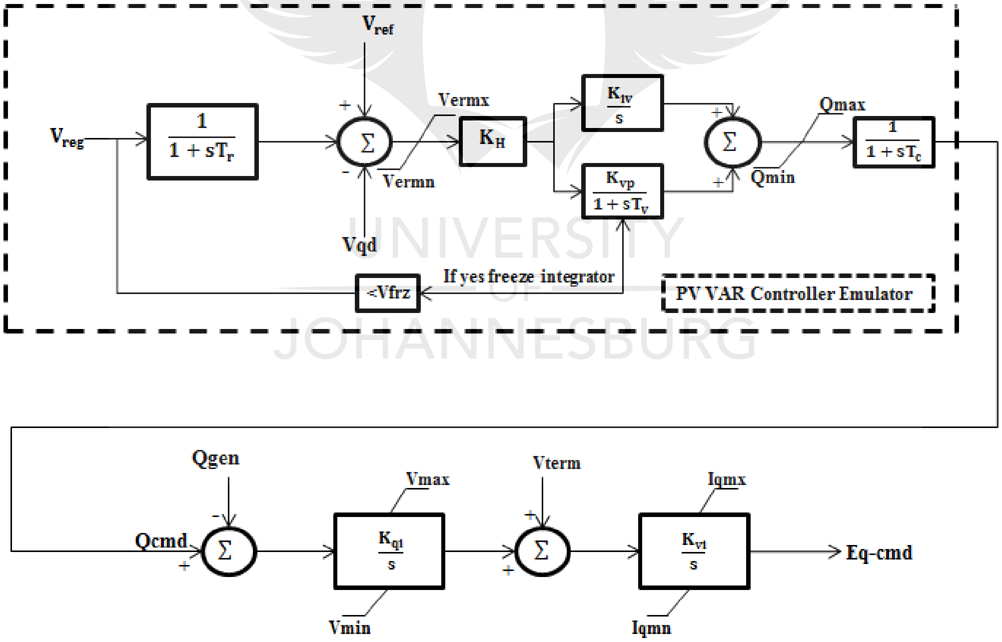

Figure 8: Voltage control mode [71]

5.6.2 Power Factor Control Mode

The system monitors the power factor and calculates and dispatches instructions to the inverters so that they generate reactive power equal to the requested value. In this mode, *Varflag* is kept disabled (*Varflag = 0*), but *Pfaflag* is enabled *(Pfaflg=1)*. The reference power factor angle (*PFAref)* is calculated from the initial load flow solution based on *Pgen* and *Qgen*. Thereafter, *PFAref* and *Pgen* are used to determine the reactive power command (*Qcmd*) to the system. Figure 9 shows the power factor control mode block diagram [71].

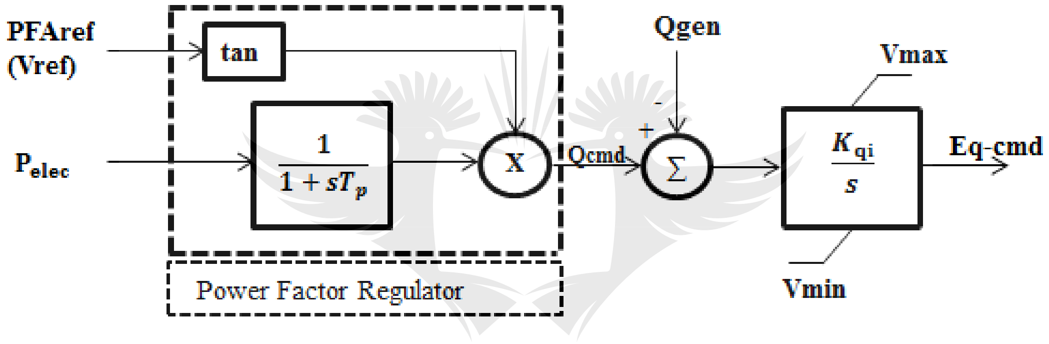

Figure 9: Power factor control mode [71]

5.6.3 Reactive Power Control Mode

The reactive power command (*Qcmd)* sends the command to the inverter electrical control system for reactive power requirements. It is compared with the reactive power generated (*Qgen*) to be delivered by the PV inverter in order to limit the control system voltage between the minimum voltage (*Vmin*) and the maximum voltage (*Vmax).* Figure 10 shows the reactive power control mode block diagram [69], [71].

