Cape Peninsula University of Technology

ALGORITHM FOR VOLTAGE STABILITY CONTROL IN A POWER SYSTEM NETWORK WITH INTEGRATED MICROGRID.

by

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DECLARATION

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

07/09/2022

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ABSTRACT

The electrical power system is a real-time energy supply system designed to generate, transport, and supply power to the load. As a rule, the electrical power system is planned to operate in stable conditions and correct loading conditions. However, these design expectations can be strained due to disturbance. Because of either the environmental concern or depletion of traditional energy source fossil fuels. The option of renewable energy has gained interest for its integration into the power system. The availability of solar has established potential demand for the rapid growth of solar photovoltaic (PV) energy connection to existing power grids at transmission and distribution levels.

The integration of a microgrid photovoltaic system into the main utility is likely to bring some technical problems that request the upgrade of the power system to a smarter energy supply system that handles the dynamic characteristic of the power system in various operating states. One of those challenges can be described as voltage stability. The impacts of connecting a photovoltaic system to existing grids were considered with emphasis on the IEEE 9 bus transmission network. The existing grid is subject to dynamic load disturbance with a corresponding increase of 35% in power consumption. The dynamic increase of power in a stage of 5% for every 2 seconds of the real-time simulation produces a disturbance that leads to voltage instability in the power system. Developing a Real-time Digital Simulator Computer-Aided Design (RSCAD) model of the power network case study, this thesis aims to study the real challenges of integration of PV microgrid into the power system network considering the disturbance. The implementation of an algorithm, which considers the dynamic behaviour of the power system, was materialised by the modelling of a controller that monitors both the PV plant and the power system behaviours in an effort of restoring the voltage stability when the system generator failed.

When the voltage collapse beyond the stability index of 0.95 p.u due to increased power consumption of the load, the controller shall generate a signal command to the inverter to allow a dynamic flow of power from the PV to the power system. Hence, the thesis contributes to the analysis of the stability of voltage in the electrical grid system with an integrated microgrid, by providing valuable algorithms for voltage stability control of the power system's electrical network with the integrated photovoltaic system in the RTDS environment.

Keywords: Solar integration impacts, photovoltaic power system microgrid, power flow analysis, voltage instability, voltage stability control, real-time digital system (RTDS).

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DEDICATION

This thesis is dedicated to my wife Tondani lumina, my kids Jeffrey Lumina and Jessica Lumina, and the Dieya family. Moreover, this thesis is dedicated to those who always think positively of me.

Sampi Denis Lumina

GLOSSARY

Smart grid: A electrical network that uses digital communications technology to sense and respond to local fluctuations in electricity usage

Microgrid: An independent electrical network capable of generating and supply of electricity. The microgrid has an option to be connected to the utility grid or operate autonomously

Power system: The power system is an electrical network that involves the generation, distribution, and transmission system of electricity.

Voltage stability: The requirement of voltage within the power system, which allow safe operation of the grid by keeping the magnitude of the voltage of the node at a required voltage magnitude.

Voltage collapse: The condition of voltage to drop beyond the acceptable magnitude for voltage stability. This is usually determined by the power utility. In this case, anything beyond 0.95 p.u is considered a voltage drop.

Voltage control: It is a monitoring system at the point of common coupling (PCC) The role of voltage control is to observe and reports any violation in voltage magnitude.

Photovoltaic plant: A generation system is to generate electricity using the energy of the sun as its sole resource.
Power system:

Adaptive volt/var algorithm: The control function for microgrid converter that is used to improve the reliability and stability of the voltage in the power system

Power system stability: This is the ability of the power system to recover and maintain its stability after being subject to disturbance.

ABBREVIATIONS/ACRONYMS

PCC	Point of common coupling
RTDS	Real Time Digital Simulator
RER	Renewable energy resource
COVID-19	Coronavirus disease 2019
IEA	International Energy Agency
RSCAD	Real Systems Computer Aided Design
IEEE	Institute of Electrical and Electronics Engineers
IRENA	International Renewable Energy Agency
MPPT	Maximum Power Point Tracking
VCM	Voltage control mode
VVC	Volt-Var Control
LTO	Linearization through Observation
FSC	Fixed Series Compensation
DSC	Dynamic Series Compensation
SVC	Static Var Compensator
UPFC	Unified Power Flow Controller
SATCOM	Static Synchronous Compensator
ANN	Artificial Neural Networks
FIS	Fuzzy-inference system
ANFIS	Adaptive Neuro-Fuzzy Inference System
STC	Standard testing condition
GTO	Gate turn-off
IGBT	Insulated gate bipolar transistor
ERES	Embedded renewable energy resources
SCADA	Supervisory Control and Data Acquisition
EPS	Electric power system
PPL	Phase locked loop
DG	Distributed generation

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CHAPTER ONE
INTRODUCTION

1.1 Introduction

Usually, an electrical power system is constructed to work in a radial system with one source of electrical power. This design allows the flow of power from the main source to the loads at every point of the network. Taking into consideration different challenges of shortage of electricity based on one single generation unit, the traditional resources of energy are at the risk of depletion, and the world is in consideration of new resources of energy that involved the use of some renewable energy sources such as solar and wind.

The eco-friendly concerns have given way to fast consideration of photovoltaic systems worldwide. In recent years, the demand for a solution to the electricity shortage has increased. So, in South Africa, the number of photovoltaic systems has increased too with a plan to reach 8.3 gigawatts (GW) of utility-scale solar PV by 2030. at the end of 2020 (Pratt *et al.*, 2021).

Classified as distributed generation (DG), solar power in this regard, located close to the loads can help not only to overcome the shortage of electricity but can also assist in the reduction of the number of transmission and distribution networks, and end reduces transmission and distribution losses. However, the microgrid integrated into the distribution network creates additional energy sources for the same electrical network which will lead to possible over voltage at the point of common coupling and also reverse power flow between the distributed generation and the utility transmission network. The issue of reverse power flow remains a huge problem for the grid-tie microgrid. These issues can intensify from problems namely related to voltage stability, reliability, and harmonic. Herein the focus of this thesis is the voltage stability issue.

1.2 Awareness of the problem

The integration of a photovoltaic microgrid into a disturbed electrical network may lead to more voltage instability at the Point of Common Coupling (PCC). By taking into consideration the network configuration and the disturbance caused by the dynamic load conditions, The penetration of the photovoltaic power may incite a change in the configuration of the network from a single-powered network to a multi-powered network, paving room for a new unstable voltage profile on the network feeders. Different algorithms have been previously established with the main to solve the issue caused by the impact of such solar penetration within the power system. The proposed algorithms may vary in approach related to tap changer, on-load tap changer, the placement of capacitor, and the fitting of voltage regulator for line drop compensation. All in common, these algorithms focus on maintaining the voltage profile within the specified voltage range as per the international grid code.

The research trend is to outline a different algorithm that aims to restore the steady state of the electrical grid by overcoming the voltage instability caused by the increase in load consumption in the power system. The focus of the algorithm is to monitor the power system behaviour, regulate the power delivered by the microgrid photovoltaic system (PV), and restore the voltage stability of the grid after disturbance. By considering the disturbance in the power system, this thesis discusses the steady state of the voltage stability in the power system after the microgrid is integrated into the transmission network. The research is based on a modified IEEE 9 buses electrical network which will be developed and simulated using DIgSILENT Power Factory and Real-Time Digital Simulator (RTDS).

1.3 Problem Statement

Today smart power system integrated PV microgrids face the challenge of growing load demand Combined with society's increasing dependency on reliable power supply and hence, the power system became exposed to voltage instability due to disturbances in the core of the grid. Therefore, the importance of dealing with voltage instability caused by a disturbance in the power system integrated with a microgrid becomes crucial in monitoring constantly the operation of the power system. The goal to control the PCC voltage at a specified reference voltage by monitoring the quantity of reactive power injected to the electrical grid by the photovoltaic system and the effort to regulate the voltage profile in the electrical network pave way for implementing fast, effective, and reliable control algorithms to manage the flow of power through the power system. And the purpose of this thesis is to come up with an Algorithm for voltage stability control in a power system network with integrated microgrids by considering the disturbance.

Problem statement: To investigate the impact of disturbance on voltage stability, design and implementation of algorithms based on adaptive volt/var scheme for a common point of coupling between the photovoltaic system and the power system.

1.4 Research Aim and Objectives

1.4.1 Aim

The research aims to develop and implement in real-time simulation a unique algorithm for the stability of voltage. The algorithm consists of a control system that will first monitor any change in voltage magnitude of the power system network with an integrated PV photovoltaic system and secondly be able to regulate the flow of power between the PV and the power system. The control algorithm shall be able to continuously monitor the power system after the power system has recovered from the voltage drop caused by the disturbance.

1.4.2 Objectives

The project focus on developing Algorithms for voltage stability control in a power system network with integrated microgrids in the following steps:

- Development of DIgSILENT and RSCAD model of the power network case study without microgrids. Load flow analysis considers disturbances influencing voltage stability.
- Development of RSCAD model of the power system integrated with microgrids. Load flow analysis considers the disturbances influencing the voltage stability.
- Development and application of an algorithm to control the voltage stability of the power system grid and investigate its performance for various disturbances.
- Comparison of the voltage behaviour from the RSCAD model without the algorithm to the system with integrated microgrid with the developed algorithm for voltage stability.

