Transient Stability Analysis of an Integrated Photovoltaic Systems in a Power System

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A thesis submitted to
the University of KwaZulu-Natal,
College of Agriculture, Engineering and Science,
in partial fulfillment of the requirements for the degree of

Master of Science (Electrical)

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November 2023

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ABSTRACT

Integration of PV systems into the grid is growing rapidly around the world, and PV penetration plays a huge role in minimizing the effect of greenhouse gases in the atmosphere and also contributes to minimizing the impact of load shedding. However, PV systems contribute to grid integration issues such as transients, voltage, and frequency instabilities and reductions in the generator's inertia, respectively; therefore, it is essential to investigate the effect of the PV system on the grid before integrating it.

This research utilized a modified IEEE 9 bus system to investigate the impact of large-scale PV on the power system, and PSCAD software has been used for this study. Four scenarios with different PV penetration levels were considered in this dissertation. Moreover, for each scenario, the transient stability was assessed based on five parameters, namely: active power, reactive power, rotor angle, rotor speed, and the terminal voltage. Scenario 1 examines the PV systems integrated into a single bus and finds that the optimal PV penetration is 60% of the total power generation. Scenario 2 investigates the effect of integrating PV systems using the optimal PV penetration of 60% distributed into two buses, which was found to be the best for transient stability improvement after a fault condition. Scenario 3 investigates the impact of the power system stabilizer (PSS), using the optimal PV penetration of 60%, and the results reveal that system stability improves when a fault occurs on the bus where the PV system is also connected. Scenario 4 investigates the effectiveness of the fault clearing time on the response of the system with an integrated PV system, using the optimal PV penetration of 60%. The results revealed that a PV system only improves transient stability if the fault-clearing time is below 0.5 seconds; otherwise, the system loses stability. Overall, the study demonstrates that the system's stability improves up to 60% of the PV penetration level of total generation power.

Keywords: Transient stability, PV systems, PV penetration, IEEE 9 bus system, Grid, Power System, Power System Computer Aided Design (PSCAD), Power System Stabilizer (PSS), Fault Clearing Time (FCT)

PUBLICATIONS ARISING

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The following article arises from this research study and forms part of and/or includes research presented in this dissertation. This paper has been accepted for publication by the International Journal of Engineering Research in Africa (JERA).

1. Sibonakaliso Mzebetshana and Dr Rudiren Sarma. Transient Stability Analysis of an Integrated Photovoltaic Systems in a Power System. *International Journal of Engineering Research in Africa (JERA)*, 2023

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Dr. Rudiren Sarma for his support and guidance throughout this research project. I would also like to thank my big brother, Mazayifani Mzebetshana, for his support and encouragement throughout this research. I would like to acknowledge the assistance provided by Ncengizwe Hlambisa, our IT personnel. Your availability and willingness to assist with the simulation tool whenever needed have greatly facilitated the progress of this research. I would like to extend my thanks to all the following individuals who have contributed in various ways: Your support has been essential to the success of this project.

- Khanyisani Makhoba
- Siyabonga Ndlovu
- Sibonelo Mzebetshana
- Sicelo Khumalo
- Boniwe Xolile Mnguni
- Seluleko Sikhakhane

Lastly, I would like to dedicate this dissertation to my lovely wife, Sinenhlanhla Mzoneli. Your unwavering belief in me and my dreams has been a constant source of inspiration. Thank you for your endless support, understanding, and encouragement throughout this journey. Your love and presence have been my rock, and I am truly grateful to have you by my side. This accomplishment is as much yours as it is mine.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Research Background

As concerns surrounding global warming continue to grow and issues such as fossil fuel energy are constrained, there has been a notable rise in the utilization of renewable energy sources in many countries and regions around the world. Among these sources are wind generators (WG) and photovoltaic (PV) systems, which have been experiencing an upward trend in their adoption rates [13] [14] [15] [16] [17]. China is one of the countries that has made considerable progress in renewable energy, including solar power [13]. China's western region, particularly areas like Xinjiang and Qinghai, is known for its abundant solar resources, which makes it an ideal location for solar power generation. China's solar PV industry has experienced rapid growth and has become the largest in the world [13].

The rapid growth of large-scale PV systems introduces intermittent and fluctuating power generation, which can substantially impact the overall stability of the grid. It is, therefore, required that when planning to integrate these large-scale PV systems into the grid, transient stability studies are performed to ensure proactive measures are implemented for the reliability and security of the grid under different operating conditions [17] [18]. Transient stability primarily deals with the system's ability to sustain stability in post-disturbance conditions. Transient stability analysis investigates how a power system responds to events such as short circuits, line faults, or sudden changes in load demand. Rotor angle stability, voltage stability, and power system oscillations are indicators of transient stability. These critical factors are investigated during the transient stability study to determine whether the system can withstand disturbances and return to a stable operating condition after the transient event.

1.2 Problem Statement

Integrating PV systems into grid networks is proliferating across the globe as solar energy is growing at all scales, including rooftop and solar farms. The PV system has several merits, as it reduces greenhouse gas emissions, reduces the use of fossil fuels, and provides a renewable source of energy. However, integrating a PV system into the grid brings several problems, such as transient instability and voltage instability, respectively, to the existing network. Therefore, conducting a transient stability study before integrating a PV system is paramount to addressing the possible challenges. Therefore, the main problem statement in this research reads: The penetration of large-scale PV systems into the grid network could bring instability to the network system, resulting in the blackout of part of the grid or the total grid.

1.3 Research Questions

The primary research question, therefore, reads: What is the effect of integrating large-scale PV systems on the transient stability of the grid? The investigative questions that help answer the primary question read:

- What is the optimum penetration level of large-scale PV systems required for the grid's transient stability?
- How does the location of the large-scale PV systems impact the grid's transient stability?
- How do the power system stabilizers impact the grid's transient stability?
- What is the effect of fault clearing time on the grid's transient stability?

1.4 Research Hypothesis

This research focuses on analyzing the impact of integrating PV systems on the transient stability of power systems. Based on the research conducted by other researchers, [13] [14] [15] suggest that the presence of PV systems in a power system may introduce certain dynamics or characteristics that influence the system's stability. This research will be conducted using the IEEE 9 bus model. This study will be conducted under various scenarios, and the obtained simulation results will be compared and analyzed.

1.5 Research Objective

The main research objective is to investigate the effect of integrating large-scale PV systems on the grid's transient stability.

The secondary objectives that support that primary objective read:

- To determine the optimum penetration level of large-scale PV systems required for grid transient stability.
- To ascertain how the location of the large-scale PV systems impacts the grid's transient stability.
- To determine the effect of fault clearing time on the grid's transient stability when optimal PV penetration is integrated into the grid.

1.6 Limitation of the Study

The following are the limitations of the research study:

- It is conducted under a simplified IEEE 9 bus test system, as it is almost impossible to conduct this study on a real-time network.
- It is conducted under a single contingency scenario: a three-phase fault, even though real power systems tend to be subjected to multiple contingencies, such as line outages or simultaneous generator trips.

- It is conducted based on static system parameters and load profiles..

1.7 Research Methodology

A thorough theoretical background was conducted in grid-PV systems, transient stability, PV systems and their support systems, classification of power system parameters, and lastly, reviewing other researchers' work in the same field as this research.

The system under consideration for this study was specified and modeled, followed by simulations carried out under various scenarios and cases using PSCAD. The simulation results have been demonstrated and discussed.

1.8 Chapter Summary

This chapter has introduced the research study in this dissertation, and it has discussed the research problem, problem statement, research questions, research premise, research objectives, limitations of the study, literature study, and research methodology.

Chapter 2 presents the theoretical background of the grid-PV system, transient stability, classification of power systems, the theoretical background of PV systems and their support systems, including converters and inverters, and lastly, a review of work in the same field as this research study.

Chapter 3 presents the methodology and steps followed to conduct this research study, simulation tool selection, demonstration of models and their respective parameters, such as single machine infinite bus system (SMIB), IEEE 9 bus system, PV system, inverter model, LCL mathematical model, and lastly load flow mathematical model.

Chapter 4 presents preliminary research simulation results such as the effect of the power system stabilizer (PSS) in transient stability through the SMIB system, the determination of the fault clearing time used in this research study, the simulation results of the PV system model, the three-phase inverter model, and the load flow analysis and fault location in IEEE 9 bus systems.

Chapter 5 presents case studies that have been used to conduct this research study. The simulation results are compared against each other using distinct color code legends. The simulation results are analyzed and discussed in this chapter.

Chapter 6 presents the research conclusions in this dissertation and provides recommendations for future research studies.

Chapter 2

Background Information and Literature Review

2.1 Introduction

This chapter provides the theoretical background of power systems, grid-PV system transient stability issues, transient stability of power systems, classification of power system stability, the effect of integration of PV systems on grid systems's stability, the effectiveness of power system stabilizers on transient stability, the effectiveness of high levels of PV penetration on transient stability of the power system, the effectiveness of fault clearing time on transient stability of the power systems, and photovoltaic systems. Similar studies that have been researched by other authors have been discussed to identify gaps in this research. The different techniques that were used by other researchers to conduct transient stability analysis are also presented in this chapter.

2.2 Power System

An electric power system is a group of generation, transmission, and distribution and other facilities that are physically connected [1]. Power systems play an important role in providing electricity to residential areas, hospitals, and industries, respectively. The power generation division is the main source of power systems, where various sources of energy are converted into real electricity. These sources of energy include solar, wind, hydro, fossil fuels, and geothermal. The transmission division is there to transmit electricity for a longer distance at a higher voltage to distribution stations, while the distribution division is responsible for distributing electricity to consumers. Figure 2.1 below illustrates the power system layout with different divisions.

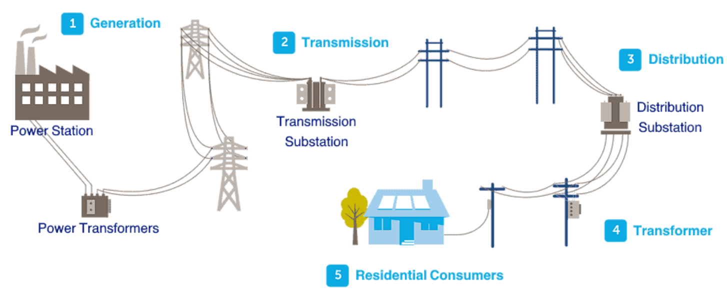


Figure 2.1 : Power system layout including all divisions [1].

2.3 Grid-PV System Theory

The demand for commercial energy is anticipated to continue increasing as both the global population and standard of living rise [12] [19]. Integration of solar power into the grid is crucial because it improves the supply of electricity to consumers and the grid while also improving the economics of PV systems and the building energy balance [12]. The network as a whole is frequently referred to as the "grid." Grid connectivity specifically denotes a connection to any area of the network. The Extra High Voltage(EHV) transmission network is typically referred to as the national grid [20].

Integration, in this research, refers to the actual physical connection of the generator to the network, taking into account the system's secure and safe operation as well as the generator's control to optimize the use of the available energy resources. A renewable energy generator can be either stand-alone or connected to the grid. In a system that is grid-connected, the renewable energy generator supplies electricity to a large interconnected grid that is also supplied by a number of other generators. The important difference in this case is that the renewable energy generator's power only accounts for a small part of the total power generated by all the generators connected to the grid. The point of common coupling on the network is where a renewable energy source is connected (PCC) [20].

Photovoltaic (PV) systems and concentrated solar power (CSP) systems, also known as solar thermal power generation, are the two forms of solar systems that can be integrated with the grid system [12]. The differences between PV and CSP systems are as follows: PV systems generate direct electric current through the PV effect using sunlight [12]. While CSP behaves like conventional thermal power generation as it converts thermal energy (steam) into electricity [12], the disadvantage of PV systems is that they cannot store energy on a large scale and directly generate electricity, while CSP can store energy using thermal storage technologies. Hence, the CSP system is more favorable than the PV system for large-scale integration due to its ability to store thermal energy. Even though the CSP system is a better technology for grid-solar integration, its expansion in power utility is limited by the cost factor, as it is quite expensive compared to the PV system. Currently, the energy market favors the PV system as its cost drops [10] [11] [12]. The PV system is normally connected to the grid system via an inverter system [21] [22] [23]. As a result, the following requirements must be followed for grid-PV integration to be successful, as shown in Table. 2.1.

Table 2.1 :Grid-PV system integration conditions[10] [11] [12].

Parameters	Description
The order of the phases	The phase order of the three-phase inverter must correspond to the phase sequence of the grid system's three-phase.
magnitude of voltage	The amount of the sinusoidal voltage generated by the inverter should be the same as the magnitude of the grid system's sinusoidal voltage.
Frequency	The frequency of the sinusoidal voltage produced after the inverter should match the frequency of the grid's system.
Phase angle	The phase angle between the inverter's sinusoidal voltages and the grid system's sinusoidal voltages must be zero.

Grid-PV system can be presented as a single-line diagram with two sources on each side with an impedance in between as shown in Figure 2.2 below.

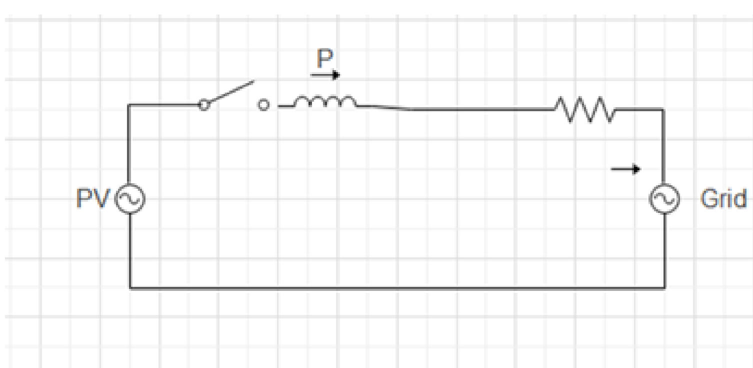


Figure 2.2 : Grid PV system equivalent circuit diagram.