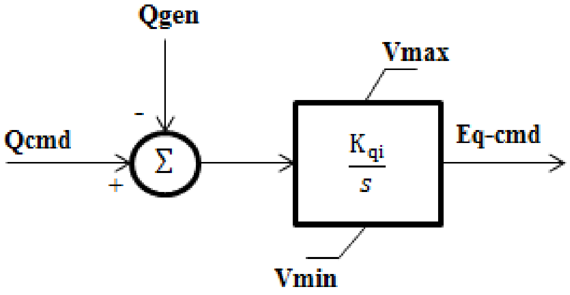

Figure 10: Reactive power control mode [71]

5.7 Inverter Response to Fault Caused by Voltage Dips

When there is a fault in the system due to voltage dips, the response of the inverter depends on the control structure. The control structure will detect when there is a voltage dip and will generate reactive power when necessary. The voltage control monitors the voltage at the point of interconnection and regulates the voltage by adjusting the inverter's reactive outputs [72].

5.8 Conclusion

This chapter discussed the theory that supports the capability of a PV plant in supplying reactive power to the grid. It was shown that PV inverters possess the ability to absorb or inject reactive power if required as long as the current and terminal voltage ratings are not within limit. The chapter further described the response of an inverter when there is a fault due to voltage dip.

The use of converters in transmission networks has increased; hence, the industry is heading towards reactive power provision capability. The inverter's reactive power capability fluctuates as an element of terminal voltage. The control structure should be able to react quickly when there is a fault in the system.

The next chapter describes a case study that assessed the impact of PV plant on commutation failures in an HVDC inverter feeding a weak ac system. The software programmes used for the simulations are PSS/E and PSCAD. A CIGRE HVDC network was used for the studies.

Chapter 6: Methodology of the Study and Case Study

6.1 Introduction

The previous chapter discussed the theory that supports the capability of a PV plant to supply reactive power to the grid. Equations and curves were used to explain the theory. Three inverter control modes were explained, namely, the current inverter limit, voltage inverter limit and the PV active power limits.

This chapter explains all the information of the case studies done to assess the impact of the inverter side of a PV plant on HVDC commutation failures. The objective is to evaluate the impact of a PV plant. The software programmes used for the simulations were PSS/E and PSCAD. PSS/E documentation was used to obtain modelling information.

The base study consists of a classic HVDC line commutated converter link (based on the first CIGRE HVDC benchmark model) and a PV plant is connected at the inverter side. Integrating the PV plant on the inverter side will provide the required commutation voltage to the HVDC inverter.

6.2 Case Study: Description of the Methodology

The CIGRE HVDC model network as shown in Figure11 was used for this study. A network was set up in PSCAD to obtain the critical voltages. Simulations were done using PSS/E software [71]. The faults applied were a three-phases-to-ground fault and a phase-to-phase-to-ground fault at the inverter side. The evaluations were done by considering the severity of the voltage dips, remaining voltages and recovery times.

The CIGRE HVDC system shown in Figure 11 is a monopolar 500 kV, 1000 MW HVDC link. It has a rectifier AC system side and an inverter AC system. Both sides have 12 pulse converters, damped filters and a capacitive reactive compensator. The AC side of the HVDC system consists of the supply network, filters and transformers on both sides of the converter [73].