It’s imperative to mention that the integration of the microgrid PV into the utility network may affect the steady operation of the main utility with various issues. Some of those issues can be limited to a conflict of power flow direction in the utility network. voltage instability, reliability, harmonic, and many others. Herein the project addresses the voltage stability only.

1.5 Hypothesis

The new proposed algorithm for voltage stability control in a power system grid with an integrated PV microgrid will assist the utility grid to restore the voltage acceptable profile and minimise the cost of power loss. It will also arm the researcher with knowledge and solution to voltage stability in power system grid-tie using real-time digital simulation.

1.6 Delimitation of research

The integration of the microgrid PV into the utility network affects the main utility performance in a way that some issues may occur. Some of those issues can be limited to voltage instability, reliability, harmonic, and many others. Herein the project only addresses the issue of voltage stability in the following steps:

- Case study without microgrids. Load flow analysis considers disturbances influencing voltage stability.
- Case study with microgrids without the algorithm. Load flow analysis considers the disturbances influencing the voltage stability.
- Development of the algorithm to control the voltage stability of the integrated power system and investigate its performance for various disturbances.
- Comparison of the two case studies to validate the algorithm for voltage stability.

1.7 Motivation for a research project

Renewable energy resources (RER) have grown to be a vital part of how worldwide energy needs are met. Despite the COVID-19 pandemic, the 2021 International Energy Agency (IEA) data report shows that the global generation of renewable energy has considerably increased, with at least 139,4GW(dc) of PV power installed and commissioned in 2021. The total contribution of solar energy at the end of 2020 was estimated at 760,4 GW(dc) and the reports predict those numbers to grow in the coming years (International Energy Agency, 2021). The rapid increase in renewable energy is motivated by worldwide economic growth and concern over the environmental benefits that renewable energy poses.

However, the integration of such energy into the traditional electrical grid have raised safety concern because renewable energy can also harm the electrical grid by creating voltage instability if proper standards of Renewable Energy Resource (RER) integration are not met and the design is not critically investigated before implementation. To comply with the standard obligations for the design of a renewable energy PV system, a testing case is mandatory. Modelling design to meet the requirements must be developed and tested in an adequate environment to attest to the sustainability of the system corresponding to the standard.

The proposed simulation of this research is a real-time simulation bench test performed in RTDS, which is motivated by the need of delivering a solution for voltage stability in a power system using real-time data and a real-time digital system. Hence the present research will develop an algorithm for voltage stability that considered disturbance in the power system, such as a voltage instability caused by the increase of load consumption, thus offering accurate data on how such conditions should be dealt with in case of a similar incident happened in the real world.

1.8 Assumptions

The following assumptions were made in the effort to solve the research topic:

- The stability and instability of the voltage of the power system grid are taken into consideration.
- Dynamic loads are considered.
- Both powers from the main utility (active and reactive) as well the microgrid penetration and the profile of the transmission line are considered in the effort to solve the control of voltage stability.
- The voltage disturbance in the grid system is monitored.
- The real-time computing methods RTDS used standard admissible grid code for power systems and PV microgrids to achieve the optimal solution.
- The Algorithms for voltage stability control in a power system network with integrated PV microgrids are established.

1.9 Research Design and Methodology

The purpose of the research is to design an algorithm to control the voltage stability in a power system integrated with a microgrid by considering the disturbance caused by the increase in load consumption. Load flow analysis of a base case of the IEEE 9 bus system, considering voltage instability and the integration of the PV system, and the control algorithm of power dispatch to stabilize the voltage is considered. By using a modified IEEE 9 bus system implemented in RTDS the above objective can be realized. The method to be used in accordance with the objectives of the thesis are :

1.9.1 Literature review

Because of the various impact of integrated PV solar in power systems and their related schemes used. Detailed research focusing only on voltage stability with embedded microgrids is highlighted in this thesis. the information is collected by reading through books, IEEE published journals, Internet browsing, and interview with specialist engineers.

1.9.2 Method for the power system voltage stability control

An adaptive control scheme with a centralised monitoring architecture is used in this research to help in solving the issues related to the control of voltage variation in power systems with microgrids considering the disturbance. The proposed adaptive volt/var method was preferred for the following advantages:

- The ability to monitor and control the voltage variation at the grid side.
- The ability to respond instantaneously and adequately to voltage instability is caused by dynamic variation of load consumption.
- The ability to remain in a constant monitoring state after the voltage is restored to stability level.

1.9.3 Simulation

Simulation software such as DIgSILENT and RSCAD/RTDS is used to investigate the modified IEEE 9 bus system. Load flow analysis considering the disturbance is performed using DIgSILENT. Results are collected and compared with RTDS results for the same electrical network. The approaches allow confirming the performances of the electrical network in both software. Creating a disturbance in the network by increasing the load consumption produces a situation of voltage instability, which requires an appropriate approach to recover the voltage. A test bench in the laboratory at the centre for substation automation and energy management systems (CSAEMS) is developed for investigation through simulation and practical work.

1.9.4 Data collection

The resulting data has been analysed through different simulation platforms such DIgSILENT power factory software and Real-time Digital Simulation. Once these results are compared for validation, a proposed control scheme for voltage stability is developed and implemented using the RTDS environment. The modelling of the proposed algorithm in RTDS provides an effective behaviour of the case study in real time.

1.10 Thesis chapters

The thesis of the research investigations is split into seven chapters and two appendixes as follows:

1.10.1 Chapter One

Chapter one gives an overview of the description of the power systems. It also covers the impact of Integrated renewable energy. in electrical networks. The awareness of the problem, problem statement, research objectives, motivation for the research work, hypothesis, delimitation of research, assumptions, and research methodology are described.

1.10.2 Chapter Two

This chapter focus on the literature on the mitigation of voltage stability in power systems. The chapter detailed different approaches used to recover the voltage stability in a power system without and with an embedded microgrid. Several IEEE journals were assessed and evaluated.

1.10.3 Chapter Three

This chapter explains a more detailed theoretical aspect of Photovoltaic technology in power systems. It also describes the conception of PV modules as well as the component of a solar plant and their integration technology into the power system.

1.10.4 Chapter Four

This chapter stipulates the investigation into the IEEE 9 bus system. The base case of the system is simulated in both DIgSILENT and RSCAD/RTDS. Results from DIgSILENT are validated in RSCAD. The chapter also presents the contingency analysis of the IEEE 9 bus system as well taking into consideration the disturbance that creates voltage instability.

1.10.5 Chapter Five

The chapter focuses on the design and integration in the power system of a photovoltaic microgrid with a non-ideal controller mechanism The impact of the penetration of the PV in the power system is investigated.

1.10.6 Chapter Six

The chapter focuses on the modelling of the photovoltaic microgrid and its integration into the power system considering the disturbance. Based on the result obtain in chapters four and five, A PV with the ideal controller has been integrated into the power system and a simulation has been run for observation. An algorithm for voltage stability considering the disturbance and the modelling of the controller in RSCAD/RTDS to regulate the integration of the PV into the power system has been proposed. The algorithm for voltage stability is achieved.

1.10.7 Chapter Seven

The results achieved, the key findings and the research deliverables are reviewed in this chapter. The suggestion for the future is also considered in this chapter.

1.10.8 Appendix A

This Appendix shows all the Network data of the IEEE 9 bus system used in this thesis. The data are those of DIgSILENT software and RSCAD software.

1.10.9 Appendix B

This Appendix shows the design of the control used in case study number one. This controller is a non-ideal controller from the RTDS library.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

Energy is recognised as one of the highly valuable contributions to economic growth. The increase in its production can lead to industrial and economic productivity growth. Unfortunately, access to energy production can be limited by either the depletion of fossil fuels, the environmental impacts associated with the use of non-renewable resources, or the increase in the number of consumers with great variation in power consumption. In the need of providing sufficient energy for the growth of their economy, many countries have opted to source for much affordable, reliable and clean energy such as photovoltaic

Thus, this thesis focuses on the solution to integrate microgrid energy into the power system in a smooth way by defeating the fundamental variations in the operation and control of traditional power systems.

The integration of PV-microgrid into the power system provides active and reactive power to the traditional grid. In a localized network, reactive power from the PV is used for compensation where grid shortages are observed. But the penetration of such power into a conventional electrical power system grid does change the system grid landscape due to new sources of active and reactive power. Thus, the need for new optimal ways of integrating PV power into traditional power system grids considering grid codes and requirements. A technical survey has revealed that the structure of the electrical system network is facing a conceptual change as microgrids and other forms of renewable energy are tied to the grid (Yan et al,2018).

This has shifted to the term “smart grid” being used to address a situation where the electrical network system is regarded as an intelligent tool. For the system integration, the flow of power between the microgrid and the grid can be efficiently managed to avoid voltage instability due to the addition of high penetration of solar power.

Voltage instability, harmonic, and power fluctuation are some of the disturbances that make the normal operations of the grid difficult. Countless researchers have previously searched for and developed various algorithms for the addition of a microgrid system into the utility grid and the impact of such penetration into the electrical network (Reddy and Manohar, 2012).