2.4 Transient Stability

Transient stability is power system's ability to maintain synchronism in the case of a significant transient disturbance, such as a transmission line failure, a loss of generation, or the loss of a huge load. The large fluctuations in bus voltages, power flows, generator rotor angles, and other system variables are some of the system's responses to such disturbances. The power system's nonlinear dynamics can influence the stability of the system. The system maintains synchronism if the ensuing angular deviations between the machines in the system stay within the allowable range [24] [25]. In most cases, system instability is prevented by the action of protective devices. These protective devices aim to stop damage to power system components, such as that caused by fault currents, overvoltage, or overspeed. Protective devices monitor the proper system quantities and disconnect the appropriate generators, loads, or lines when they detect the presence of unusual system conditions. The protective devices must meet three fundamental characteristics in order to function satisfactorily, namely selectivity, speed, and dependability [26] [27] [28]. On many occasions, the topology modification of the system restores the stability of the power system by removing the faulty component that has been threatening it [29] [30] [31]. After a disturbance, a stable operating point may be reached that differs from the initial state. This is valid if the disturbance itself or the activities of any protective measures used during the temporary occurrence alter the topology of the power system permanently. A generator or line trip, as well as a load change, are examples of such topological changes. The topology of the power system is not permanently altered when a fault is cleared without tripping any components. However, the steady state in this situation is typically the same as it was prior to the incident [31].

2.5 Classification of Power System Stability

While power system stability is a single issue, understanding and efficiently managing the numerous instabilities that can occur is challenging. Deal with it as such. To study stability problems, it's important to establish simplifying assumptions and utilize appropriate system representation and analytical approaches, given their high dimensionality and complexity [3]. Therefore, the classification of power system stability is important for relevant practical studies and solving power system stability problems [32] [33] [2]. The following issues should be taken into consideration for the classification of power system stability [32].

- The physical nature of instability is shown by the main parameters in which instability can be studied.
- The magnitude of disturbance observed affects the methods of calculation and prediction of stability.
- The tools, procedures, and time must be taken into consideration to evaluate stability.

Figure 2.3 below shows power system stability; it includes categories and sub-categories. In this research, three categories, namely rotor angle, bus voltage, and frequency, will be well investigated.

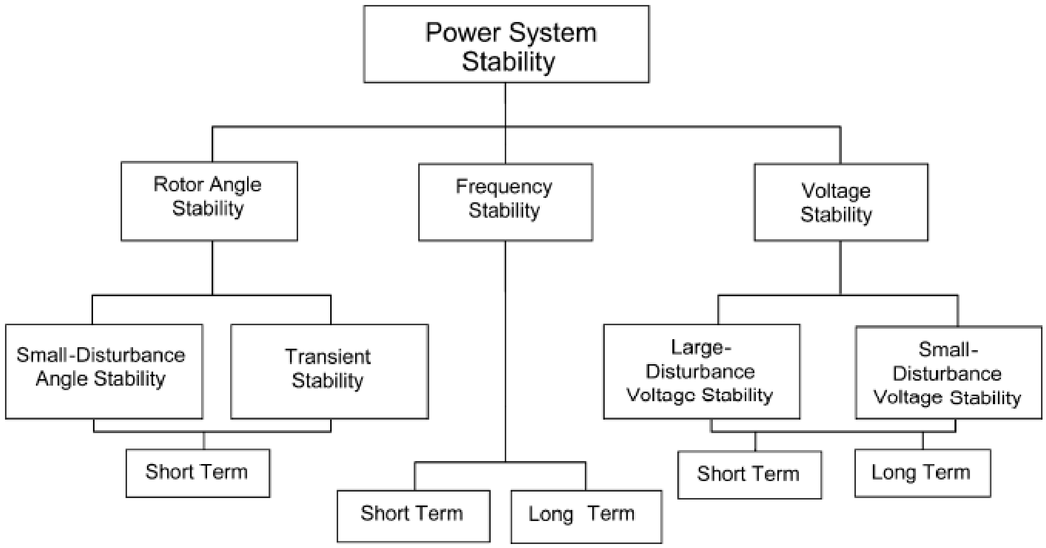


Figure 2.3 : Classification of power system stability [2] [3].

2.5.1 Rotor Angle

The ability of a power system synchronous machine to maintain synchronism under typical operating conditions and to restore synchronism after a small or significant disturbance is known as rotor angle stability. A machine remains synchronized if the electromagnetic torque produced by the prime mover is equal to and opposite to the mechanical torque generated by the prime mover. As a result, this type of stability is based on the synchronous machine's ability to maintain or restore equilibrium between these two opposing torques. [2]. Aperiodic or non-oscillatory transient instability is caused by a lack of synchronizing torque or by a negative torque. Numerical integration techniques are frequently employed in the study of this kind of instability, which results in notable rotor angle fluctuations in synchronous machines. Conversely, small-disturbance oscillatory stability will occur in the absence of negative damping torque. This kind of instability is characterized by a complex conjugate pair of relatively poorly damped eigenvalues of the linearized system state matrix moving from the left-half plane (stable) to the right half-plane (unstable) of the complicated plane [2] [34] after a system disturbance or change in the system topology.

2.5.2 Voltage Stability

Voltage stability is defined as the ability of the power system to maintain or restore the system voltage to an allowable range after a minor or major disturbance without voltage collapse [35]. Voltage stability is classified into two classes, which are small disturbance and large disturbance, and both are categorized into short-term and long-term [33]. Static voltage stability and high-disruption voltage stability are two categories of voltage stability based on the size of the disturbance. Static voltage stability is the ability of the system voltage to continue or recover after experiencing a minor disturbance without experiencing a voltage breakdown. It is mostly used to determine the voltage static stability reserve in the event of an accident or normal system operation. Major disturbance voltage stability, which includes transient, dynamic, and long time voltage stability, ensures that the power system does not experience voltage collapse when it encounters a large disturbance [36]. There are several methods that are used to analyze transient voltage stability, which include the time domain simulation approach, the transient energy function method, and the nonlinear dynamic techniques [35].

2.5.3 Frequency Stability

Frequency stability refers to the ability of a power system to maintain steady state frequency following a severe disturbance resulting in a significant imbalance between generation and load. Large system upsets are typically accompanied by considerable fluctuations in frequency, power flow, voltage, and other system characteristics. During frequency excursions, voltage magnitude may change significantly, especially for islanding conditions with under-frequency load shedding that unloads the system. Voltage magnitude changes may be higher in percentage than frequency changes [3] [2] [35].

2.6 The Effectiveness of PV System into Power System Stability

The integration of PV systems into grid affects the power flow [37] [38]. In [37], it is stated that a power system's inertia plays a vital role in grid system stability [37] [39]. PV systems are inertia-less compared to conventional generators [37] [40]; therefore, PV systems reduce power system stability [37] [39] [41]. The dynamic behavior of the power system can be described by the swing equation 2.1 shown below [37]

$$M\frac{d^2\delta}{dt^2} = P_m - P_e \tag{2.1}$$

Ref in [42], indicate that the PV system integrated into the grid system has significant effects on the power quality, voltage stability, and frequency stability of the power system, respectively. Ref in [42], state that for proper operation of the power system, active power and reactive power must be balanced according to the load system; hence, adjusting the power factor of the PV system is crucial for large power system applications [42].

Ref in [39], proposed a PV system with an energy storage device to reduce transient stability problems in power systems. This energy storage device, known as virtual inertia, provides short-term power during disturbances to improve the inertia of the system [39]. Ref in [40], proposed fault ride-through capability to improve short-term voltage instability. Fault ride-through capability is defined as the ability of a power system to ride through voltage sag and frequency variation [40].

2.7 The Effectiveness of High PV Penetration to Transient Stability of the Power System

Ajit Kumar K et al. [43], indicate that an increase in PV penetration without specialized controls such as Low Voltage Ride Through(LVRT) [40] negatively affects steady state performance and transient stability of the system. Ref in [44], indicate that an increase in penetration of PV systems improves power system oscillatory stability. Ref in [45] [46] [47], indicate that higher levels of PV penetration can affect the system's voltage stability positively; however, ref in [48] [17], indicate that large-scale PV systems can have a detrimental and beneficial impact on the grid's system stability. Ref in [49], indicate that the small signal stability of the power system can be negatively affected by PV penetration when it operates beyond the critical operating condition. Reference in [50], reveals that transient stability has improved when a fault occurs at less critical points, and hence fault proximity to solar PV generation is a critical determinant of transient stability. Reference in [51], reveals that high levels of PV penetration result in high fault current and negatively affect protective devices of the system.

2.8 The Effectiveness of FCT on Transient Stability of the Power Systems

In transient stability analysis, the fault clearing time (FCT) is a crucial parameter used to assess the stability of a power system following a disturbance. It refers to the maximum time duration within which a fault or disturbance must be cleared in order to maintain stable operation without experiencing a loss of synchronism [52]. Ref in [53], indicate that time delay on power systems with small signal stability can be ignored, but if it is large, it can significantly affect the dynamic characteristics of the power systems. Ref in [54], proposed STATCOM-based damping stabilizers to improve Critical Clearing Time(CCT) and greatly improve the power system transient stability. Ref in [55], proposed a new computational method based on critical trajectory and simultaneous equations for determining CCT on the transient stability of the power systems, and the author indicated that this method reduces the simulation time and is potentially suitable for online transient stability analysis. Ref in [56] developed a method for accurately and efficiently analyzing transient stability in power systems using CCT functions, and based on the results, it demonstrated its effectiveness.

2.9 The Effectiveness of PSS in Transient Stability of the Power Systems

Ref in [57], [58], and [59] indicate that PSS can effectively damp low-frequency oscillations and improve the stability of power systems and voltage profiles. Ref in [60] compared the effectiveness of PSS and static Var compensator (SVC) in improving transient stability, and the author indicates that SVC is better than PSS. Ref in [61] proposed three nonlinear methods to improve conventional PSS, and the author indicate that these improved PSS improve the stability of the system greatly.

2.10 PV System

The PV generation system and its supporting controls are depicted in a single-line diagram in figure 2.4 below. PV arrays or modules, a DC-DC converter to increase voltage, an inverter to alter the voltage from DC-AC, and line filters make up the PV system [21] [23].

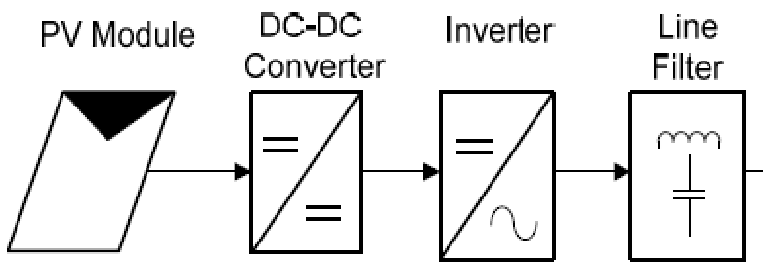


Figure 2.4 : CPV system diagram.

2.10.1 PV Cell

Solar panels are the building blocks of PV systems, which are constructed from solar arrays, solar modules, and solar cells connected in series or parallel. A straightforward circuit diagram of a solar cell shows the photocurrent source I ph, a parallel-to-the-source diode, series resistance R s, and shunt resistance R sh. The p-n of a semiconductor called a PV diode is exposed to light [21] [12] [62] [4]. Figure 2.5 below demonstrates a PV cell equivalent circuit diagram.

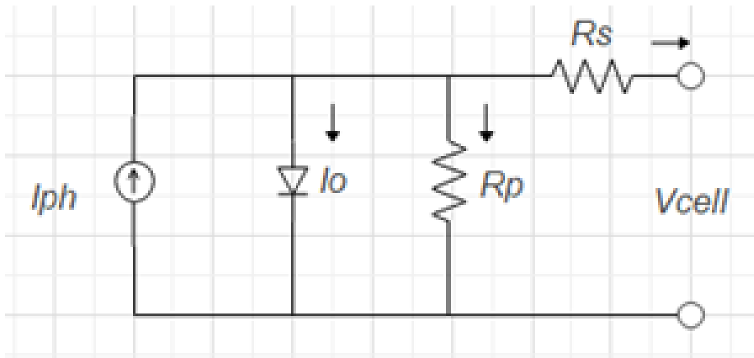


Figure 2.5 : PV cell equivalent circuit diagram [4].

2.10.2 DC-DC Converter

The step-up converter is another term for the boost converter. The term suggests that it is often used to convert a low input voltage to a high output value. For this research, a DC-DC boost converter is employed to ensure that the photovoltaic module always operates at the maximum power point [21] [5] [63] [6]. Figure 2.6 below illustrate the DC-DC boost converter equivalent circuit diagram.

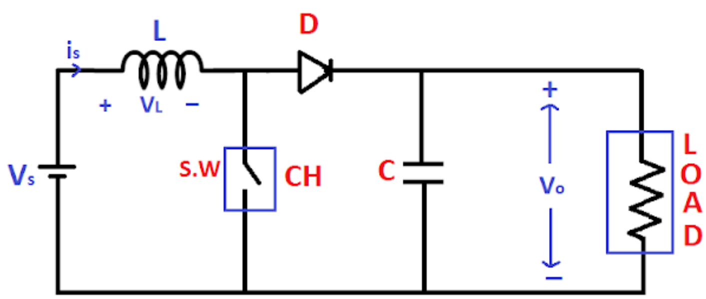


Figure 2.6 : DC-DC boost converter equivalent circuit diagram [5] [6]

2.10.3 Voltage Source Inverter

A PV inverter is a crucial component of a grid-connected PV system that converts DC electricity from the PV system into AC power that is delivered to the grid. Various types of inverters have been proposed and researched [64] [65] [66] [67]. A three-phase voltage source inverter with six switches and inversely linked diodes is depicted in Figure 2.7 below. The role of capacitors in DC voltage is evident. Pulse-width modulation (PWM) is a technique used by IGBTs to convert sinusoidal waveforms from a DC voltage to an AC voltage.