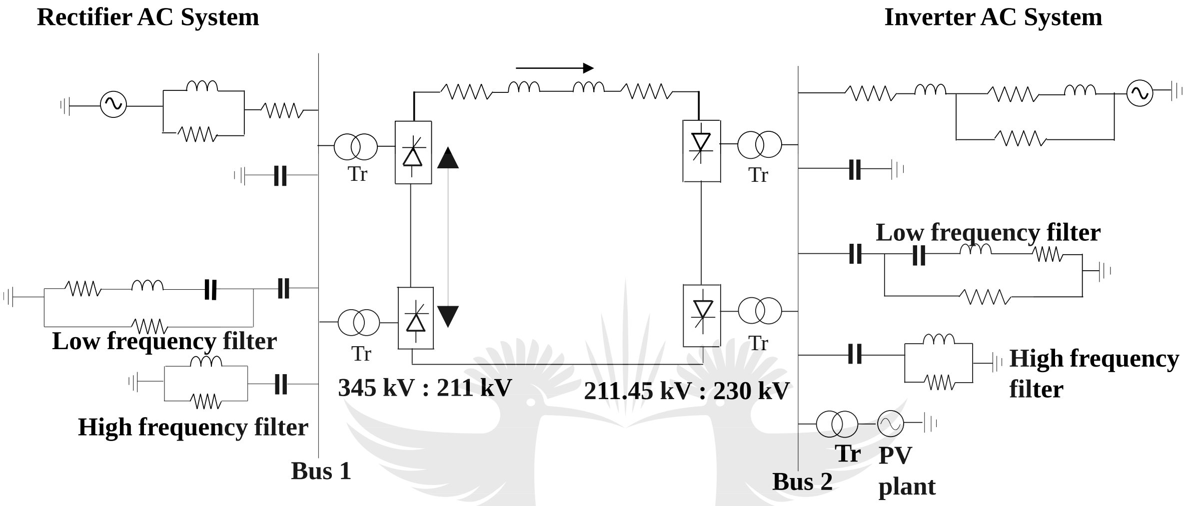

Figure 11: Proposed HVDC PV system [73]

The AC supply is represented by the Thevenin equivalent voltage source with equivalent source impedance. The DC side of the converter consists of smoothing reactors for both the rectifier and the inverter side. A DC transmission line is represented by an equivalent T-network [73].

6.3 Photovoltaic System Modelling

The PSS/E solar PV unit dynamic stability model was developed to simulate the performance of a PV plant connected to the grid through a power converter as shown in Figure 12. The IRRAD is a pitch module, panel is the mechanical module, PVGU is the generator or convertor module and PVEU is the electrical control module. The model is generally based on the generic type 4 wind model, WT4, which has the capability to simulate output changes due to solar radiation.

The PV plant connected to the grid uses the identical technology used for type 4 wind farms, thus the type 4 wind model is used [71].

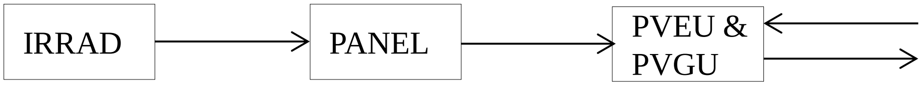

Figure 12: PV plant dynamic model [71]

6.4 Preparation of a Dynamics Data File

PSS/E model is a system of computer programs and structured data files designed to handle the basic functions of a power system performance simulation work. It simulates, analyses, and optimises power system performance, and provides probabilistic and dynamic modelling features [71]. Dynamics in the system were represented by the PSS/E round rotor machine model, namely, Genrou. IEEET2 was used as exciter model. The machine data is shown in Appendix A. The dynamic data was prepared as follows:

- Prepare the case file to ensure that the load flow solves properly.
- Call the case data to ensure that the case starts properly.
- Run the system in dynamics without applying a fault to confirm that steady state voltages correspond with dynamic voltages.
- Apply a fault after 1 second and run it until 1.1 seconds, then clear the fault.
- Repeat the studies and apply the different fault impedances for both the phase-to-phase-to-ground fault and the three-phases-to-ground fault.
- Display the results in graphs and record the results in tables.

6.5 Conclusion

This chapter discussed all the information of the case studies done to assess the impact of an inverter side PV plant on HVDC commutation failures. The objective was to evaluate the impact of PV plant, which was carried out by considering the severity of the voltage dips, remaining voltages and recovery times. The PSS/E and PSCAD software programmes were used for simulations.

The CIGRE HVDC network was shown and the components were explained. Both the PV plant technology and type 4 wind technology use similar control and inverter technology to inject power to the grid. The PV model and the preparation of the dynamic data file were also discussed in the chapter. The chapter highlighted the type of machine and exciter used for the study.

The next chapter presents the results obtained from the simulations. Two case studies that were done are: case with PV plant and a case without PV plant. Tables are used to show the results. Each case study is represented in two tables, one for phase-to-phase to ground fault and the other for three-phase fault.

Chapter 7: Results and Discussion

7.1 Introduction

The previous chapter discussed all information of the case studies done to assess the impact of an inverter side PV plant on HVDC commutation failures. PSCAD and PSS/E software programs were used for simulations. The CIGRE HVDC network was used to conduct the studies. PSS/E documentation was used to obtain modelling information.

This chapter presents the results obtained from the simulations. A comparison is done for a case with PV plant and without PV in a network. A phase-to-phase-to-ground fault and a three-phases-to-ground fault were applied to the network at different impedances. Each case study is represented in two tables according to the type of fault applied to the network.

The objective of the study is to evaluate the impact of the inverter side PV plant on commutation failure. The evaluation was done by considering the severity of the commutation failure, the magnitudes of the remaining voltages, and the recovery time. The results prove that integrating a PV plant into a network improves the probability of commutation failure. The magnitudes of remaining voltages also showed improvement and the recovery time was observed to be shorter.