This chapter presents a literature review of the concept of the electrical power system grid as well as that of the microgrid with the application of photovoltaics in the power system. A review of the standard grid code for the integration of microgrids into power systems is also presented. Section 2.2 of this chapter focuses on the concept of the electrical power systems grid. Section 2.3 addresses the fundamentals of load flow analysis in power systems. In section 2.4, the concept of voltage stability in power systems is covered. The section of voltage stability is followed by the analysis of the power quality in the electrical grid in section 2.5. Section 2.6 of the chapter focuses on the smart grid whereas in section 2.7 the focus is on renewable energy and microgrid technology in power systems. The following section, 2.8 is focused on the challenges of integrating renewable energy in power systems while section 2.9 address the microgrid technology. The PV application in the power system is reviewed in section 2.10 while section 2.11 is dealing with the photovoltaic integration in an electrical power system. The literature review of various algorithms used to deal with voltage stability is discussed in section 2.12 where consideration is on both the power system without PV integrated as well as the power system with integrated PV microgrid for voltage stability enhancement. This chapter also presents the discussion on different algorithms in section 2.13 and closes off with a conclusion in section 2.14.

2.2 Concept of electrical power system grid

An electrical power system grid is a configuration of various electrical components with the mission to provide, transfer and facilitate the use of electric power. This configuration is well known as an electrical power grid. The electrical power grid generally consists of generators that provide power, transmission lines designed to feed various loads, and a distribution system designed to provide power to consumers at a lower voltage (Weedy *et al.*, 2015). Figure 2.1 below is a description of a basic electrical power configuration that highlights the main component that makes a basic electrical network. The network consists of a generating unit, a step-up transformer, some transmission lines, and a step-down transformer to adapt the current to an acceptable level for consumers.

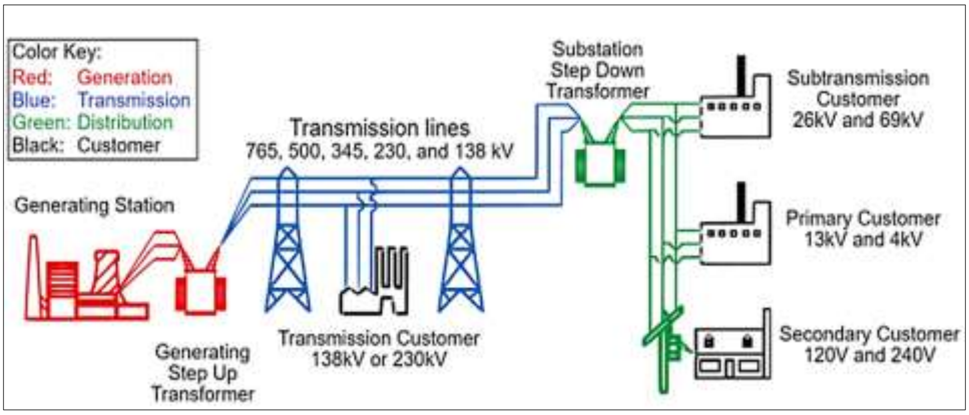


Figure 2.1: **Basic structure of the electrical power system (Calearo, 2019)**

Generally, an electrical power system network is constructed to work in a radial system with one source of electrical power. This design allows the flow of power from the main source to the loads at every point of the network. Taking into consideration different challenges of shortage of electricity based on one single generation unit(Prakash *et al.*, 2017).

2.2.1 Standards for the integration of microgrids into power systems

By definition "microgrid-tie" refers to a distributed generation that is linked to the main utility of a power system via a Point of Common Coupling (PCC). The concept of microgrid-tie describes the integration of an autonomous system of distributed generation links into the utility grid. In some cases, it does not require any system of batteries for the storage of electricity (Gao *et al.*, 2021). Figure 2.2 below describes a complete representation of microgrid-tied technology in the power system.

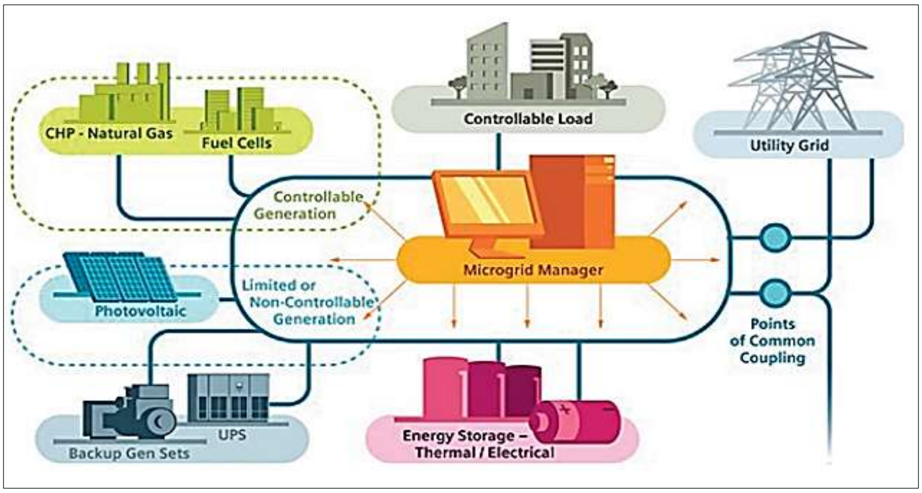


Figure 2.2: **Overview of microgrid system (Yeshalem and Khan, 2018)**

In figure 2.2 different distributed generation (DG) sources are integrated into the power system by a corresponding bus, which is described as a point of common coupling. The DG microgrid-tied PV injects power into the main utility to increase the electricity generation of the utility. Some consequences can occur when such a connection is implemented into the main utility network. The most serious issues of microgrid-tie are the opposite flow of current from the microgrid and the rise of voltage at the point of coupling with the power system. These related issues of microgrid integration into power systems are addressed by the grid integration requirement for renewable energy as determined by the International Electrotechnical Commission code (IEC 61727), which states that the synchronisation of microgrid PV into the utility grid is done concerning the following:

- The voltage of the infinity bus
- The frequency and
- The Phases sequences (Yeshalem and Khan, 2018).

The above-mentioned conditions are related to the photovoltaic penetration level which is described to be the ratio between the total peak photovoltaic power and the peak load apparent power on the feeder:

$$Pv\ Penetration = \frac{Peak\ PV\ Power}{Peak\ Load\ Apparent\ Power} \times 100 \tag{2.1}$$

Where $Pv\ Penetration$ is the amount of the capacity installed in the power system based on the load demand, $Peak\ PV\ Power$ is the total energy generated by the PV plant and $Peak\ Load\ Apparent\ Power$ is the amount of the loads power the electrical grid or power system is able to withstand.

The fluctuation of the energy generated by the PV raise concerns about its penetration into the utility grid in such a way the microgrid may create an unstable condition where the voltage may affect the index of voltage limitation as per the grid design (Roy and Pota, 2013). The uncontrolled introduction of a microgrid into a traditional power system affects the normal operation of the power system, The high penetration power from the photovoltaic microgrid will generate great challenges to voltage stability control and the security system of the electrical power grid (Quan et al., 2018).

To prevent such conditions, the modern grid recommends an adequate voltage regulator which paves the way to a smart approach as part of the grid regulation. By gathering important information regarding the grid status, the microgrid production, and the load consumption, the smart operation of the grid contribute to controlling the voltage stability of the power grid (Lee et al, 2014).

2.3 Load flow analysis in a power system

A load flow analysis is a mathematical procedure in electrical engineering used to investigate the flow of electrical power in the grid. Load flow is made possible use of elementary notation such as per unit system that gives a notation indices of the permitted level of an ordinary steady-state operation of the grid in diverse variations of AC power characteristics such as voltage magnitude and angle, reactive and active power and network impedances that are known to be healthy for the power system(Lal and Mubeen, 2014) The nodal equation for power flow analysis is generally carry-out by the methods of Newton-Raphson method and Gauss-seidel method.

2.3.1 Newton-Raphson

The method is a mathematical procedure for answering nonlinear algebraic equations. For this reason, quadratic convergence is recognized to be a more practical technique for a huge grid system. The Jacobian matrix gives the linearized affiliation between variations in voltage magnitude ΔV and angle $\Delta\delta$ with the alternation in power ΔP and ΔQ (Vijayvargia *et al.*, 2016). Below equation that summarizes the Newton-Raphson method:

$$S_i = P_i + JQ_i = V_i \sum_{k=1}^{n} V_{ik} V_k \quad (2.2)$$

$$S_i = \sum_{k=1}^{n} {(V_i V_k V_{ik}} \Big/ {(\delta_i - \delta_k - \theta_{ik})} \quad (2.3)$$

$$P_i = \sum_{k=1}^{n} {(V_i V_k V_{ik}} \Big/ {\cos(\delta_i - \delta_k - \theta_{ik})} \quad (2.4)$$

$$Q_i \sum_{k=1}^{n} {(V_i V_k V_{ik}} \Big/ {\sin(\delta_i - \delta_k - \theta_{ik})} \quad (2.5)$$

We have Δf = J ΔX

If $\Delta P_i = P_{i(sp)} - P_{i(cal)}$ (2.6)

then I = 1, 2, ….n, I ≠ slack, and if

$$\Delta Q_i = Q_{i(sp)} - Q_{i(cal)} \quad (2.7)$$

Then I = 1, 2, ….n, i ≠ slack, i ≠ PV bus

Where, the symbolizations sp and cal designate the detailed and designed values, correspondingly, then the equation (2.5) may be articulated as revealed below.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J] = \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad \text{Here } [J] = \begin{vmatrix} J1 & J2 \\ J3 & J4 \end{vmatrix} \qquad (2.8)$$

J1, J2, J3, and J4, which are the off-diagonal and diagonal elements of the sub-matrices are specified by differentiating equations (2.4) and (2.5) concerning δ and |V|.