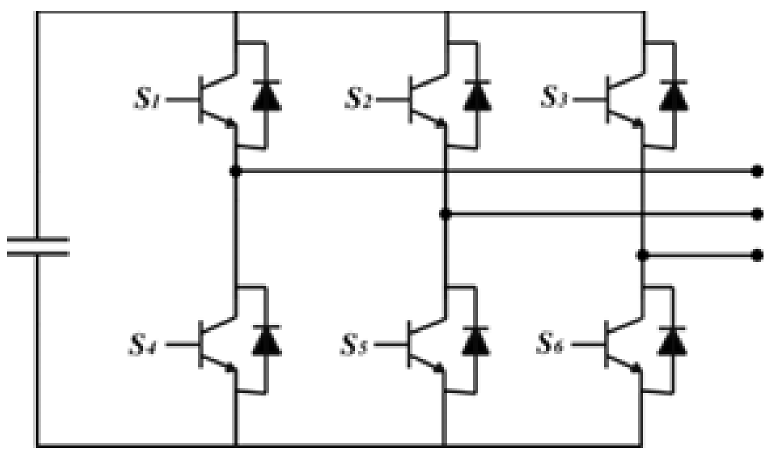


Figure 2.7 : Voltage source inverter circuit diagram.

2.10.4 Maximum Power Point Tracking(MPPT)

The MMPT is used to automatically find the voltage VMPP or current IMPP at which the PV array should operate to obtain the maximum power out of PMPP under a given temperature and irradiance. It is possible to have multiple local maximums due to partial shading conditions, even though overall there should be only one true MPP. Most techniques have the ability to respond to changes in temperature or irradiance [21] [63] [7] [6]. Figure 2.8 below depicts the PV cell I-V characteristics curve.

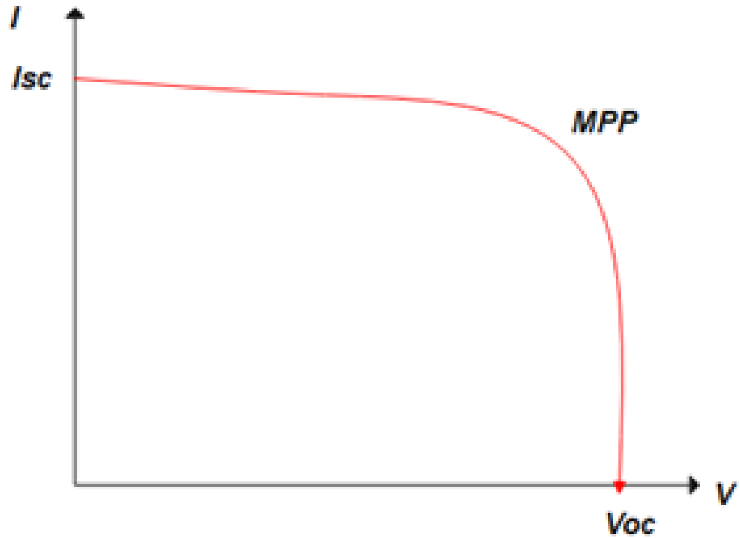


Figure 2.8 : PV cell typical I-V curve characteristics [7] [6].

2.11 Transient Stability Analysis of an Integrated PV System in a Power System in Literature

Over the years, researchers have been investigating the impact of PV systems on distribution levels [68] [69] [70]. These investigations have focused on how the system behaves while PV systems are connected to the grid, including factors like location points and control strategies that could be considered for better system performance. With the increase in PV installations, there has been an increased interest in researching high PV penetration at the transmission level [71]. Currently, many researchers are focusing on the impact of large-scale PV systems on the grid. In [72], this paper investigated the impact of increased penetration of large-scale PV systems on the short-term stability of power systems. The findings revealed that instability is reported in full replacement of conventional generating units; however, if partial replacement is adopted, only a few instability conditions are observed. Additionally, the results demonstrate that the utilization of large-scale PV systems with reactive power regulation capabilities is more beneficial than employing large-scale PV systems without reactive power regulations.

In [73], a study using the IEEE 39 bus test system to analyze the impacts of integrating PV systems is considered. It aimed to evaluate the dynamic behavior of the IEEE 39 bus test system under various penetration levels of integrated PV systems. PV systems were connected to specific buses within the IEEE 39 bus system without replacing conventional power generation systems connected to those buses. The focus was on three different buses with integrated PV systems. It examined the effects of PV system loss and three-phase faults occurring at the bus where the PV systems were connected. The impact of penetration levels on bus voltage, system frequency, conventional generator power, and the net injected current was investigated. The results revealed that integrating PV systems and the subsequent changes in voltage profile can pose significant risks to the stability and reliability of the power system. As a result, the need for protection coordination at the distribution end becomes essential, especially when the frequency drops. Additionally, it was found that the dynamic response of active power delivered by the PV system is faster compared to that of conventional units when achieving a stable state after a fault event. This implies that PV systems respond faster to disturbances compared to conventional power generation systems, and hence their stability can be improved at certain specific operation conditions.

In [74], the impact of integrating PV systems into grid systems is investigated. The study reveals that large-scale PV penetration provides stability for the grid. Additionally, it was noted that the stability of the system is influenced by the positioning of the fault and fault clearing time. In [75], transient stability analysis was performed on a real network using the Digsilent Power Factory program. The investigation was conducted based on three specific cases: increasing the system load, compensating for power shortages from a generator using a large-scale PV system, and replacing a synchronous generator with a large-scale PV system. Additionally, various levels of large-scale PV system penetration were observed in hypothetical cases to observe the variation of rotor angle and bus voltage after a three-phase fault. The study was conducted based on three scenarios. In the first scenario, where the system load increased and various levels of PV penetration up to 30% were considered, the rotor angle and bus voltage oscillations were positively damped. In the second scenario, where the generator's output power is gradually reduced and compensated by a large-scale PV system, the rotor angle and speed of the generator oscillations were positively damped until 60% PV penetration. In the third scenario, when a large-scale PV system replaces a conventional generator, the results show an improvement in voltage response in the power grid, and the active power oscillations are positively damped.

In [16], the transient stability analysis and determination of the optimal location for PV penetration were conducted on an IEEE 5 bus system with and without PV penetration. The results revealed that the system failed to maintain its stability at a higher level of PV penetration.

In [13], the study of transient stability is conducted based on an actual PV project of 200 MW. The simulation and analysis reveal that large-scale PV systems disrupt load flow balance, power angle, and voltage instability. Additionally, it is suggested that it is important to disconnect the PV power as soon as instability in the power system occurs.

In [17], thorough fault studies on the transmission network of the Western Electric Coordinated Council (WECC) power system are conducted. The main objective of this study was to investigate the impact of PV integration on the transient stability of the system. This study was conducted with and without PV system penetration. The simulation results indicate that PV penetration may pose both positive and negative effects on the power grid system depending on the system topology, PV system penetration level, location of PV system integration, and fault location [6].

In [43], the effect of large-scale PV systems on steady-state performance and transient stability without specialized controllers is investigated. The study reveals that voltages are affected adversely by the location and level of PV penetration. Furthermore, voltage magnitudes and rotor angles are adversely affected by the transient's performance with high penetration of PV.

In [76], the dynamic behavior of the power system following severe disturbances is investigated. The study initially conducted a power flow analysis using the Newton-Raphson method.

Reference in [77], proposes a linearized model of the power system to analyze transient stability when the photovoltaic system is integrated into the grid using the IEEE-14 bus test system and Q-V model analysis. The equation for static analysis is shown below.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix} \times \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \tag{2.2}$$

Where ΔP and ΔQ are mismatch power vectors and ΔV and $\Delta\theta$ are correction vectors.

$$\begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix}$$

The above expression is known as the Jacobian matrix used in Newton Raphson load flow analysis [78].

For this study, active power was considered constant.

$$\begin{bmatrix} 0 \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix} \times \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix}$$

Q-V modal analysis was proposed as it gives a clear indication of voltage instability and the key factors that contribute to the instability of the system. The Q-V modal analysis can be derived from the expression above as follows:

$$\Delta Q = J_R \Delta V \tag{2.3}$$

Where J_R is the reduced Jacobian system matrix. The mode of the network can be defined by the eigenvalues and eigenvectors of the J_R[79].

Assume:

$$J_R = \xi \triangle \eta \tag{2.4}$$

Where: ξ is the matrix of right eigenvectors correlating with all eigenvalues of the system; $\triangle$ is a diagonal matrix of the system eigenvalues; and η is the matrix of left eigenvectors correlating with all eigenvalues of the system.

Referring to expressions 2.3 and 2.4 above, the variation of voltage can be expressed as:

$$\Delta V = \xi \triangle^{-1} \eta \Delta Q \tag{2.5}$$

As it can be seen in the expression 2.5 above, a large eigenvalue means there is a small change in the modal voltage for reactive power changes, and an eigenvalue that approaches zero means there is a large change in the modal voltage and the system is close to collapse. The system is said to be stable if all eigenvalues of the J_R system matrix are positive, and if any eigenvalue is negative, the system is unstable [79]. The right and left eigenvectors provide information about what leads to voltage instability. The bus participation factor measuring the participation of the k_{th} bus to the i_{th} bus can be given as:

$$P_{ki} = \xi_{ki} \eta_{ki} \tag{2.6}$$

Ref in [80] [81] [82], conducted transient stability analysis using differential algebraic equations (DAEs). DAEs are a combination of ordinary differential equations (ODEs) and algebraic equations. The ODEs describe the rate of change of dynamic variables, such as generator rotor angles and rotor speeds, while the algebraic equations represent the relationships between the variables, such as the power flow equations and Kirchhoff's law.

$$\dot{x} = f(x, y, p) \tag{2.7}$$

$$0 = g(x, y, p) \tag{2.8}$$

Where the x variable represents the mathematical model that captures the behavior of generators, loads, transmission lines, transformers, and other power system parameters, y represents steady state variables, which include initial rotor angles, rotor speed, and voltages. When p presents a disturbance, such as a three-phase fault or the sudden loss of a generator, it is simulated in the system. This disturbance causes deviations in the dynamic variables, leading to transient behavior.

Numerous researchers have conducted extensive investigations into various aspects of transient stability analysis in power systems when integrating PV systems into the grid. These studies have provided valuable insights into the factors influencing grid stability. However, it is worth noting that there exists a noticeable gap in the existing literature concerning the impact of distributed PV systems, PV penetration without PSS, and PV penetration with a longer fault clearing time on the transient stability of power systems. This research highlights the need for additional studies that comprehensively delve into the analysis of transients when large-scale PV systems are distributed across different busbars within the system, the influence of PV systems when generators are without PSS on power system transient stability, and finally, the effect of PV systems when the power system is subjected to longer fault clearing time on power system transient stability

2.12 Chapter Summary

The theoretical background in this chapter reveals that there are two types of solar systems, and their differences were discussed thoroughly. The classification of power system stability was discussed in this chapter, and transient stability, also known as rotor stability, was discussed thoroughly in this chapter as it is the focus of the study. The effect of high PV integration on the transient stability of the power system literature conducted by other researchers was reviewed and compared. There are different techniques proposed by other researchers that can be utilized to determine CCT for conducting transient stability analysis. Several transient stability evaluations conducted by several researchers have been presented and compared in this chapter. The PSS control proposed by other researchers is discussed in this chapter. In the next chapter, will discuss the methodology adopted for this study.

Chapter 3

Research Methodology

3.1 Introduction

This chapter presents the methodological approach adopted in this study to meet the aims and objectives of this research study. As stated in Chapter 1, the research study investigates transient stability when a photovoltaic system is integrated into a power system.

This chapter is structured as follows:

- Study organization
- Selection of tool
- Analysis of results
- Transient stability analysis techniques

- Generator control model
- Fixed load model
- system model
- IEEE 9 bus system model
- Photovoltaic system model and specifications parameters
- Inverter system model
- LCL Model
- Load flow mathematical model

3.2 Study Organisation

The following is the study organization adopted for this research study:

- A comprehensive literature review was conducted to get extensive information and knowledge on transient stability, photovoltaic systems and their controls, and the effect of integrating photovoltaic systems into the grid. The literature of similar studies to this research was also reviewed and compared with each other.
- Based on the literature review conducted in Chapter 2 a focus area was identified, and the research scope was identified.
- The power system model, parameters, controllers, critical clearing time, fault type, fault duration, fault location, photovoltaic system type, and size were adopted from the IEEE benchmark and modeled to suit this research study.

3.3 Selection of the Tool

It is vital to select a tool that has suitable features to conduct a transient stability study and enable the modeling of power system generators and PV systems integrated into the grid. The modeling tools that were under consideration for this study are PSCAD and Digsilent Power Factory. The suitability of the software tool was selected based on ease of usability, availability, and its ability to conduct transient stability analysis (EMT).

Digsilent Power Factory provides EMT for solving power system transient problems, such as lighting, switching, temporary overvoltage, and sub-synchronous resonance problems. The studies that can be conducted using this simulation tool include the integrated simulation of electromagnetic transients in multiple-phase AC and DC systems. It enables the user to conduct an accurate EMT model of renewable generation (PV, Wind).

Power system computer-aided design (PSCAD) is mainly used to design, analyze, optimize, and verify power electronic control. For this research, power electronics design is very crucial for the PV design of low-voltage ride-through (LVRT). PSCAD equips the end user with the platform to schematically construct a circuit, run a simulation, analyze the time domain, and graphically display results. PSCAD has additional modules available in PSCAD libraries, such as wind and solar. Lastly, PSCAD gives the power sector the software needed to solve complex engineering problems. Based on their features, PSCAD and Digsilent Power Factory are equally suitable for this study. Hence, PSCAD was selected for this research based on its accessibility at the university and its ability to conduct time-domain simulations.