7.2 Simulation Results

This section presents the results for the evaluation of the impact of an inverter side PV plant on commutation failure. The severity of the commutation failures, the magnitudes for the remaining voltages, and the recovery time were taken into consideration when performing the studies.

A phase-to-phase-to-ground fault and a three-phases-to-ground fault were applied to the network. The records were tabulated according to the faults applied to the network.

7.2.1 Impact of a PV Plant

This study has two cases: a case that evaluated the impact of integrating a PV plant in the inverter side of HVDC network and a case without PV plant integration; both were done at a normal power factor. A phase-to-phase-to-ground fault and a three-phases-to-ground fault were applied to the network at the same bus for both cases. The severity of the faults applied is shown according to different impedances.

Table 1 displays the results of the comparison for the case without a PV plant and the case with a PV plant. A phase-to-phase-to-ground fault was applied. A more severe fault results in less severe commutation failures when a PV plant is present in the network. The magnitudes of the remaining voltages improved and the time taken for the network to recover from the fault was observed to be shorter when a PV plant was present.

Table 1: Impact of a PV plant phase-to-phase-to-ground fault at inverter side

Impedance	**Without Photovoltaic Plant**			**With Photovoltaic Plant**		
	Commutation Failure During Fault	Recovery Time (s)	Voltage (pu)	Commutation Failure During Failure	Recovery Time (s)	Voltage (pu)
0.01	CF	0.09	0.406	CF	0.05	0.451
0.03	CF	0.07	0.596	CF	0.03	0.667
0.05	CF	0.06	0.676	NO CF	0.02	0.741
0.07	CF	0.04	0.735	NO CF	–	0.823
0.09	NO CF	0.04	0.794	NO CF	–	0.867
0.11	NO CF	–	0.835	NO CF	–	0.894
0.13	NO CF	–	0.864	NO CF	–	0.914

CF: Commutation failure

The results for the three-phases-to-ground fault are shown in Table 2. The case with a PV plant present in the network is compared with the case without a PV plant according to the severity of the fault. The integration of a PV plant into the network resulted in an improvement in terms of the severity of the commutation failures. The magnitudes of the remaining voltages also improved and the recovery time was observed to be shorter. The network without a PV plant showed commutation failures even for a less severe fault.

Table 2: Impact of a PV plant three-phases-to-ground fault at inverter side

Impedance	**Without Photovoltaic**			**With Photovoltaic Plant**		
	Commutation Failure During Fault	Recovery Time (s)	Voltage (pu)	Commutation Failure During Fault	Recovery Time (s)	Voltage (pu)
27	CF	0.09	0.516	CF	0.03	0.586
47	CF	0.04	0.654	CF	0.03	0.705
67	CF	0.04	0.687	NO CF	0.01	0.775
87	CF	0.03	0.759	NO CF	–	0.840
107	NO CF	0.02	0.808	NO CF	–	0.878
127	NO CF	0.01	0.843	NO CF	–	0.902
147	NO CF	–	0.869	NO CF	–	0.920

CF: Commutation failure

7.3 Conclusion

This chapter presented the results obtained from the simulations. It was discovered that the probability of commutation failures reduced more significantly when the PV plant was incorporated in the network. The magnitudes of the remaining voltages also improved and the recovery time was observed to be shorter.

Various DG systems have been used for voltage sag mitigation in previous studies. In the review done in Chapter 4 it was observed that incorporating DG in the network has a positive impact on the voltage sag improvement. This study focused on evaluating the impact of the PV plant as one of the DG and it was found that the result corresponds with the previous studies.

The final chapter provides conclusions and recommendation for future studies. The chapter highlights the problem of how commutation failures affect the HVDC system. The aim, objectives of the study and conclusions made on the study are discussed in the final chapter.

Chapter 8: Conclusion and Proposal for Future Studies

8.1 Problem Statement and Research Gap

An HVDC system is a crucial transmission technology, but this system suffers from commutation failure. Commutation failure is an adverse dynamic event that occurs when a converter valve that is supposed to turn off continues to conduct without transferring its current to the next valve in the firing sequence.

Several publications relating to commutation failures have been done. A study was conducted to evaluate the impact of a STATCOM on commutation failures in an HVDC inverter feeding a weak AC system. The STATCOM was connected to an AC system. Simulation results showed an improvement in commutation failure occurrence. Another study evaluated the smallest size of an inductor bank whose connection does not cause commutation failure.