Advantages and disadvantages of Newton Raphson method

The Newton Raphson method possesses some advantages and disadvantages, which can be described as follow:

- The method makes use of quadratic convergence characteristics. Hence, the convergence is accurate and very fast.
- The number of iterations during the mathematical conversion depends on the configuration of the electrical power system network. The result of high accuracy is normally obtained in second or third iterations for both small-size and large-size power system grids.
- The method of convergence does not depend on the choice of the slack bus.
- The method is fast in solving the power flow of an electrical power system since only a few numbers of iterations are required.
- The technical part of the solution is difficult.
- The memory of the computer required to compute the equation is large.

2.3.2 Gauss seidel method

This is the method of consecutive shift, used to explain the linear system of equations. With the slack bus voltage assumed at 1.0 p.u., the remaining (*n*-1) bus voltages are solved through a process of the linear system (Vijayvargia *et al.*, 2016). The idea behind the application of the Gauss-Seidel method is to assume that all buses in the electrical power grid other than the slack bus are P-Q or load buses. At the slack bus, both V and δ are determined and will remain fixed throughout. There are (n – 1) buses where P and Q are specified. At first, we assign the magnitudes and angles at these (n – 1) buses and change them through each step of the iteration.

Express the current flow in one bus. For example, the bus I

$$I_i = V_i \sum_{J=0}^{n} y_{iJ} - \sum_{J=1}^{n} y_{lJ} V_J \; for \; J \neq i \tag{2.9}$$

Now express the current I_i in terms of P, Q.

$$I_i = \frac{P_i - JQ_i}{V^*_i} \tag{2.10}$$

From Equations 1 and 2, the power flow became.

$$\frac{P_i - JQ_i}{V^*_i} = V_i \sum_{J=0}^{n} y_{iJ} - \sum_{J=1}^{n} y_{lJ} V_J \text{ for } J \neq i \tag{2.11}$$

The power flow expression outcomes are in form of an algebraic nonlinear equation, which needs to be solved by the method of iteration.

- Solving for V_i : for P and Q assuming that P and Q are known.

$$V^{(k+1)}{}_i = \frac{\frac{P^{(sch)}{}_i - JQ^{(sch)}{}_i}{V^{*(K)}{}_i} + \sum V^*{}_i y_{lJ}}{\sum y_{lJ}} \qquad \text{for } J \neq i \tag{2.12}$$

- Solving for P_i : for the slack bus, assuming that V is known.

$$P^{(k+1)}{}_i = Re\{V^{*(K)}{}_i [V^{(K)}{}_i \sum_{J=0}^{n} y_{iJ} - \sum_{J=1}^{n} y_{lJ} V^{(K)}{}_J]\} \text{ for } J \neq i \tag{2.13}$$

- Solving for Q_i: for PV bus, assuming |V| is known.

$$Q^{(k+1)}{}_i = -Im\{V^{*(K)}{}_i [V^{(K)}{}_i \sum_{J=0}^{n} y_{iJ} - \sum_{J=1}^{n} y_{lJ} V^{(K)}{}_J]\} \text{for} J \neq i \tag{2.14}$$

Advantages and disadvantages of the Gauss-seidel method

The method has the following advantages and disadvantages:

1. Advantages:
    - The method has proven to be a Simplicity of technique.
    - The method doesn't require large computer memory to execute.
2. Disadvantages:
    - The iterations depend on the number of buses, the more buses the network has, the more iterations are needed.
    - The use of the Gauss-Seidel method is limited to a small electrical network system with a small number of buses.

2.4 Voltage stability in power system

Voltage stability in an electrical power system refers to the stable operation of the electric power grid, which operates within the acceptable limit of voltage magnitude The acceptable index of voltage stability is generally endorsed by the power utility. The stability of the voltage normally raises concern after the grid is subject to disturbance either by a fault in the system, an increase in load demand, or loss of generation (Hill, 2004).

2.4.1 Causes of voltage instability in power system grid

The electric power system is said to be unstable when the voltage magnitude and the reactive power at a given bus decrease or increase behind the threshold percentage of 0.5% to 1 p.u index (Hill,2004). The cause of voltage instability in power systems has been classified into three groups, which are:

- Rotor angle stability
- Frequency stability
- Voltage stability

Figure 2.3 below describes the classification of power stability. Power system stability is the ability of an electric power system, for a given initial operational state to regain a normal operation state after being subjected to a physical disturbance.

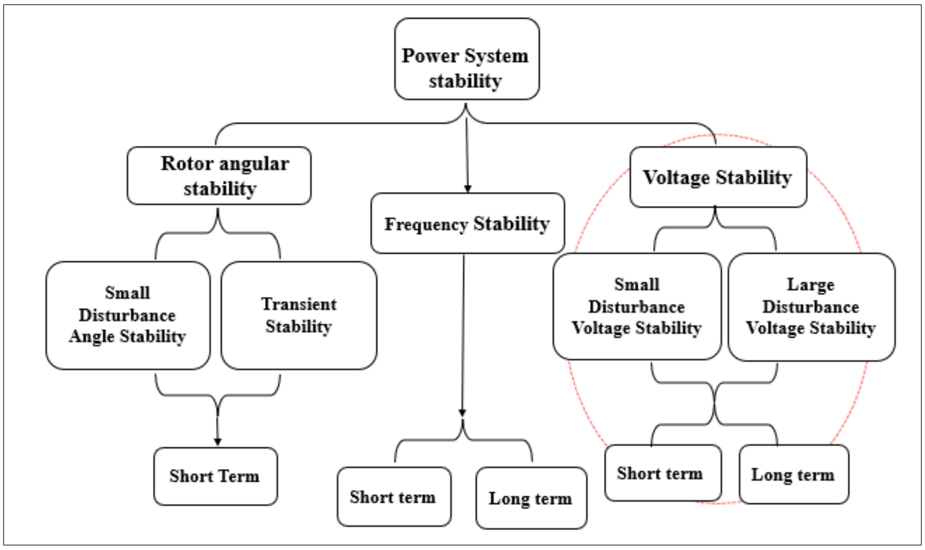


Figure 2.3: **Overview of power system stability (Hill,2004*)***

The power system as shown in figure 2.3 can be classified in rotor angle, voltage collapse, and some combination of these, which is frequency stability. Each of these stabilities can be further classified into large disturbance or small disturbance, short term, or long term.

2.4.2 Rotor angle stability

Rotor angle stability relates to the capability of synchronous machines of a grid-tie electrical power grid to stay in synchronization after being exposed to an electrical disturbance (Kundur et al., 2004). Generally, under the steady-state operation of the power grid, there is a specific balance between the output electromagnetic torque of each generator and the input mechanical torque, the equilibrium tends to maintain a constant speed of all generators attached to the power system. In the case where the system is perturbed, the balance is subject to disturbance, which results in speed trouble (acceleration or deceleration) of all machines' rotors. This happened as prescribed by the laws of motion of a rotating body. In the case of one machine running faster than the rest of the generator, the angular position of the rotor associated with the slow machine will advance. The difference in angle will be then established between the machines. The scenario affects the speed of the generator and hence the angular separation is considered to lead to rotor angle instability (Kundur et al., 2004).

2.4.3 Frequency stability

Frequency stability relates to the capability of an electrical power grid to maintain its normal frequency after a system disturbance due to an incorrect balance between generator and loads. The stability of the frequency depends on the capability of the grid to maintain the balance between the load and the generator(Kundur *et al.*, 2004). The form of power instability that occurred when there is a frequency disturbance usually happens in form of frequency swings leading to tripping of a load and /or generator. When frequency instability occurs, the voltage magnitude of the power system may change its conditions by either being higher or lower in percentage than the frequency. High voltage in the power system may cause unpredicted generator tripping, therefore causing power instability.

2.4.4 Voltage stability

Voltage stability is the ability of an electrical power grid to keep a stable voltage at all buses in the network after being confronted with trouble from a prearranged operational condition. The stability of the power grid depends on the capability of the power grid to restore and maintain the balance between the load and the electricity supplied by the generator. The voltage instability may happen in form of a progressive drop or rise of voltages at some buses in the electrical system.

A possible scenario that follows voltage instability is either a loss of load in a specific area or again tripping of other equipment such as transmission lines at a large scale (Kundur et al., 2004).

Voltage stability is generally classified into two subcategories as follows:

- Large-disturbance voltage stability relates to the electrical system's capability to keep adequate voltages following great disturbances. This is usually caused by loss of generation and circuit contingencies like unplanned excessive load increase. The large disturbance is usually determined by the interaction of both discrete and continuous controls and the protection of the load and the generation unit.
- Small-disturbance voltage stability relates to the system's capability to keep steady voltages when minor trouble occurs in the operational state of the power grid. This type of stability is caused by the characteristic of the load and the generator at a given time of the operation of the grid.

This notion is valuable in showing, how the electrical power system will respond at a given time to a short disturbance. Figure 2.4 below illustrates a radial feed to load from generating power through a transmission line. The component includes a voltage source (E_S) supplying a load (Z_{LD}) through a series impedance (Z_{LN}).