3.4 Output Results Steps

The following are the output results steps:

- Defining the parameters to be analyzed.
- Conduct load flow analysis before introducing a fault condition in the test system.
- Implement a fault condition system in the most critical location of the test network.
- Run a simulation to carry out the transient stability analysis of the test network after a fault condition.
- The results obtained from the simulation are displayed in time-domain graphs.
- For a better comparison of the results, various types of plots are generated from the obtained results and plotted against each other on the same graph plane, and all the results are differentiated by different colors legends.

3.5 Analysis of Results

The following steps were taken to analyze the obtained results:

- From the obtained results, the behavior of the selected machine variables is analyzed to determine whether the machine loses its synchronism or not.

- Analyzing the effect of different levels of PV penetration on the transient stability of the system.
- Compare the basic scenario of the study with all other scenarios based on simulation results.
- Draw a conclusion on the transient stability analysis after comparing the results from all study scenarios.

3.6 Transient Stability Analysis Techniques

Here are several traditional techniques for analyzing transient stability. The list below shows a summary of those techniques, their applications, and their differences. For this study, the time domain technique is adopted to conduct transient stability analysis, as PSCAD is the chosen simulation tool since it enables the user to conduct steady-state studies for stability analysis and electromagnetic transients for stability, respectively [83] [84] [41].

- **Equal area criteria**: The equal area criterion is a graphical method used to determine the stability of a power system after a disturbance. It involves plotting the area under the power-angle curve and comparing it with a critical value. If the area falls below the critical value, the system is considered stable; otherwise, it is unstable.
- **Time domain simulation technique**: Time-domain simulation is the most basic and widely used technique for transient stability analysis. It involves solving differential equations that describe the dynamic behavior of the power systems. The commonly used numerical methods for time domain simulation are as follows: the Euler method, the modified Euler method,

the Runge-Kutta (R-K) method, the numerical stability of the explicit integration method, and the simple integration method.

- **Energy function method**: Energy function methods are based on the principle of energy conservation in power systems. These methods involve defining an energy function that represents the total energy in the system and analyzing its behavior during transient events. Lyapunov's Direct Method and the Second Method of Lyapunov are two commonly used energy function methods.

- **Modal analysis**: The modal analysis involves studying the system's dynamic response in terms of its eigenvalues and eigenvectors. By analyzing the eigenvalues, which represent the system's modes of oscillation, the stability and damping characteristics of the system can be assessed. Modal analysis is particularly useful for identifying critical modes that may lead to instability.

3.7 Generator Control Model

In this study, all generators are equipped with a power system stabilizer (PSS) and an automatic voltage regulator controller [85]. These controllers introduce a damping signal to mitigate the oscillations in the generators. The PSS achieves this by generating an electrical torque that aligns with changes in rotor speed [41]. The provided block diagram illustrates the underlying principle of the PSS. However, it is important to exercise caution while using the PSS to ensure that it enhances the stability of the entire system, not just the small signals. In this study, the other controllers in the generator system, such as the governor controller, were assumed to remain constant [85] [86]. Figure 3.1 is the PSS and terminal voltage transducer block diagram.

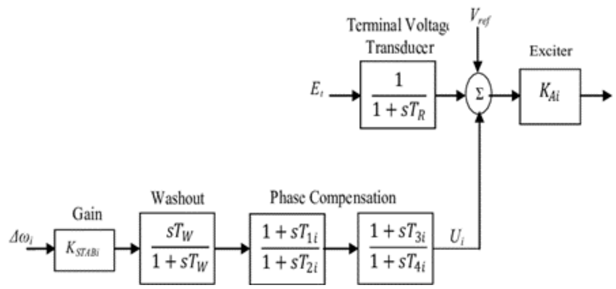


Figure 3.1 : Power system stabilizer (PSS) block diagram.

Table 3.1 : Gain, washout, phase compensation, terminal voltage, and exciter parameters.

Parameters	**Description**
K_{STAB}	Stability gain
T_1, T_3	The initial time constants
T_2, T_4	The primary delay constants
T_W	Washout out constant
K_A	Integral gain of the regulator
T_R	Time constant of the transducer
$\Delta\ w_r$	Variation in angular speed
E_{fd}	Voltage produced by exciter
E_{Fmin}	Lowest output voltage from regulator
V_{ref}	Voltage regulators set as references
V_s	Integrated power system stabilizer and potentially interrupted control output following limit
E_t	The voltage at the terminal of the transducer and the compensating element for the load

3.8 Single Machine Infinite Bus System Model and Parameters

The single-machine infinite bus system (SMIB) was adopted in [41]. It is used for this study to determine critical clearing time and the effect of a PSS and automatic voltage regulator (AVR) on power system stability. The SMIB system is used only in Chapter 4 for the preliminary study. The SMIB system consists of a synchronous generator rated at 2220 MVA, a 24kV base terminal voltage of $E_t = 1.0\angle 36$, and active and reactive power rated at $P = 0.9pu$ and $Q = 0.9pu$ and $E_B = 0.995\angle 0$. Figure 3.2 is single machine infinite bus (SMIB) system, as well as the tables (3.2 and **??**) below show the internal parameters of the generator.

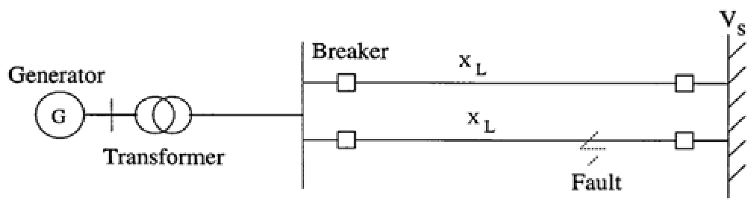


Figure 3.2 :Single machine infinite bus system (SMIB)

Table 3.2 : SMIB Generator parameters .

Basic parameters	Symbols	Ratings
RMS voltage measured between line and neutral	V_{ln}	13.86 kV
RMS line current flowing through the line	I_l	53.41 A
Basic angular frquency	ω	314.16 rad/s
Inertia constant	I	6.5 s
Iron loss resistance	R_{lr}	300 pu

3.9 IEEE 9 Bus System Model

The system considered for this research is a modified benchmark model known as the IEEE 9-BUS system, also called the Anderson system. It was first introduced in a book called Power System Control, Stability, and Fouad in 1977 [41] [87]. A single-line diagram of the IEEE 9 BUS system is depicted in Figure B.5 below. The system consists of nine buses (nodes), three synchronous generator machines representing conventional generators, three winding step-up transformers 100 MVA each, six transmission lines, and three fixed loads (35.3129 MVA, 44.876 MVA, and 31.622 MVA). The base case levels are 13.8 kV, 16.5 kV, and 18.0 kV at generator buses (nodes), and 230.0 kV at the other remaining buses. This system model is similar to the model used in [87] and [76].

Tables, from 3.3 to 3.5 below depict IEEE 9 bus system parameters.

Table 3.3 :Generators initial conditions.

Buses	**V(kV)**	$\delta(deg)$	**P(pu)**	**Q(pu)**
1	16.50	0.0000	0.7163	0.2791
2	18.00	9.3507	1.6300	0.0490
3	13.50	5.1420	0.8500	-0.1145

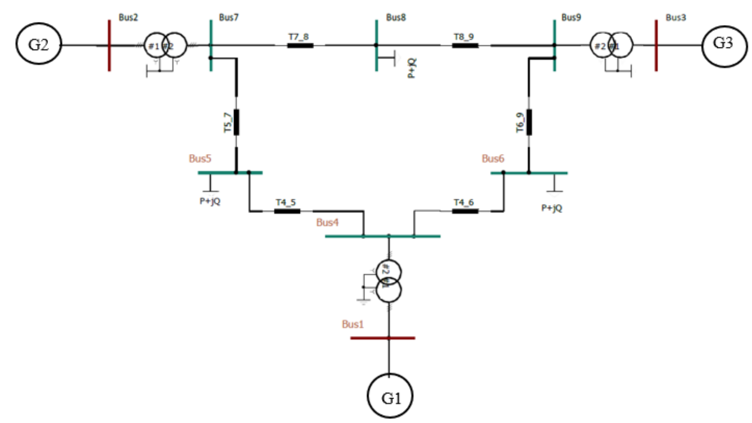


Figure 3.3 : IEEE 9 bus test system modified benchmark model

Table 3.4 :Transfomer ratings and parameters.

Transformer rating
$S_T = 100\ MVA$, $F_0 = 60\ Hz$, $V_{LI,HV} = 230\ kV$,$X_T(pu) = 0.0586$
$V_{LI,LV-SG1} = 16.5\ kV$, $V_{LI,LV-SG2} = 18.0\ kV$, $V_{LI,LV-SG3} = 13.5\ kV$

Table 3.5 :Generators, Exciter, PSS and Load parameters .

Sections	Parameters and Values
SG1(Infinite bus)	$V_{LL,Rated} = 16.5\ kV$, $F_0 = 60\ Hz$
SG2,SG3	$R_a = 0.0025$, $X_l(pu) = 0.102$, $X_d(pu) = 1.81$, $X_q(pu) = 1.59$, $X'_d(pu) = 0.300$,$X'_q(pu) = 0.550$, $X''_d(pu) = 0.25$,$X''_q(pu) = 0.25$, $T'_{d0}(s) = 8.0$, $T'_{q0}(s) = 0.4$, $T''_{d0}(s) = 0.033$, $T''_{q0}(s) = 0.070$,, $X_p(pu) = 0.20$, $H = 8.0$
AC4A	$T_A(s) = 0.015$, $T_B(s) = 3$,$K_A = 200$, $X_C = 0$, $V_{RMAX} = 7.0$, $V_{RMIN} = -4.6$, $K_C = 0.0$, $V_{IMAX} = 20.0$, $V_{IMIN} = -20.0$
PSS1A	$K_{ss}(pu) = 9.5$, $T_1(s) = 0.254$, $T_2(s) = 0.033$, $T_3(s) = 0.0$, $T_4(s) = 0.0$, $T_5(s) = 1.41$, $T_6(s) = 0.0$, $V_{SMAX} = 0.2$, $V_{SMIN} = -0.2$
Fixed Loads	$P_5(pu) = 1.25$, $P_6(pu) = 0.90$, $P_8(pu) = 1.00$,$Q_5(pu) = 0.50$, $Q_6(pu) = 0.30$, $Q_8(pu) = 0.35$

3.10 Fixed Load Model

The loads for this research are modeled as a function of voltage magnitude and frequency, where the real and reactive power are considered separately using the expression as shown in equations 3.3 and 3.2 [88]. Table 3.6 shows fixed load parameters and their respective descriptions.

$$P = P_0(\frac{V}{V_0})^{NP}.(1+K_{PF}.df) \tag{3.1}$$

and

$$Q = Q_0(\frac{V}{V_0})^{NQ}.(1 + K_{QF}.df) \quad (3.2)$$

Table 3.6 :Fixed load parameters and description.

Parameters	**Description**
P	Real power of an equal load
P_0	Rated actual power per phase
V	Load voltage
V_0	Specific load voltage
N_P	$\frac{dP}{dV}$ Voltage factor used to determine real power
K_{PF}	$\frac{dP}{dF}$ Frequency factor used to determine real power
Q	Reactive power of an equal load
Q_0	Rated reactive power per phase
N_q	$\frac{dQ}{dV}$ Voltage factor used to determine reactive power
K_{QF}	$\frac{dQ}{dF}$ Frequency factor used to determine reactive power

3.11 PV Model

PSCAD has already developed an available PV system generic model with its own controls. The PV system is simulated as a collection of PV panels that can be linked to a grid via an inverter. To create a model, a simple circuit comprising a current source and a diode is used to represent the solar cells [37] [39] [38]. The output of the current source is influenced directly and proportionally by the intensity of light falling on the cell. Figure 3.4 illustrates the single-line diagram that depicts the model employed in this research study. Table 3.7 below shows I-V characteristics parameters.

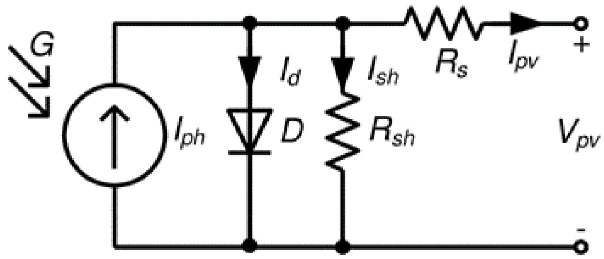


Figure 3.4 : Single line diagram for solar cell model

The equation which illustrates the I-V characteristics of the cell is as follows:

$$i = I_{ph} - I_0 \times (exp^{\frac{v+iR_S}{n_s \times v_t}} - 1) - \frac{v + iR_s}{R_{sh}} \tag{3.3}$$

Table 3.7 : I-V characteristics equation parameters description and values.

Parameters	Description and Value
I_{ph}	Current generated by the incident light A
I_0	Diode saturation current A
R_{sh}	Cell parallel shunt resistance omh
R_s	Cell series omh
n_s	Number of PV cells connected in series
V_t	Diode thermal voltage
a	Diode quality identity factor
K	Bolzmanns constant (1.381×10^{-23} $\frac{J}{K}$)
q	charge of the electron (1.602×10^{-19} C)
T	Kelvin temperature at standard test condition K

Table 3.8 :Array and PV cell parameters.

PV array parameters	**Values**	**PV cell parameters**	**Values**
Number of modules in series connected per array	35	Per cell effective area	0.01 m^2
Number of module strings in parallel per array	130	Series resistance per cell	0.02 Ω
Number of cells connected in series per module	35	Shunt resistance per cell	1000 Ω
Number of parallel cell strings per module	1	Diode ideality factor	1.5
Reference irradiation	1000 $W\,m^{-2}$	Band gap energy	1.103
Reference cell temperature	28°C.	Saturation current at reference conditions per cell	1×10^{-12} kA
Graphics display	Industrial	Short circuit current at reference conditions per cell	0.0025 kA
		Temperature coefficient of photo current	0.001

The adopted photovoltaic system for this paper is configured as shown in the Table 3.8 above .