In this dissertation, the objective was to evaluate the impact of the inverter side PV plant on HVDC commutation failures. The case studies are done by considering the commutation failure severity, the magnitudes of the remaining voltages after different types of faults occurring, and the recovery time required to clear a fault.

8.2 Aims and Objectives

The objective of this study was to evaluate the impact of an inverter side PV plant on HVDC commutation failures. The evaluation is done by considering the commutation failure severity, the magnitudes of the remaining voltages after different types of faults occurring, and the recovery time required to clear a fault.

8.3 Findings and Conclusion

8.3.1 Findings

The simulations showed that the presence of a PV plant resulted in less severe commutation failures – even for a more severe fault. The magnitudes of the remaining voltages improved: the magnitudes of the voltages remaining that were recorded at the monitored Bus 2 were generally higher for the case with a PV plant incorporated.

The voltage recovery time was shorter for the case with a PV plant than the case without it. Furthermore, it was discovered that the voltage recovery was quicker for the case with a PV plant and a more severe fault was required for voltages to exceed the acceptable operational range. However, for the case without a PV plant, a milder fault could exceed the acceptable voltage limits.

It was observed that without a PV plant, it took a milder fault to initiate commutation failure in the HVDC inverter. When a PV plant was incorporated in the network, a more severe fault was required for commutation failure to occur. It was further observed that for a three-phase fault in a network without a PV plant, a less severe fault would cause commutation failure. This is as opposed to a much more serious fault as was the case with a PV plant in the network.

8.3.2 Conclusion

The study evaluated the impact of an inverter side PV plant on HVDC commutation failures. The presence of a PV plant in the network improved the severity of commutation failures. The magnitudes of the remaining voltages improved when compared with the case without a PV plant and the recovery time was shorter. The results showed that the presence of a PV plant in the network had a positive impact.

8.4 Proposal for Future Studies

This study evaluated the impact of an inverter side PV plant on HVDC commutation failures. The following further work is proposed: an investigation to evaluate the impact of a battery energy storage system on HVDC commutation failures, the impact of control modes, and the impact of changing the power factor.

Investigating the impact of an inverter side wind plant on HVDC commutation failures is also proposed for future studies. A study could be done to assess the impact of changing the power factor and impact of three control modes, namely, voltage, reactive power and power factor. It could monitor whether integrating the wind plant affects commutation failures by considering the severity of voltage dips, magnitudes of remaining voltages, and the time taken for the system to recover from the fault.

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Appendix A: Dynamic Data

```
1 'GENROU' 1    6      0.05        0.2          0.06
      3          0      1.6         1.55        0.70000
      0.850000     0.2      0.1000      0.09000      0.380000    /
    1 ‘IEEEX1’ 1   0   40    0.06    1    1    1.05    -1.05    0    0.5    0.2    1    0    2.47    0.035    3.5
0.6 /

    8 'GENROU' 1    6      0.05        0.2          0.06
      3          0      1.6         1.55        0.70000
      0.850000     0.2      0.1000      0.09000      0.380000    /
    8 'IEEEX1' 1   0   40    0.06    1    1    1.05    -1.05    0    0.5    0.2    1    0    2.47    0.035    3.5
0.6  /

    1 'CDC6T' 8 18 0.05 0.05 0.6 0.65 0.1 0.6 0.65 0.1 200 500 5 5 300 300 1000 500 3000 500
3000 0.1 0.5 0.05 0.05 0.5 0.05 0.5 0.05 0.05 0.05 0.05   /

   10 'USRMDL' 1 'PVGU1' 101 1 0 9 3 3
        0.20000E-01 0.20000E- 01 0.40000 0.90000
        1.1100 1.2000 2.0000 2.0000 0.20000E-01 /

   10     'USRMDL' 1 'PVEU1' 102 0 4 24 10 4
        5 0 1 0
        0.15000 18.000 5.0000 0.50000E-01 0.10000
```

```
     0.0000 0.80000E-01 0.47000 -0.47000 1.1000
     0.0000 0.50000 -0.50000 0.50000E-01 0.10000
     0.90000 1.1000 120.00 0.50000E-01
     0.50000E-01
     1.7000 1.1100 1.1100 10.0/

10 'USRMDL' 1 'PANELU1' 103 0 0 5 0 1
     0.16 0.38 0.59 0.85 1 /

10 'USRMDL' 1 'IRRADU1' 104 0 1 20 0 1
     1
     5 1000 10 900 15 850 20 800 25 700
     30 600 35 700 0 0 0 0 0 0 /
```