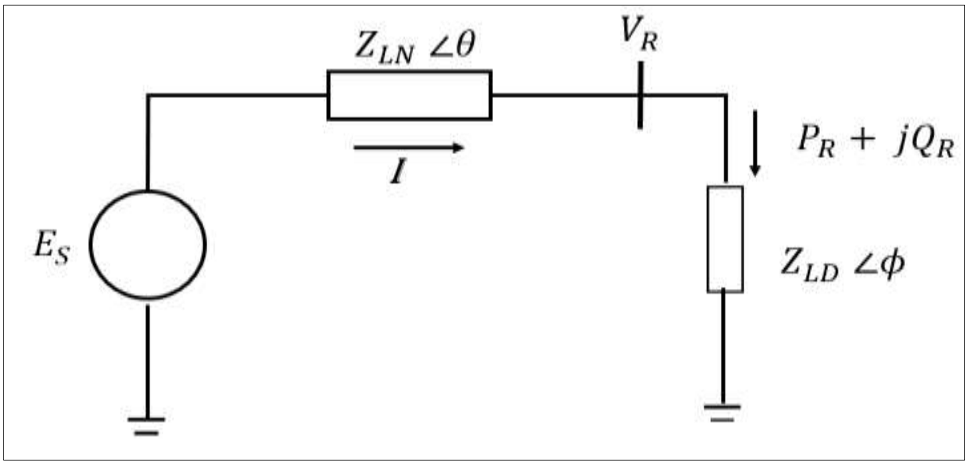


Figure 2.4: Voltage stability phenomenon by the simple radial system (Reddy and Manohar, 2012)

This thesis focuses on voltage stability, which is the ability of the power system to maintain an acceptable voltage on all the system buses when subjected to a disturbance. One of the phenomena in voltage disturbance is the slow gradual change in load demand. This type of voltage stability is qualified as a short-term phenomenon (Kundur et al., 2004).

The expression of voltage stability in the electrical power system is subject to the relation between active and reactive power with voltage. Figure 2.5 next page describes how voltage analysis provides an assessment of the weak area in the electric power system. In the case of the present thesis, the emphasis is on the voltage collapse due to load growth.

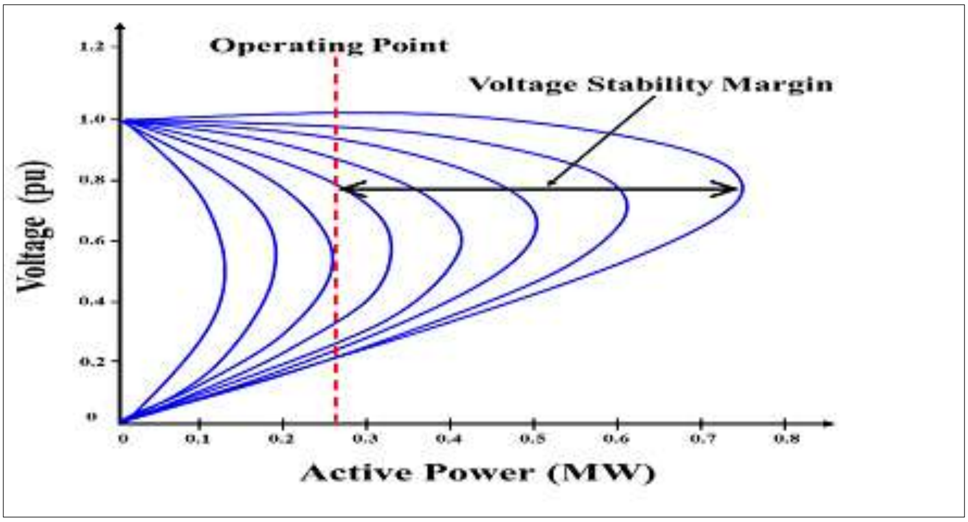


Figure 2.5: **Voltage stability margin with PV curve (Lee and Han, 2019)**

2.5 Power quality in the electrical grid

Power quality in the electrical grid is defined as the state of well-being and functionality of a power network. The operation of a grid needs to be considered in a manner that the power supply from the generation to the consumer is constant at the acceptable level of security as prescribed by the international Institutes of Electrical and Electronics Engineers (IEEE). Any disturbance within the grid can lead to operational instability. The instability of the power system is defined as the impossibility of the power system to operate as per standard (Akwukwaegbu and Ibe, 2013).

Generally, in a power system, any violation of the IEEE standard or grid code results in the grid's vulnerability to operating at its accepted performance. The violation of grid code usually leads to common related issues of power failure like:

- Voltage instability,
- Harmonics,
- Flicker,
- Frequency deviation. (Short, 2004)

2.6 Smart grid

Conventional electrical power systems depend on synchronous generators to ensure that the magnitude of the voltage is kept within the permissible range of the grid stability. The synchronous generators are the principal source of power production in the conventional power system. In today’s world, the conventional power system has become obsolete and consequently incapable of accommodating new applications that involve the integration of distributed technology. This includes renewable energy sources (RES) and other protection technology such as intelligent electronic devices. Since the early 21st century, there has been a new development to include new technology in the traditional electrical power system under the umbrella of a “smart grid”(Malik, 2013).

A smart grid is described as a power grid using computer-based technology to improve the generation, supply, and consumption of electrical power to sustain the stability of the grid. The smart grid also includes grid-tie technology which implied the addition of various renewable power such as wind energy, photovoltaic power, and other renewable energy to the conventional generation of power. A smart grid is generally built to operate as meshed structure(a closed-loop distribution system) (Lee et al, 2014).
Figure 2.6 below describes a smart grid technology that includes a conventional power utility with integrated renewable energy. These distributed generations described as microgrids are connected to the main utility grid as per the electric power system connectivity grid code (Yeshalem and Khan, 2018).

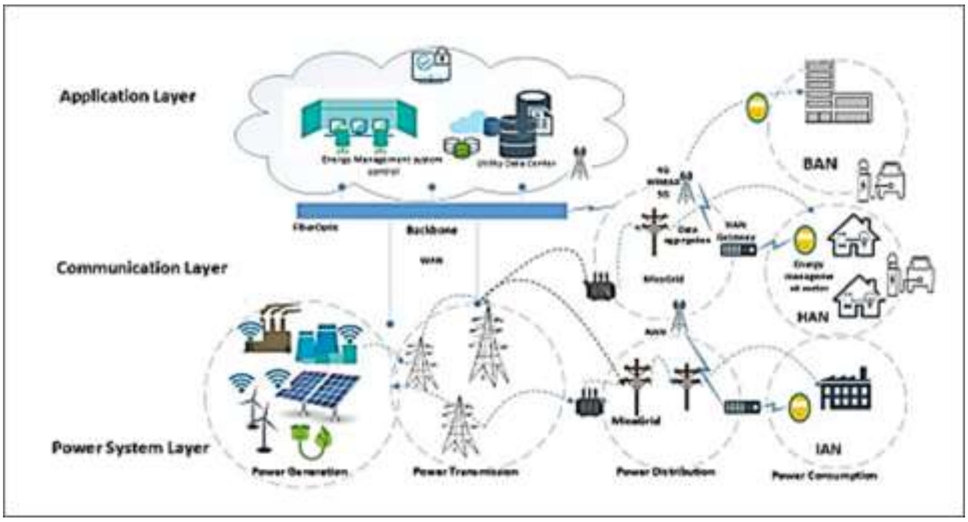


Figure 2.6: **smart grid architecture (Qarabsh, Sabry and Qarabash, 2020)**

The integration of distributed generation into the utility grid power system proves to have a great impact on the real-time operational activity of the power system. Such impact is considered for a better performance of the power grid so that the security is not compromised. In addition of distributed generations to the electrical network power grid often results in bidirectional power flow, which can disturb the normal operation of the existing power grid configuration. Although the distributed generation brings great relief to the power distribution system, it also complicates the protection systems and related control apparatus. The microgrid tie intensifies the complexity of caring for, protecting, and maintaining the distribution system (Nouredine Hadjsaid, 1999).

2.7 Renewable energy and microgrid technology

Renewable energy is an essential energy that is collected from renewable resources. The resources include sunlight, rain, wind, geothermal, biogas, and other forms of resources, which are considered naturally replenished on a human timescale. As of the year 2020, the global production of all renewable energy mixed was estimated to be 270 Gigawatts. Figure 2.7 below shows data from the International Renewable Energy Agency (IRENA), which describes the global trend in renewable energy as of 2020 (IRENA, 2020).