3.12 Maximum Power Point Tracking

Maximum power point tracking (MPPT) is the point at which the output power of a PV cell is at its maximum for present environmental conditions. For this research, both solar irradiance level and temperature are set to be constant as factors of environmental conditions. There are two methods of MPPT available in PSCAD software, and for this research, Perturb and Observe (P and O) is employed [8][9]. Figure 3.5 below demonstrates the perturbed and observed chart.

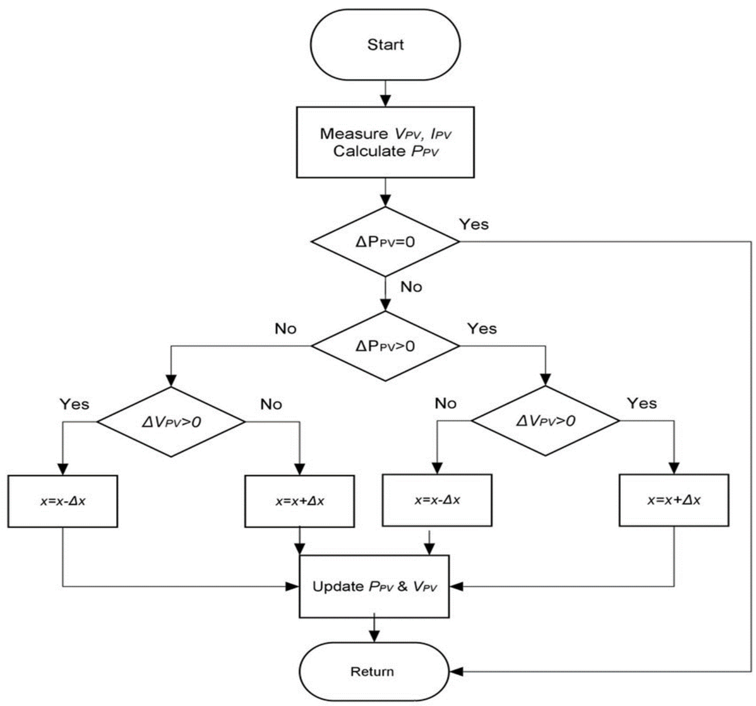


Figure 3.5 : Perturbed and Observe Maximum power point tracking chart [8][9]

3.13 Inverter Model

To integrate a PV system into an electrical grid, it is necessary to convert the direct current (DC) output voltage to the alternating current (AC) voltage. This conversion is achieved by employing a three-phase DC-AC inverter. The technique used to regulate the output voltage in these inverters is called sinusoidal pulse width modulation (SPWM) [89] [90]. A three-phase inverter is an electronic device that transforms DC into variable AC, allowing for changes in voltage magnitude, frequency, and number of phases. This involves a phase shift of 120 degrees and a conduction period of 120 degrees for each silicon-controlled rectifier (SCR). The phase angle between two consecutive thyristors from either the upper or lower group is 120 degrees. If the load is unbalanced, then no specific phase voltage is determined during intervals when neither phase is connected to the positive terminal. For this research, the inverter model is connected to an LCL filter, which is used to eliminate unwanted harmonics. Figure 3.6 below shows a three-phase inverter with an LCL filter. Table 3.9 shows the three-phase inverter parameters and description.

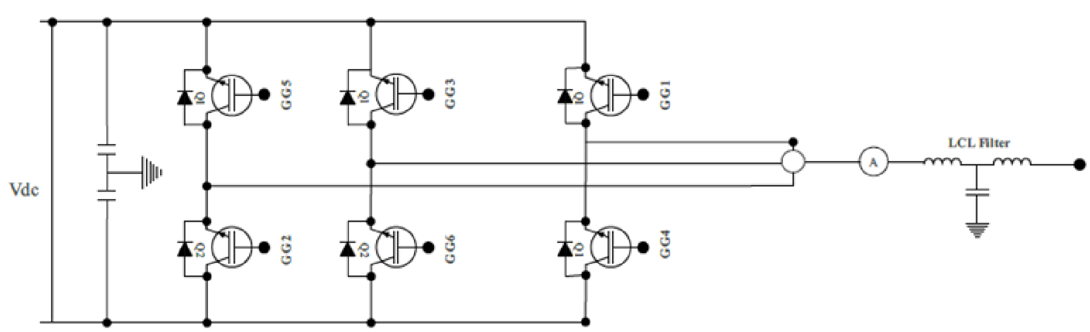


Figure 3.6 : Three-phase inverter and LCL single-line diagram

Table 3.9 :Three Phase inverter parameters.

Parameters	**Description**	**Values**
V_{DC}	DC voltage	1000 V
V_g	Grid voltage	230 kV
F_g	Fundamental frequency	60 Hz
F_{sw}	Switching frequency	1050 Hz
PF	Power factor	1.0 pu

The inverter for this paper is connected to the three-phase grid through a point of common coupling (PCC). The PCC is the interface between the inverter and the grid, through three phase step-up transformer.

3.14 LCL filter model

For this study, the LCL model is used based on the lower rating of the inductor and capacitor to reduce the same amount of harmonics from voltage compared to other filters, such as the LC and L filters. LCL filter design can be done using the equations 3.4 to 3.7 below. where C_B and Z_B are base parameters. While L_1 is an inverter-side series inductor, L_2 is a grid-side series inductor, and C_f is a shunt capacitor, as shown in figure 3.6.

$$C_B = \frac{1}{\omega Z_B} \tag{3.4}$$

Where: $Z_B = \frac{V_{ll}}{p}$

$$C_f = \frac{0.01}{0.05} \times C_B \tag{3.5}$$

$$L_1 = \frac{V_{dc}}{6F_{SW}\Delta I_{max}} \tag{3.6}$$

Where: $\Delta I_{max} = 0.1 \times I_{max}$

$$L_2 = \frac{\sqrt{\frac{1}{k_a^2} - 1}}{C_f \times w_{sw}} \tag{3.7}$$

Where K_a is the attenuation factor.

3.15 Load Flow Mathematical Model

Load flow studies in power systems are very crucial before expanding the network system, adding local generation, installing new utility feed, adding new transformers, or adding new significant load. Load flow studies are normally performed to investigate voltage magnitude, phase angle at each bus (node), and, real and reactive power flow in the network. Load flow studies can be performed using various methods named decouple method, Gauss-Seidel method, and Newton Raphson method. See the equations below that are used to conduct load flow studies[91] [92]. The power system network is made of several buses, lines, and loads resulting in the network.

$$\left[I_{BUS}\right] = \left[Y_{BUS}\right] \times \left[V_{BUS}\right] \tag{3.8}$$

Where $[I_{BUS}]$ and $[V_{BUS}]$ are $n \times I$ matrixes, $[Y_{BUS}]$ called a bus admittance matrix, is an $n \times n$ Matrix.

The power injection into the buses can be assumed to be complex and expressed as follows:

$$S_i = P_i + jQ_i = V_i \times I_i^* \tag{3.9}$$

Where $i = 1, 2, \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots n$

The complex conjugate of the above equation can be expressed as follows:

$$P_i - jQ_i = V_i^* \times I_i \tag{3.10}$$

When equating real and imaginary parts, the results are as follows:

$$P_i = |V_i| \times \sum_{k=1}^{n} \times |V_k| \times |Y_{ik}| \times \cos(\theta_{ik} + \delta_k - \delta_i) \tag{3.11}$$

$$Q_i = |V_i| \times \sum_{k=1}^{n} \times |V_k| \times |Y_{ik}| \times \sin(\theta_{ik} + \delta_k - \delta_i) \tag{3.12}$$

The above equations are known as power flow equations. Each bus in the power system has two equations and four parameters (P, Q, δ, V). Due to the complexity and nonlinearity of the above equations, the numerical iteration technique was used to conduct power flow studies. More information is in Jackson Prajapati et.el [91]. Newton Raphson's method is widely used when conducting load flow studies due to its simplicity and requiring few iterations compared to other methods. For this study, the power flow in the IEEE 9 bus system is governed by these two power flow equations.

3.16 Chapter Summary

In this chapter two potential software for the study were discussed and power system computer aided design (PSCAD) was selected based on its accessibility and its ability to conduct EMT simulations, the steps that will be taken to analyze results obtained in this research study were discussed in this chapter. Various techniques to conduct transient stability analysis was discussed and all system models that will be employed for this research were discussed. Load flow mathematical model was presented in this chapter. In this dissertation, all the models presented in this chapter will be integrated together to conduct transient stability analysis when a PV system is integrated into a grid network. Some of the models presented in this chapter will be adopted to conduct preliminary research in the next chapter.

Chapter 4

Preliminary Research Analysis and Results

4.1 Introduction

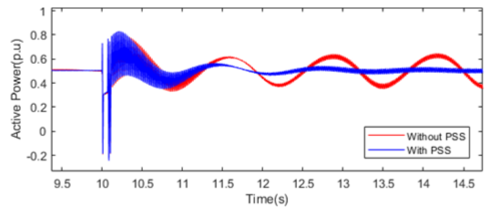
In this chapter, the preliminary research simulation results will be presented and discussed. These results will be compared to previously published research. In the previous chapter, various models were presented, and some of those models will be adopted in this chapter to conduct a preliminary research study. This chapter will mainly focus on preliminary research simulation results as follows: the role that PSS plays in power system stability and the effect of critical clearing time on power system stability. Both simulations will be conducted using the SMIB system. On the other hand, this chapter presents power flow and determination of the fault location using IEEE 9 bus systems.

4.2 Generator Control (PSS) Model

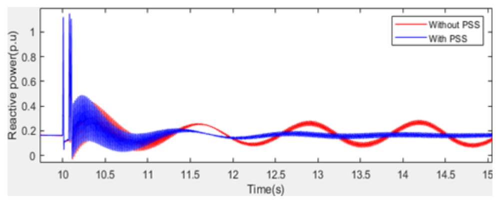
The SMIB system detailed in Chapter 3 was employed in this chapter to determine the effectiveness of the PSS on the generator when there is a disturbance [93] [94] [41]. The three-phase fault was employed in bus 8, as shown in Chapter 3. This bus was selected because it is midway between generator 2 and generator 3. fault was applied after 10 seconds of the simulation time in order to allow transients of PSCAD to settle down, and it cleared at 10.01 seconds to reduce settling time. This study was conducted under two scenarios, namely, scenario 1 where the system is equipped with PSS and scenario 2 when the system operates without PSS. Figure 4.1 illustrates the simulation results for all variables under study, namely, active power, reactive power, rotor angle, terminal voltage, and rotor speed.

4.2.1 Simulation Results and Discussion

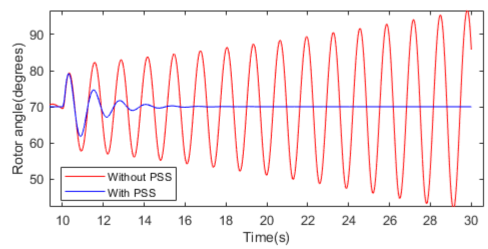
The results presented below depict the effectiveness of the PSS on power system stability. From all variables, comparing the red (without PSS scenario) and blue (with PSS scenario) curves reveals that the maximum overshoot of the blue curve is lower than that of the red curve, indicating improved transient stability. Additionally, the oscillations of the blue curve are observed to be smaller in both magnitude and frequency compared to the red curve, indicating better dynamic stability. In terms of steady stability, represented by settling time and steady-state error, the results demonstrate that with the PSS, there is additional damping added to the system following the disturbance. Hence, based on the simulation results presented in Figure 4.1, it can be concluded that the presence of PSS improves the stability of the system when it is subjected to disturbances. Similar studies, as depicted in [94] and [41], have also shown the effectiveness of PSS in enhancing power system stability. In this particular study, the PSS will be utilized for all generators in the IEEE 9 bus test system; therefore, it is crucial to determine the credibility of this control system.



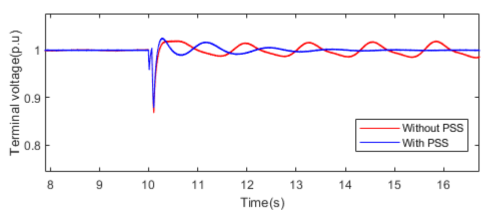
(a) Active power



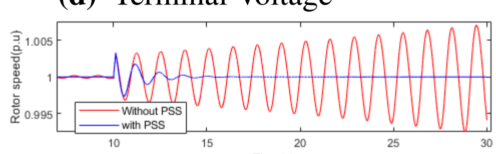
(b) Reactive power



(c) Rotor angle



(d) Terminal Voltage



(e) Rotor Speed

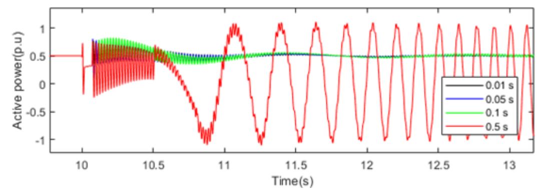
Figure 4.1 (a) Real Power (pu) vs Time (s), (b) Reactive Power (pu) vs Time(s), (c) Rotor Angle (degrees) vs Time (t), (d) Terminal Voltage (pu) vs Time (t), (e) Rotor Speed (pu) vs Time (t) SMIB system with and without PSS.

4.3 Fault Clearing Time

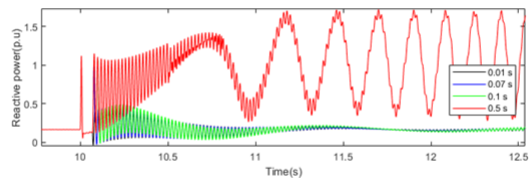
The SMIB system was adopted to determine the fault clearing time for this research study [95] [96]. Numerous simulations were conducted to determine the effective fault clearing time and the stability of the system. Figures 4.2 below depict active power, reactive power, rotor angle, terminal voltage, and rotor speed variables under consideration for this research. For this study, a three-phase fault was introduced at 10 seconds of the simulation time, and the critical clearing time was varied for the purpose of determining the minimal time that enables the system to recover after it is subjected to severe disturbance. Four fault clearing times were tested in this research, and results were compared for all variables as shown in Figure 4.2.