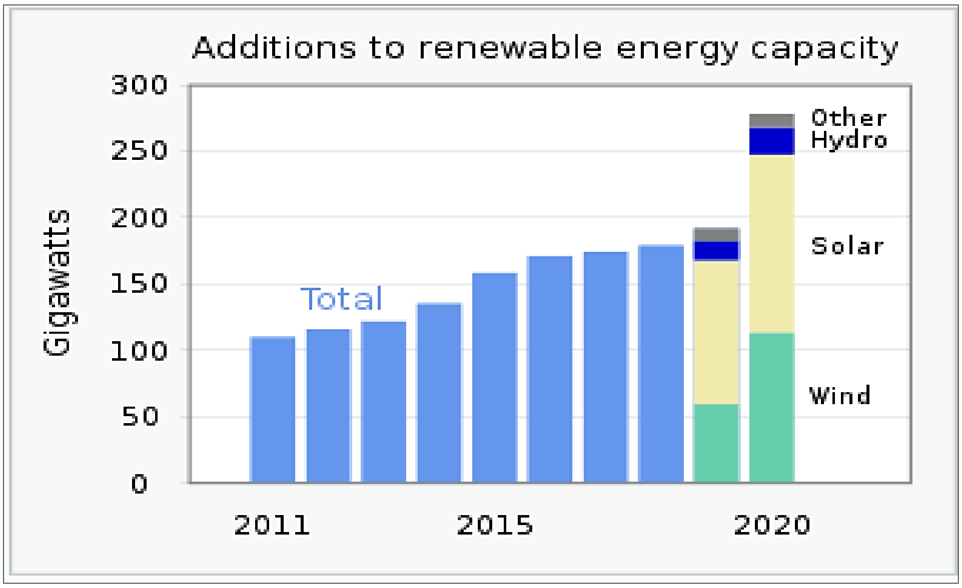


Figure 2.7: **The Global renewable energy report, IRENA 2020**

Renewable energy long-term-based development can help to increase the quantity and quality of electricity needed for a sustainable generation of electricity.

The renewable energy industry also increases awareness of the consciousness of the negative environmental impact of traditional power generation Additionally such awareness prompted an impressive interest in an environmentally friendly generation of electricity. Realizing the positive impact of the expansion of renewable energy resources, most countries worldwide have considered strengthening their bulk traditional energy generation capacity by addicting renewable energy generation to their traditional electrical grid. Figure 2.8 describes the trading and necessity of renewable energy.

Figure 2.8: **Energy trading and necessity chat (Hossain and Mahmud,2013)**

The principle of using renewable energy generation is based on the economics and geographical circumstances of each location. The Following advantages need to be considered together with the above-mentioned circumstances:

- Renewable energy is contributing to improving the capacity and rentability of the traditional electrical power grid.
- Renewable energy is maintainable and therefore cannot run out.
- Renewable energy requires minor maintenance than other forms of traditional sources of energy.
- Renewable energy is environmentally friendly by not producing any carbon dioxide back to nature.
- Renewable energy can bring economic growth to many countries.

2.8 Challenges when using Renewable energy

Although all known renewable energy is clean and rentable sources of power. They have some challenges, which can be environmental, social, technical, and economic. Below are some of the challenges that affect the renewable energy industry of PV.

- Efficiency

  For the PV to become a real source of electrical power, the solar panels need to have a productive performance that process not less than 20% of solar energy in electrical power. A solar panel with an efficiency below 40% is a hazard to the rentability of the PV (Tsoutsos et al, 2005).

- Visual impact

  The visual disturbance of PV modules depends on the landscape variation from one site to another. However adverse visual and PV system syndrome effects can be avoided by selecting a suitable site for a PV plant (Fabrizio and Garnero, 2012).

- Environmental impact

  Every distributed generation and its transmission method impact the environment by affecting negatively the landscape, the climate, and the wildlife. The incorrectly PV plant designed may affect the landscape as well as wildlife (Fabrizio and Garnero, 2012).

- Cost-effective.

  PV plant usually has high implementation cost. The system requires a large investment than most renewable energy systems even though the system cost is more rentable over the year (Rikhi Ramkissoon, 2015).

2.9 Microgrid Technology

The recurrent nature of renewable energy system technologies, particularly wind and solar, introduces operational challenges to electrical power system grid integration. In the case of wind power, the output power can vary from zero to the rated capacity of the wind plant, this singularity depends on the variation of wind. In the same way, the output power of the PV can reach zero at night and its full capacity during the time of high sunlight. A high or less penetration level of power associated with the high demand of load may put the grid under strain, which leads to power instability if no voltage control is considered. Some of the issues that arise during PV integration into an electrical system power grid are categorised into technical and non-technical challenges.

2.9.1 Technical issues when integrating PV systems

The technical issues of PV integrated into an electrical system power grid are mainly related to disturbances that affect the operation of the grid. Below are some common technical issues that affect the grid operation with PV integrated:

- Voltage fluctuation

  Voltage fluctuation is a change in supply voltage. The grid connectivity code request that the voltage supply from the distributed generation must correspond to the voltage of the main grid. The fluctuation occurred when there is a swing of 10% or more from the supply voltage.
- Frequency fluctuation.

  The frequency fluctuation usually occurs when there is a gap between the supply and the power needed by the load. The intermittence nature of the output power of PV is a major cause of frequency fluctuation. This can be managed with an adequate controller, which monitors the desired amount of power to be injected into the grid.
- Power fluctuation

  Power fluctuation is more common in the renewable energy system. The fluctuation can be for a short period or a long period. The uncontrolled increase of output power from the PV can easily affect the speed deviation of traditional generators in the electric power system. The difference in the speed deviation of generators is usually observed when the output of PV changes.
- Harmonics

  PV in power system uses an inverter to convert DC to AC power. These inverters are potentially able to create harmonic problems in electric power systems. In general, the harmonics in a PV integrated system are considered as a specific disturbance that is created by the presence of non-linear equipment in the power system that regulates a permanent modification of the nature of the voltages and the current from the PV.

  The above-mentioned technical issues can be dealt with by putting in place some voltage power system control to deal with the disturbance in the operation of the electrical power grid with PV integrated.

2.9.2 Non-technical issues when the PV is integrated into a grid

Non-technical issues of a PV integrated system are generally linked to the economic factor of the investment. This can be influenced by:

- Large investment in transmission lines in cases where the PV plant is located far from the electrical power network.
- The shortage of investments needs for big power plants needed to meet the output voltage of the electrical power grid.
- Lack of qualified technicians to deal with the renewable energy system in some areas.

The above non-technical issues are generally handled by good planning and strong government policies combined with more research in renewable energy system technologies.

2.10 PV application in power system

Photovoltaics (PV) is a technique that involves the generation of electricity by transforming solar radiation into electricity using semiconductors that caused photovoltaic outcomes (Goetzberger and Hoffmann, 2005). The use of PV in the electrical power system has some advantages, which are the following:

- Technology: cost efficiencies and cost savings
  Crystalline silicon, which is the prime material in the construction of solar cells is available worldwide. The availability of crystalline silicon has contributed to the maintenance of a low-cost solar cell.
- Environmental care
  PV is a source of electrical energy that is ecologically friendly, viable, and indefinitely renewable.
- Long lifetime and low maintenance
  A module can last for 25 years or more and need almost no maintenance.
- Islanding contribution
  The photovoltaic system can be remotely used in a zone where a connection to the utility grid is not reachable. The remote area from the main utility grid can take advantage of solar energy (Goetzberger and Hoffmann, 2005).

The growing interest in global warming and the growing demand for access to electricity has increased the demand for new isolated PV plants across the globe where access to electricity is still a major concern.

2.10.1 PV architecture design

PV system consists of the following electrical components:

- A system of PV panels that are mounted on a fixed or mobile structure.
- A system of powerful inverters that converts direct current to alternating current.

- A powerful controller to regulate the flow of both active and reactive power.
- A Protection technology.
- A power transformer to step up the voltage for synchronization with the grid.
- A Smart metering device.

An overview of the operation of the PV to generate and inject both active and reactive power into the utility electrical power system grid is described in figure 2.9 below. The proposed method for voltage stability consists of controlling the transmission of power generated by the distributed generation during the presence of voltage instability in an electrical network grid thus, avoiding excessive voltage in the electrical network system. The proposed controller will be used to analyse the response of the voltage at the Point of Common Coupling (PCC). The results of the analysis will be used as a reference warning factor in determining the power input needed from the distributed generation. To be able to stabilize the voltage, the proposed control requires two main functions, which are:

- The controller needs to control the voltage output at the PCC. The regulation is done based on the instantaneous power concept that prevents the excess voltage at the PCC.
- The Controller will regulate the reactive power from the PV using of power factor and current drop control.

The proposed controller will keep the output voltage of the electrical system power grid-tie PV within an adequate limit by responding in real time to voltage variation(Khan, 2019).

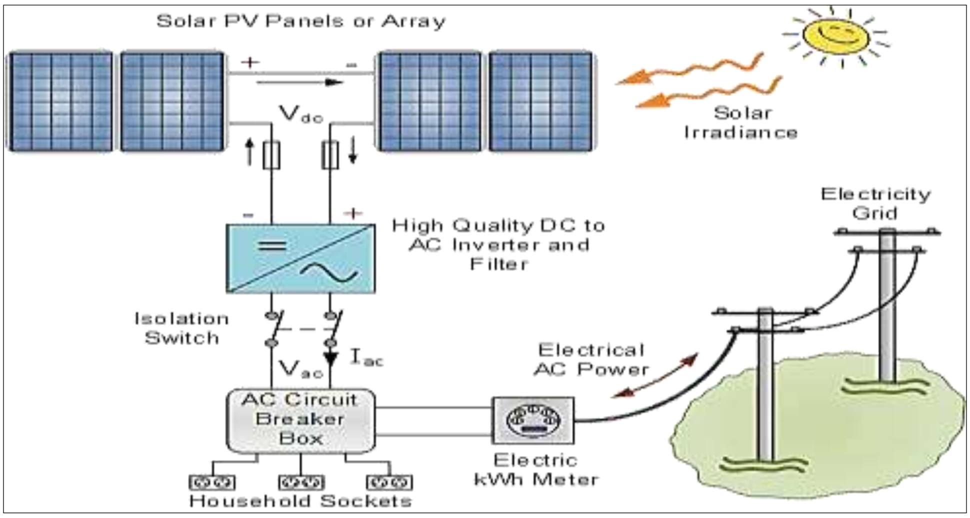


Figure 2.9: **PV architecture from start to finish (Khan, 2019)**

Equivalent diagrams for PV microgrid-tie with basic components from the solar panel, which convert solar energy into Direct Current (DC). DC is converted into Alternating Current (AC) through High-quality DC to AC inverter and filter. The AC passed through an isolation switch, which is part of the protection system before being sent to the electrical power grid.

2.11 Photovoltaic Integration in electrical power system

The main task of integrating PV distributed generation resources into the electrical power system grid is to guarantee a safe and balanced flow of power into the electrical grid. Reliability and security are key concerns for power utilities and all entities involved in the electrical sector. The electrical power grid code together with the PV plant code is considered a guideline for grid interconnection with distributed generation (Shahid, 2018).

2.11.1 Impact of the PV system on power quality

The sending and receiving ports in normal transmission are constantly affected by the connection of the PV to the grid. Figure 2.10 below describes how U_1 and U_2 respectively sending end and receiving end ports in a normal transmission network are integrated with a PV power at the load bus. The PV power injects active power into the bus at power factor 1 with zero reactive power (Alzyoud et al., 2021).

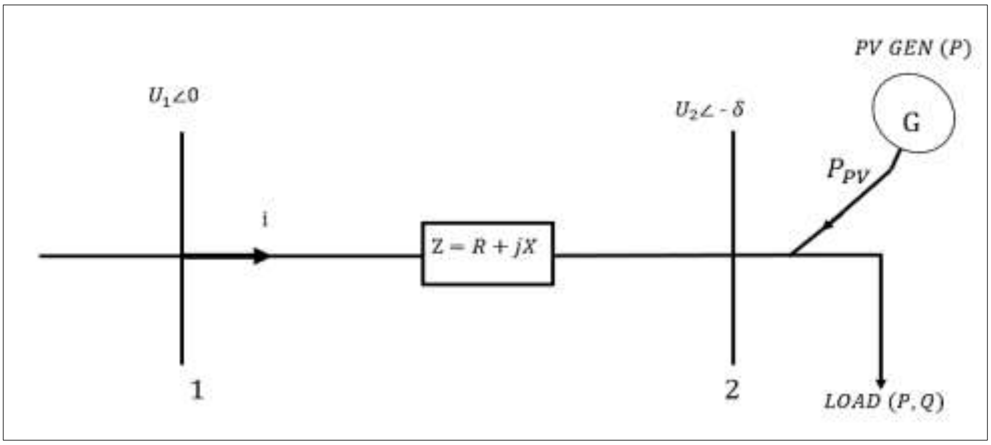


Figure 2.10: **Two-port Grid with solar PV power (Alzyoud et al., 2021)**

In the above scenario, the PV plant is connected to the load bus to provide power (P_{PV}) to the grid. When the output side of the inverter is operating at the unit power factor, the reactive power shall be zero. The profile of the voltage in the transmission system is modified due to the presence of the power from the PV. The equation of the transmission line is expressed in terms of :

$$|U_1|=|U_2|-\left(\frac{R(P-P_{PV})+XQ}{|U_1|}\right) \quad (2.15)$$

Voltage drops:

$$\Delta U=\frac{R(P-P_{PV})+XQ}{|U_1|} \quad (2.16)$$

$$P_{LOSS} = I^2R = \frac{(P-P_{PV})^2+Q^2}{|U_2|^2} R \quad (2.17)$$

$$Q_{LOSS} = I^2X = \frac{(P-P_{PV})^2+Q^2}{|U_2|^2} X \quad (2.18)$$

Where The concept of voltage stability of a transmission grid can be consequent by considering a short transmission line (Z = R + jX), U_1 and U_2 respectively sending end and receiving end voltage, P_{PV} the power from the PV plant and connection of a load (P, Q) at the receiving end in what is described as a two-port grid. The two-port grid is used to derive the concepts of system behaviour in terms of the influence of the PV on the voltage profile and voltage stability. The expected results of integrating the PV into the electric grid will improve the voltage profile of the grid. The presence of the PV at bus 2 is likely to cause a reduction of voltage drop along the transmission line (Alzyoud *et al.*, 2021).

2.11.2 Voltage violations in grid integrated with PV

Voltage violations are considered one of the big challenges in PV integration into the power system. IEEE 1547, the international standard for interconnecting distributed resources with electric power systems makes it mandatory for all power utilities to observe a voltage limit within the prescribed upper and lower limits of 0.95 and 1.05 p.u (IEEE Std 1547, 2018) Both overvoltage and undervoltage are possible in solar PV integrated into the utility power system. In figure 2.10 above for example, if more power from the PV is injected at node 2, it is possible for U_2 to exceed U_1 magnitude due to reverse power flow. Interestingly, solar PVs can also trigger low voltage when it is put between voltage regulators and their regulating point. It violates the conventional technique of voltage regulation regarding line drop compensation. The violation affects the voltage drop which triggers under-voltage.

2.11.3 Power control capability in grid integrated with PV

The renewable energy power plant code makes provision for the plant to be fitted with constraint functions, such as active power control. The role of active power control in this regard is to avoid unbalances in the electrical power system network by correcting the output power of the microgrid. Furthermore, to ensure that the ramp rate of the active power does not exceed the threshold set by the power regulator for the electrical power grid. (Homann and Ismail, 2020). Figure 2.11 below describes the exchange of power between the PV microgrid and the electric power system. In the effort to maximise the power generated by the microgrid, a tracking power control is needed at the point of common coupling to regulate the power flow from the PV into the grid. The stability of the grid voltage and its power quality depends on the active power setpoint defined at the level of the Maximum Power Point Tracking (MPPT).

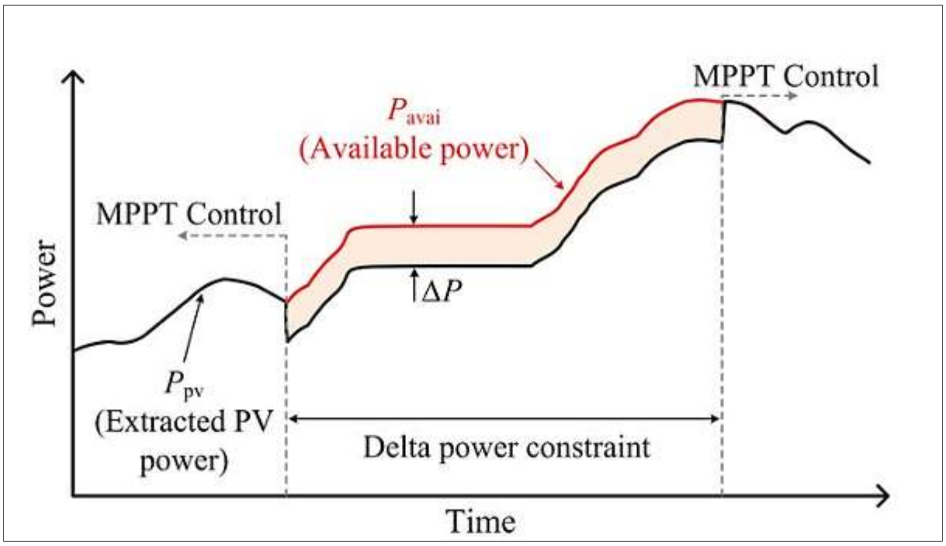


Figure 2.11: **Operation of the Delta Power Control (DPC) with combined MPPT (Sangwongwanich *et al.*, 2017)**

Figure 2.11 describes a delta power strategy control for a large-scale PV integrated plant where P_{pv} represents the PV output power, P_{limit} is the limit level of the power flowing from the PV to the grid, P_{Avail} is the total AC power from the PV, ΔP is the reserve of power required and f is the grid frequency. The active power reduction control is used in large-scale PV power plants to limit the flow of active power to the grid. The described delta power strategy offers an efficient solution when it comes to the control of power exchange between the PV and the grid without the need for extra components such as battery storage or irradiance measurement components.

By using the P-V characteristic curve, the delta power control operates in MPPT mode to determine the percentage of power to be injected into the grid. This strategy allows the PV to keep some reserve power from the total power generated, thus ensuring the stable and reliable operation of the grid while keeping some reserve power on the PV side. The role of the control power function can be defined in three roles namely:

1. *Absolute Production Constraint*

   Absolute production constraint is a function that controls and limits the quantity of active power generated by the microgrid PV at the common point of coupling. Based on the electrical system power grid reconfiguration, the active power control of the renewable power plant shall be able to select an amount of the output power required from the microgrid.

2. *Delta Production Constraint*

   The Delta production is the function with the ability to constrain the PV output active power at a required constant rate in proportion with the set point of the active power of the electrical power grid.

3. *A Power Gradient Constraint function*

   The function is used to determine the maximum setpoint ramp that determines the amount of active power supplied from the PV plant in case of voltage instability in the electrical power grid. The power gradient prevents the electrical grid to collapse in case of a shortage of active power. The renewable energy plant is liable for the stability of active power.