4.3.1 Simulation Results and discussion

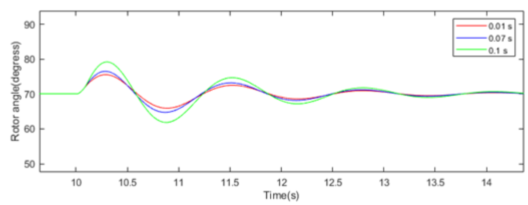
The results presented below depict different fault clearing time. In this scenario, the fault clearing time is 0.01 seconds, the oscillations in all variables after the disturbance are positively damped, and the steady state condition is reached quickly after the fault condition. As the fault duration is increased to 0.07s and 0.1s, the amplitude of the oscillations in all the variables is observed to be slightly higher, and the system takes a longer time to settle to a steady state as compared to the initial fault duration of 0.01s. In the case of a fault clearing time of 0.5 seconds, it was observed that the power system loses synchronism and fails to recover after the fault. This indicates that the electrical power exceeds the mechanical power in the system. Hence, based on the simulation results obtained in this study, a fault clearing time of 0.01 seconds will be chosen for further studies in the dissertation. The method adopted to determine fault clearing time for this study is time simulation techniques [97] [76].



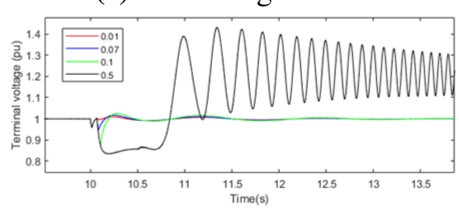
(a) Active power



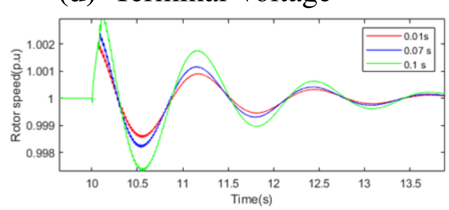
(b) Reactive power



(c) Rotor angle



(d) Terminal Voltage



(e) Rotor Speed

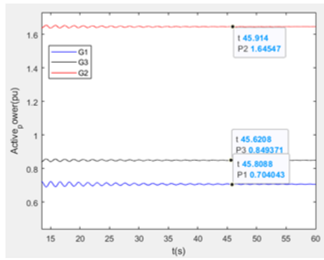
Figure 4.2 (a) Active Power (pu) vs Time (s), (b) Reactive Power (pu) vs Time(s), (c) Rotor Angle (degrees) vs Time (t), (d) Terminal Voltage (pu) vs Time (t), (e) Rotor Speed (pu) vs Time (t) determination of critical clearing time.

4.4 Power Flow Analysis

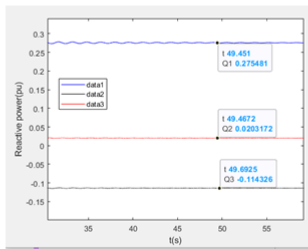
Table 4.1 is through power flow analysis. Figures 4.3 (a) and (b) displayed below show the power flow of the IEEE 9 bus test system. Figure 4.3 (a) illustrates the active power generated by all generators in the test system, while Figure 4.3 (b) represents the reactive power generated by all generators. Based on the simulation results obtained from both figures, it can be concluded that the observed power flow aligns with the expected outcomes, compared to the findings from [76].

Table 4.1 :Power flow analysis.

Generator	Active Power (pu)	Reactive Power (pu)
G1	0.70	0.2754
G2	1.65	0.0203
G3	0.849	-0.1143
Total	3.199	0.4101



(a) Active power

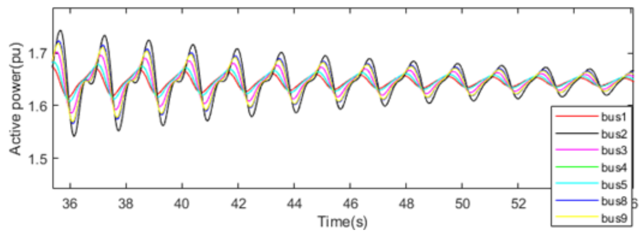


(b) Reactive power

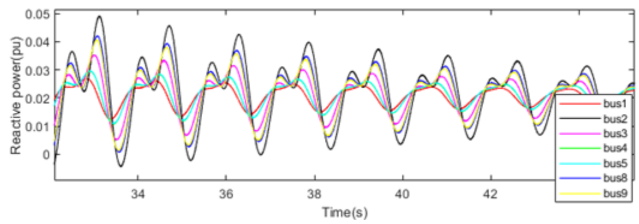
Figure 4.3 (a) Active Power (pu) vs Time (s), (b) Reactive Power (pu) vs Time (s), Power flows.

4.5 Optimal Fault Location in IEEE 9 Bus System

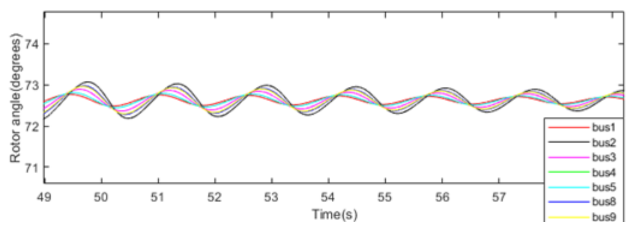
The IEEE 9 bus system was utilized to identify the optimal location for a fault condition. Various parameters were under consideration, namely, active power, reactive power, rotor angle, terminal voltage, and rotor speed. In this study, the system was initially simulated under normal conditions without any faults to evaluate the power flow. Subsequently, the system was subjected to a three-phase fault at 10 s, and the fault duration was 0.01 s.The fault was applied first to bus 1 and then to the other bus until bus 9. Multiple simulations were conducted, and the results for all parameters were compared in Figure 4.4 using Generator 2 as a reference.



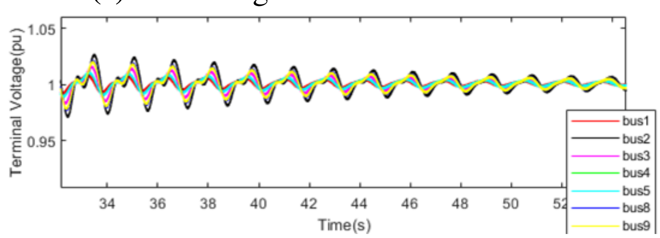
(a) Active power



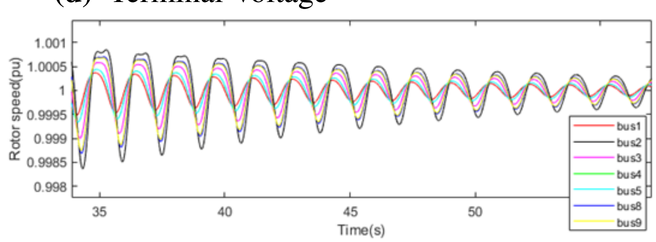
(b) Reactive power



(c) Rotor angle



(d) Terminal Voltage



(e) Rotor Speed

Figure 4.4 Active power (pu) vs time (s), (b) Reactive power (pu) vs time (s), (c) Rotor angle (degrees) vs time (s), (d) terminal voltage (pu) vs time(s), (e) Rotor speed (pu) vs time (s).

4.5.1 Simulation Results Analysis

All the simulation results presented in Figure 4.4 show variables of generator 2 of the IEEE 9 bus system. In cases where the fault condition is in bus 1, the amplitude of oscillations in all the variables is lower than in all other fault location cases since the fault condition is located far from reference generator 2. In the case when a fault condition is introduced in bus 2, the oscillations in all the variables are observed to be higher than in all other cases since the fault is introduced at the terminals of generator 2, as shown in Figure 3.3. In the case where the fault is introduced at Bus 3, 4, and 9, the simulation results show fewer oscillations and attain steady state conditions quicker than when a fault is at Bus 2. When the fault condition is introduced at bus 8 of the network system, the simulation results show that the system oscillates with an amplitude that is below the extreme case at bus 2, hence the bus 8 system was selected as the optimal bus location for the fault in this study [98] [99].

4.6 Chapter Summary

In this chapter, the effectiveness of PSS and fault clearing time on the transient stability of the power system was depicted and analyzed, and the power flow of the adopted system under study for this research was analyzed. The following chapter will introduce scenarios from this research study, and simulation results will be analysed and compared.

Chapter 5

Main Research Results and Analysis

5.1 Introduction

This chapter discusses the main research results. Transient stability analysis in this chapter was performed under four scenarios, namely, scenario 1 where the PV system is integrated at a single bus of the IEEE 9 Bus Test System, scenario 2 where the PV system is integrated into two buses, scenario 3 where the PV system penetrates the system when the generators are without a PSS control, and scenario 4 where the PV system penetrates the system while it is subjected to a longer fault clearing time. The variables analyzed and discussed in the different scenarios are active power, reactive power, rotor angle, terminal voltage, and rotor speed. All the scenarios discussed in this chapter will be summarized in Chapter 6 of this research.

5.2 Transient Stability Analysis

To conduct transient stability analysis for a PV system integrated into a power system, (PV) system, the configuration depicted in Figure 3.3 is employed to assess the power system's reaction after a significant disturbance when a PV system is present. A three-phase fault is introduced at bus 8 of the system at 10 seconds into the simulation and is cleared after 10.01 seconds. Generator 2 was chosen as the reference generator for the analysis. It was observed that all generators exhibited similar behavior; therefore, a single generator was considered sufficient for this study. As mentioned earlier, four scenarios were examined to analyze the impact of PV systems on the stability of the power system. The total generation, PV penetration into the grid, and the percentage of PV penetration are shown in Table 5.1. The following formula was used to determine the level of PV penetration, and the PV penetration was assumed to occur in steps of 20% up to 100% for scenario 1. The system variables analyzed and discussed in the different scenarios include active power, reactive power, rotor angle, terminal voltage, and rotor speed.

$$PV_{penetration}[MW] = \%PV_{penetration} \times Grid_{Total_{Generation}}[MW] \quad (5.1)$$

Table 5.1 Total power generation and PV penetration based on percentages.

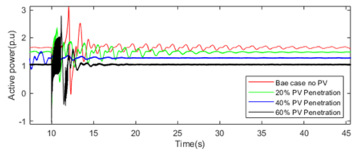
Total Generation	**PV Penetration of the total generation**	**PV penetration in %**
319.63 MW	00.00 MW	00.00%
255.70 MW	63.92 MW	20%
191.78 MW	127.85 MW	40%
127.85 MW	191.78 MW	60%
63.93 MW	255.70 MW	80%
00.00 MW	319.63 MW	100%

5.2.1 Scenario 1: The PV System Integrated at a Single Bus 5 of the IEEE 9 Bus Test System.

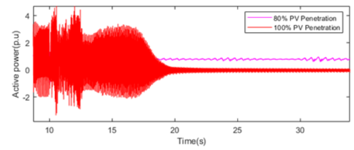
The primary objective of scenario 1 is to identify the optimal PV system capacity that can be integrated into the grid without compromising its stability. The PV penetration is adjusted in increments of 20% from 0% up to 100%, as shown in Table 5.1. In order to demonstrate the impact of increasing PV penetration levels on the transient stability of the test system, figure 5.1 shows the response of the generator active power, generator reactive power, generator rotor angle, generator terminal voltage, and generator rotor speed results following the large disturbance.

The base case with 0% PV penetration, as depicted in figure 5.1, shows stable conditions before the fault but sustained oscillations after the disturbance. When the PV penetration is increased to 20%, the results indicate that the system stabilizes faster compared to the base case. With a further increase in PV penetration to 40%, all system variables exhibit slight fluctuations before the fault, and the results demonstrate faster stabilization compared to the 20% PV penetration case after the fault.

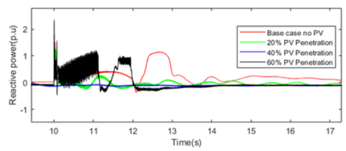
At a 60% PV penetration level, all system variables remain stable before the fault, and during the fault condition, they exhibit significant improvement in stability compared to the cases with 0%, 20%, and 40% PV penetration levels. However, at higher PV penetration levels of 80% and 100%, the results show negative damping on the stability of the system. These results are consistent with those presented in reference [72], which demonstrated that full replacement of a conventional generator can lead to negative damping on the stability of the system.



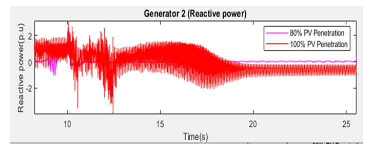
(a) Active power



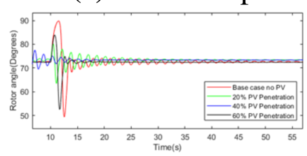
(b) Active power



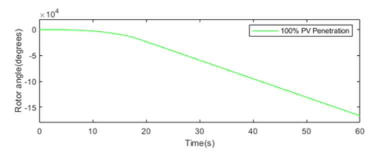
(c) Reactive power



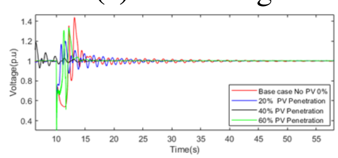
(d) Reactive power



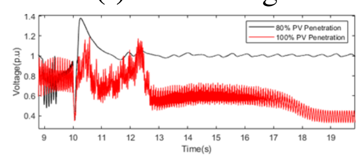
(e) Rotor angle



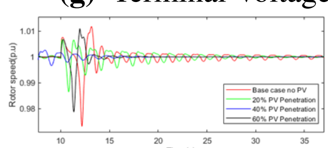
(f) Rotor Angle



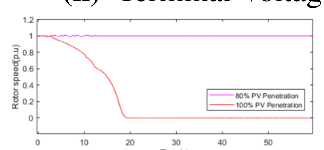
(g) Terminal Voltage



(h) Terminal Voltage



(i) Rotor Speed



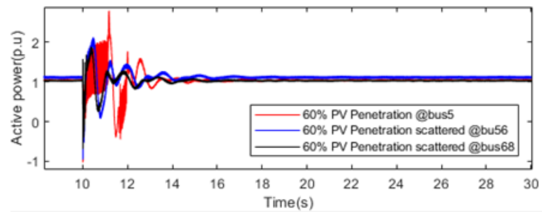
(j) Rotor Speed

Figure 5.1 (a)-(b) Active Power (pu) vs Time (s), (c)-(d) Reactive Power (pu) vs Time (s), (e)-(f) Rotor Angle (degrees) vs Time (t), (g)-(h) Terminal Voltage (pu) vs Time(t), (i)-(j) Rotor Speed (pu) vs Time (t) when PV System is Integrated at a Single Bus 5 of IEEE 9 Bus Test System.

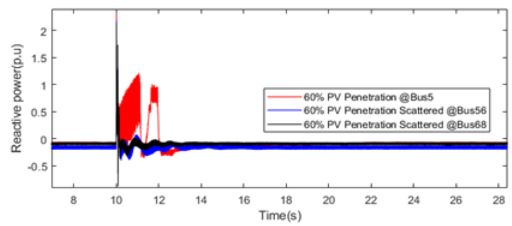
5.2.2 Scenario 2: Optimal PV Penetration Integrated into Two Buses

In this particular scenario, transient stability analysis is conducted based on the optimal penetration level identified from scenario 1, which is 60% PV penetration. The primary aim for this scenario is to investigate the impact of PV penetration when a 60% PV penetration level is distributed across two different buses of the test system. The fault condition is still located at bus 8, which is consistent with scenario 1. In order to demonstrate the impact of a distributed PV system on the transient stability of the power system, Figure 5.2 shows the responses of the generator active power, generator reactive power, generator rotor angle, generator terminal voltage, and generator rotor speed results following the disturbance.

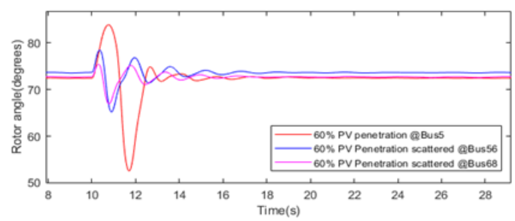
The results show that all system variables under consideration for Scenario 2 have an improved response. When integrating the PV system with the same penetration level into two different buses, the results demonstrate that positive damping in the system oscillations is added. The system analysis was conducted in three cases: in the first case, the PV system was integrated only into bus 5; in the second case, it was distributed between buses 5 and 6; and in the third case, it was distributed between buses 6 and 8. Based on the results shown in Figure 5.2 for all variables, when a PV system is integrated into buses 5 and 6, there is a positive damping added to the system oscillations compared to the case when the PV system is integrated through bus 5 only. When a PV system is integrated into buses 6 and 8, the system's response is even better compared to the two previous cases. The results are thus related to reference [100], which demonstrate that distributed PV penetration adds more damping factor to the oscillations of the power system than solar farms.



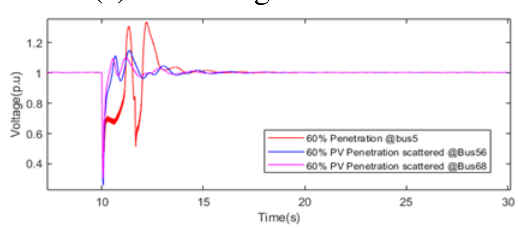
(a) Active power



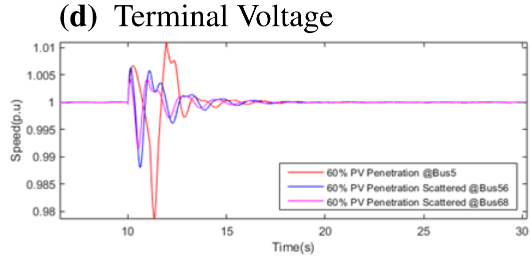
(b) Reactive power



(c) Rotor angle



(d) Terminal Voltage



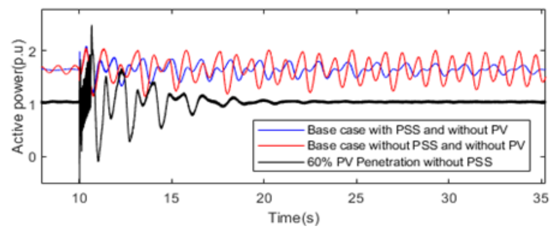
(e) Rotor Speed

Figure 5.2 (a) Active Power (pu) vs Time (s), (b) Reactive Power(pu) vs Time (s), (c) Rotor Angle (degrees) vs Time (t), (d) Terminal Voltage (pu) vs Time (t), (e) Rotor Speed (pu) vs Time (t) when the PV system is Integrated into Two Buses.

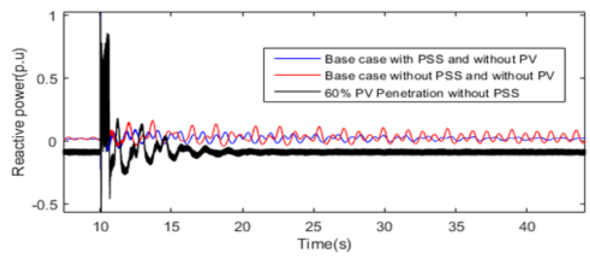
5.2.3 Scenario 3: Optimal PV penetration without PSS.

In the previous studies presented so far, all the generators were equipped with a PSS.The primary objective of this scenario is to evaluate the effect of optimal PV penetration on system oscillation damping without PSS. The fault condition was introduced in bus 8 as in the other scenarios. The variables under consideration are the same as in the other case. This scenario is divided into three cases. The first case is a base case with 0% PV penetration when all generators are equipped with PSS in the test system. The second case is when all the generators are without both PSS and PV systems. The third case is when all the generators are without PSS but with the 60% optimal PV penetration level into the test system at bus 8. Figure 5.3 shows the response of the study system following a fault applied to bus 8.

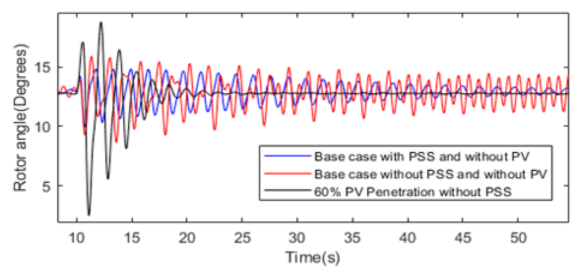
The results shown in Figure 5.3 for all variables under consideration exhibit a similar behavior to the base case with 0% PV penetration from scenario 1, where it was observed that the system takes some time to settle into a steady state. The results further show that when all the generators are without PSS and PV systems, the oscillation in all the variables experiences negative damping after the fault. However, when all the generators are without PSS but with the optimal 60% PV penetration level integrated at bus 8 of the test system, the results show that positive damping is added to the system's oscillations following the disturbance. Nevertheless, the magnitude of the oscillations in Figure 5.3 is higher when compared to the case when the PV penetration level was 60% and equipped with PSS, as shown in the previous scenario in Figure 5.2 for single-bus PV penetration.



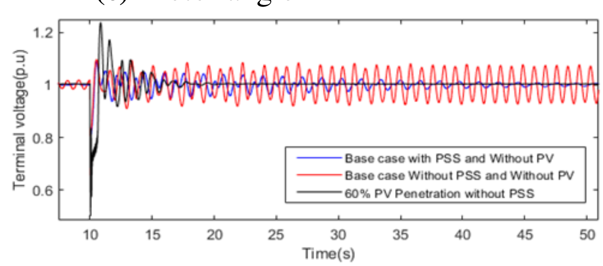
(a) Active power



(b) Reactive power



(c) Rotor angle



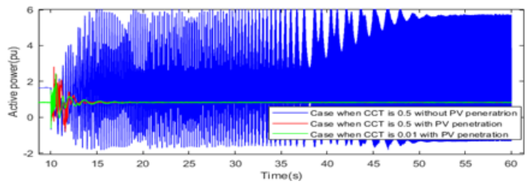
(d) Terminal Voltage

Figure 5.3 Active Power (pu) vs Time (s), (b) Reactive Power (pu) vs Time (s), (c) Rotor Angle (degrees) vs Time (t), (d) Terminal Voltage (pu) vs Time (t), when PV System Penetrates the System when the Generators are without a PSS Control.

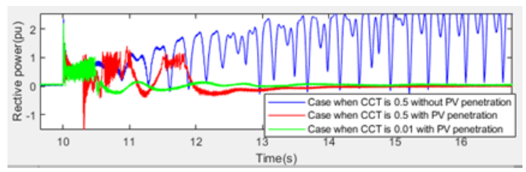
5.2.4 Scenario 4: Optimal PV penetration with a longer fault clearing time.

In the previous scenarios, the fault clearing time was kept at the same value of 0.01s. The aim of this scenario is to focus on the transient stability analysis of the system when the fault clearing time is higher than in all the other case studies. The fault condition is introduced at bus 8 as in other scenarios, and the 60% optimal PV penetration level is integrated at the same bus 8 as in scenario 3. Three cases are under consideration: the first case is when the fault clearing time is 0.5 seconds and there is no PV integrated into the test system; the second case is when the fault clearing time is 0.5 seconds and the PV system is integrated into the test system; and the third case is when the fault clearing time is 0.01 seconds and there is a PV system as in Scenario 2 for single bus penetration. Figure 5.4 (a)-(d) shows the response of the study system following a fault applied at bus 8.

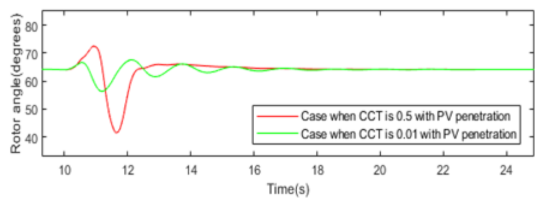
The results in Figure 5.4 (c) show that in the case of no PV integration into the test system, the study system loses synchronism following the longer disturbance to the power system. The results are thus related to reference [101], which demonstrate that if that fault clearing time is beyond critical clearing time, the system will experience out-of-step in generators. In the case when the fault clearing time is 0.5 seconds and there is a PV system integrated into the test system, the results show that positive damping is added to the system oscillations even though the system takes a longer time to reach a steady state. However, in the case of a shorter fault clearing time of 0.01 seconds, the results show that the system quickly reaches a steady state after a fault, and all the variables demonstrate that positive damping has been added to the system oscillations. Based on the results shown in Figure 5.4, it can be concluded that optimal PV penetration adds a positive damping factor to power system stability, even if it is subjected to a longer fault duration.



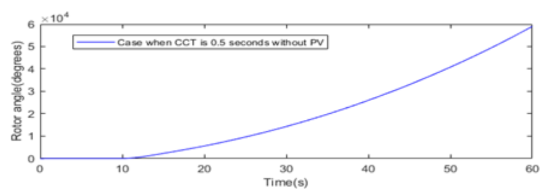
(a) Active power



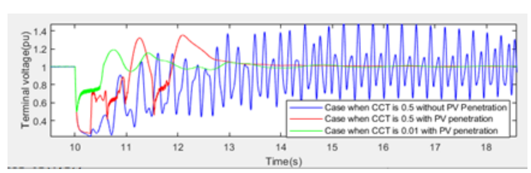
(b) Reactive power



(c) Rotor angle



(d) Rotor angle



(e) Terminal Voltage

Figure 5.4 Active Power (pu) vs Time (s), (b) Reactive Power (pu) vs Time (s), (c-d) Rotor Angle (degrees) vs Time (t), (d) Terminal Voltage (pu) vs Time (t) when PV System Penetrates the System while it is Subjected to Longer Fault Clearing Time.

Chapter 6

Conclusion and Recommendations

6.1 Conclusion

The studies conducted by other researchers revealed that integrating PV systems into the grid can have both a positive and negative impact on the system's stability. The results obtained in this research study support the findings of these other researchers. However, this study has extended previous studies to conduct transient stability analysis on the power system. Different test systems have been used to conduct transient stability analyses; this study in particular chose a modified IEEE 9 bus test system, and PSCAD software was used to perform the analysis. Four scenarios were investigated, and based on these scenarios, the transient stability of the study system was evaluated using four variables: active power, reactive power, rotor angle, terminal voltage, and rotor speed of generator 2 of the system. The results in scenario 1 reveal that PV penetration improves the system's stability when the penetration is up to 60% of total power generation. Scenario 2 reveals that when 60% of PV penetration is distributed among two buses, the system stabilizes even better compared to all other penetration levels in this research study. In scenario 3, the system was integrated with 60% of PV systems, and three cases were considered; the results in the first case reveal that when the system is not equipped with a PSS and without PV, the system loses synchronism after the disturbance. In the case when there is no PSS and 60% of PV penetration on the same bus with the fault condition, the system managed to stabilize after higher oscillations at post-fault conditions. In scenario 4, the effect of 60% PV penetration was investigated when fault clearing time was prolonged. The results reveal that PV penetration can only improve the stability of the system if the PV system is at the same bus as the fault condition for prolonged fault clearing time.

Based on the findings from this research, the level of PV penetration should be kept at 40%–60% of the total generation of the grid system for the power systems to respond positively under fault conditions. It is recommended that the PV system with a penetration level of no more than 60% of the total generation be distributed in different buses of the system, more specifically to the buses that pose a risk during fault conditions. The findings of this research have shown that when the PV system is distributed at least between two buses in the system, together with the action of the PSS, a positive impact on the transient stability of the power system can be observed. The findings have also demonstrated that distributed PV integration can also make the power system more robust for longer fault durations.

6.2 Recommendations for Future Work

This research has investigated the transient stability of a Power system upon integrating a PV system into a grid, considering different scenarios. However, there are areas that can still need to be investigated for future wok. Several recommendations for future research in this area include:

- This study was conducted based on the IEEE 9 bus system. This study can also be extended to consider a more complex systems such as the IEEE 39 Bus system.
- This study was conducted based on PV systems; further studies can be considered but using different renewable energy sources such as wind power, hydroelectric power, and biomass energy, respectively.
- In chapter 5, scenario 3, the effectiveness of the PV system on transient stability is considered when the generators of the system are without PSS The study can be extended to consider the inclusion of FACTS devices such as STATCOM (static synchronous compensator) and SVC (static variable compensator), respectively.

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Appendix A

Appendix

A.1 Appendix

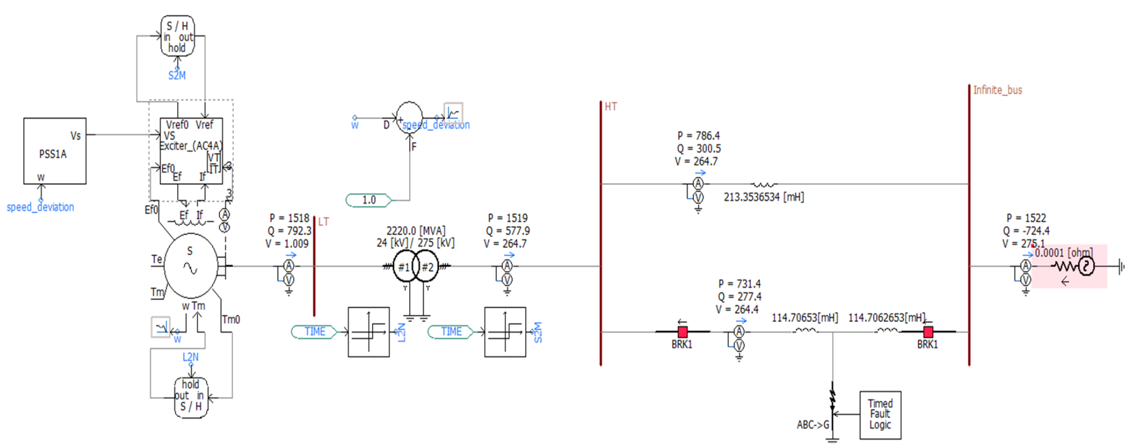

Figure A.1 :SMIB system model.

A.2 Appendix

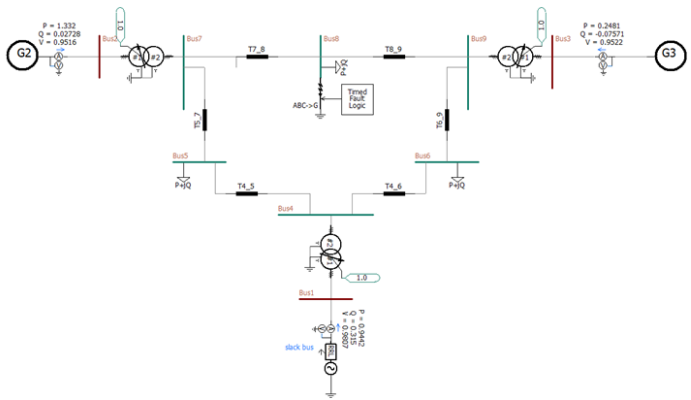

Figure A.2 :IEEE 9 bus system model.

A.3 Appendix

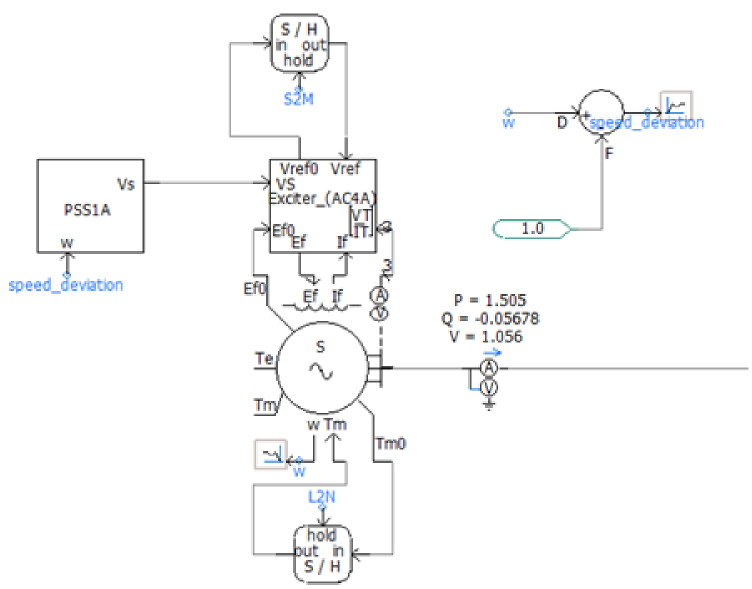

Figure A.3 :Synchronous generator and controls on PSCAD.

Appendix B

Appendix

B.1 Appendix

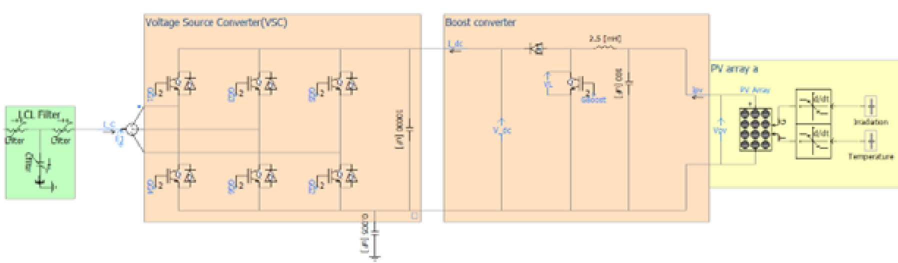

Figure B.1 :PV system, Boost converter, Three phase inverter and, LCL filter model on PSCAD.

B.2 Appendix

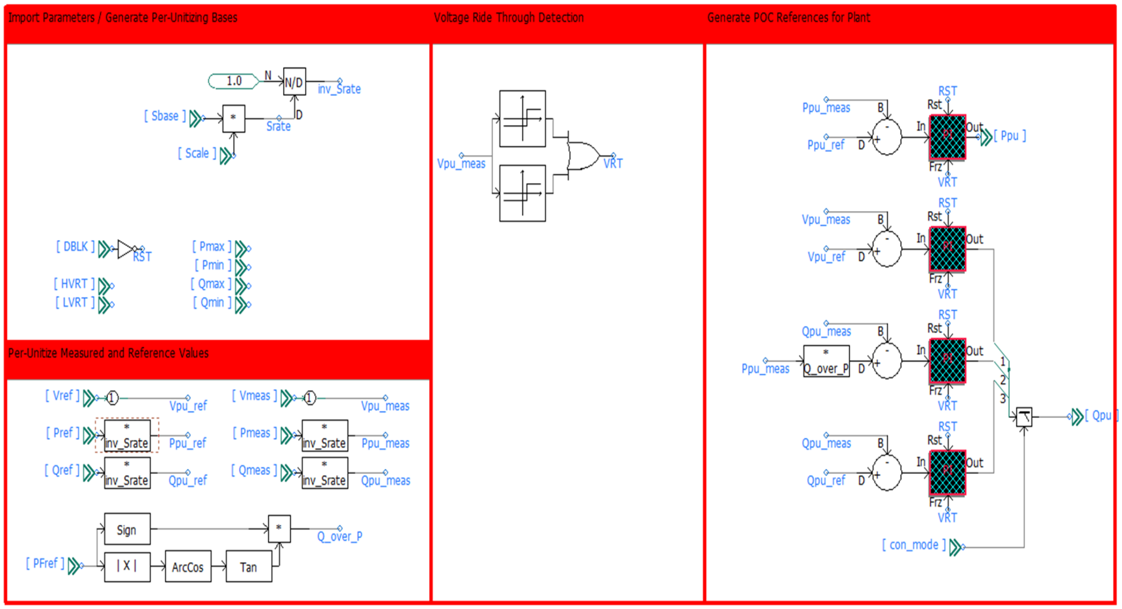

Figure B.2 :PV system controls setup and parameters.

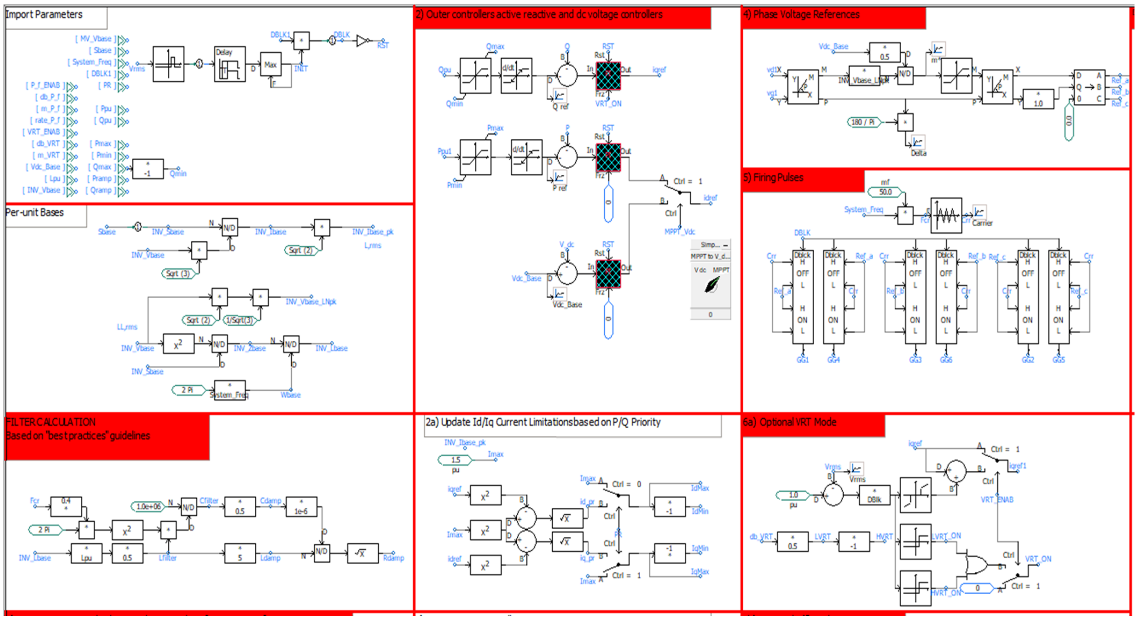

Figure B.3 :PV system controls setup and parameters.

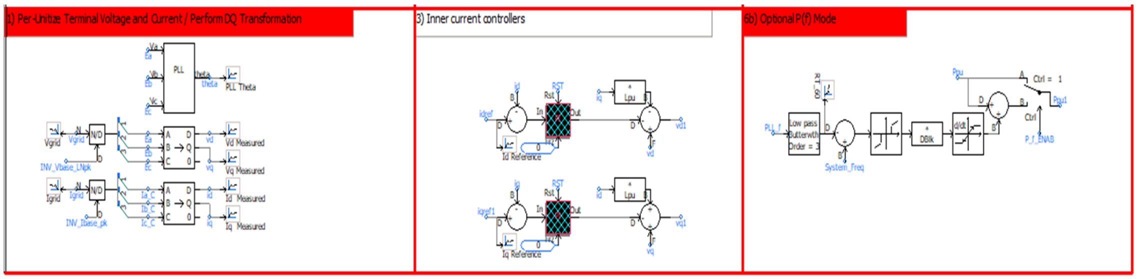

Figure B.4 :PV system controls setup and parameters.

B.3 Appendix

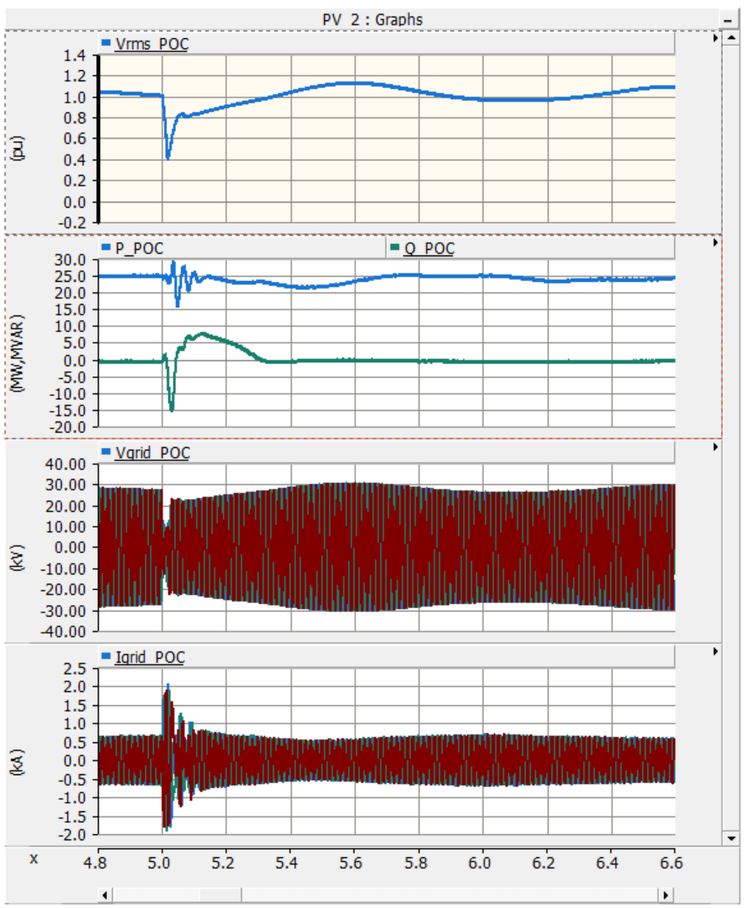

Figure B.5 :PV plant parameter measured at point of connection.