2.11.4 Solar PV Smart Inverters Volt/Var Control Capability

The integrated solar PV generation system includes an inverter whose role is not limited only to the conversion of DC power to output AC power. In a grid-connected solar PV generation system, an inverter can also be used to regulate the voltage at the point of common coupling by injecting and absorbing the reactive power. The capability of the inverter to perform multiple functions is frequently termed a " smart inverter" and subsequently identified as voltage control mode (VCM). To add to this mode of operation of the smart inverter, the solar system is operated at unity power factor or other constant power factors, which are usually lagging power factors to compensate for voltage rise. The capability of the inverter to limit the injection and absorption of reactive power depends on its rating. The inverter must comply with the following equation

$$\sqrt{P^2 + Q^2} \leq S \qquad (2.19)$$

Where,

P is the real power,

Q is the var output power

S is the rated capacity of the inverter.

So, the maximum var magnitude which can be injected or absorbed by the inverter at any given time can be estimated as

$$Q_{max=}\sqrt{S^2 - P^2}\ldots\ldots \qquad (2.20)$$

Because of the inverter's fast-switching control capability at a second's timescale and due to their dynamic function of control, the solar system inverters emerged as effective volt/var controllers to handle rapid variations in the modern power system by offering rapid and continuous volt/var control capability, which was not the case in the traditional Variable Voltage Converter (VVC) devices such capacitor, STACOM, and other VVC devices.

2.11.5 Feasibility of Volt-Var Control Algorithm

Five parameters characterised the volt var control algorithm. These parameters are represented in the curve shown in Figure 2.12 below. Parameters Q_{max} and Q_{min} are used to represent the inverter's reactive power ability;u_{min} and u_{max} represent the dead-band where the reactive power from the inverter is not exchanged, and d is the droop parameters to the slope of the curve. The remaining parameters are u_{meas} and S_{nom} which are respectively the voltage as measured at the PCC and expressed in p.u and the total apparent power of the smart inverter. From the above five parameters, the resulting reactive power is computed as follows:

$$Q_{inj}=100(u_{min} - u_{max}).\ S_{nom} / d \qquad (2.21)$$

$$Q_{abs} = 100.\ (u_{max} - u_{meas}).\ S_{nom} / d \qquad (2.22)$$

$$Q_{max} \leq Q_{inj} <= Q_{min} \qquad (2.23)$$

$$Q_{max} \leq Q_{abs} <= Q_{min} \qquad (2.24)$$

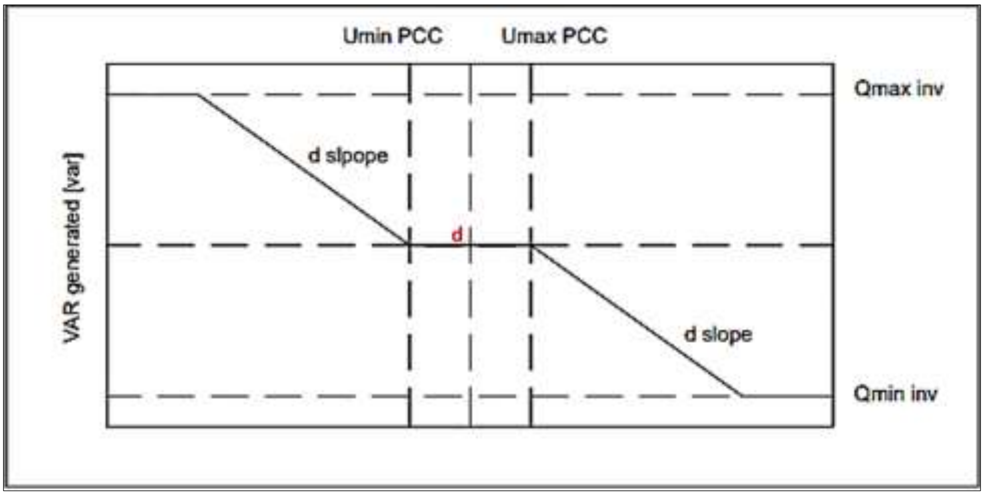


Figure 2.12: **Representation of volt var control setting curve (Gubert et al., 2021)**

In Figure 2.12, the curve is used to represent the common control functions of the volt/var algorithm used to enhance the reliability and stability of voltage in the integrated grid. The setting of the curve is determined in compliance with the IEEE 1547-2018 standard as autonomous grid support capability functions for smart converter-based DERs. From the look of the curve, the amount of the reactive power discharge from the PV to the grid is defined by the percentage margin of disposable reactive power versus the per-unit voltage at the point of common coupling. The inverter of the PV plant does not allow the flow of power during the dead band "d" situated between (u_{min} and u_{max}) range. In the case where the voltage at the point of common coupling is below the u_{min} threshold as fixed by the utility power and the smart inverter will operate in a capacitive mode, thereby supplying reactive power to the grid. On the contrary, if the voltage at the point of common coupling is above u_{max}, the inverter is designed to operate in inductive mode thus absorbing the reactive power.

2.12 Literature review of existing papers for integrated PV microgrid

There has been increasing interest and research when it comes to voltage instability and voltage collapse in the power system. As the research in the field is increased, the literature review has also increased. The classification of the review is based on the following criteria:

- Review of theory of voltage stability in power systems without integrated microgrids.
- Review of theory of voltage stability in power system with integrated microgrids.

2.12.1 Review of theory of voltage stability in power system without integrated microgrids

For a given power system, any method to stabilise the voltage may not be suitable. The greatest method is a probable combination of numerous methods carefully chosen to effectively assist to provide system stability for diverse eventualities and system circumstances.

(Bongiorno and Svensson, 2006) proposed a method of parallel connection of a voltage source converter and a shunt capacitor to mitigate the sensitive process of voltage dips. The voltage source system is designed to keep the magnitude of the grid voltage constant at the point of the connection while the shunt capacitor is designed to inject the reactive power needed for voltage dips compensation. This process is achieved by using a cascade controller which makes use of an inner vector current-controller and an external voltage controller to calculate the current reference for the voltage-controlled converter (VCC). Furthermore, the researcher recommends that for better voltage stability, the control of both positive and negative sequences of the grid voltage must be done separately to compensate for unbalanced dips. (Radman et al., 2007) developed a method for fast voltage collapse recovery based on the control of reactive power. The controller system known as Power System Voltage Stabiliser consists of dividing the electrical power grid into multiple zones, each with a power factor correction device such as a capacitor bank or a STATCOM. A dynamic voltage index is designed to control the voltage deviation in each area to provide sufficient reactive power for all loads in the specific area. Finally, the method provides a dynamic voltage index during voltage disturbance in the power system. The proposed method used an IEEE 14-bus system to test for a different form of voltage collapse.

(Yue, Xuehong and Kejun, 2007) made use of the preventive-corrective control method to monitor the operation of a 168-bus real power system. Through the preventive control method, they managed to consider the lower permitted voltage as the smaller limit of automatic voltage control for voltage stability, which controls the voltage index in real power. The corrective control is used to carry out voltage control when the system voltage is exposed to disturbance and can only be restored by correcting the busbar voltage. By coordinating the optimal power flow as well as the automatic voltage controller they manage to put an engineering practice that manages the voltage profile of the power system at a stability level where the power system operates with voltage stability margins (Ri et al., 2007) analysed the influence of the induction motor on voltage profile to determine how the rotor angle of the motor may affect the voltage stability of the power grid. The investigation shows that the stability of the rotor angle is a important factor in the stability of the voltage grid.

(Sreejaya and Rejitha, 2008) propose a generic algorithm-based approach method of dispatching reactive power devices for reactive power control at each bus through a power system of 171 buses. These devices are generators, shunt capacitors, and tap positions of on-load tap changers of transformers. By varying the devices that control the reactive power, a significant reduction in power loss is achieved. The decrease in power losses restores the stability of the Karalla power system.

(Phadke, Bansal and Niazi, 2008) developed a strategy of control of voltage stability based on the placement of the shunt controller. The researchers proposed to investigate the power system for the weakest busbar, which will be used for the placement of the shunt capacitor for best control of the voltage profile of the power system.

(Liu et al. 2009) proposed the use of the accuracy of the voltage phase angle as perceived by the Phasor Measurement Unit to regulate the requirement of power system analysis and monitoring for power system stability. The control algorithm is named Linearization through Observation (LTO) for a controlling objective track which linearizes its nonlinear state equations by online monitoring of the state variable with the assistance of the Phasor Measurement Unit (PMU) and completes a strategy for voltage control, which forces the power system into a stable operation.

(Reddy and Manohar 2012) discussed voltage stability analysis using two methods, which are: voltage sensitivity methods and method of modal analysis including participation factor. The result shows how the method helps to track the collapse of voltage in the power system and provides a relative measure of voltage instability. The application is verified on the IEEE 14-bus system.

(Ahire and Dake, 2018) later proposed the best compensation algorithm that regulates the voltage profile and reactive power compensation in five regional interconnected grid networks in India. To keep the reactive power stability in the power system, they proposed a mitigation technique, which includes the use of

Fixed Series Compensation (FSC) and Dynamic Series Compensation (DSC) components together with shunt compensation in the system.

The Static Var Compensator(SVC), Unified Power Flow Controller(UPFC), and Static Synchronous Compensator(SATCOM) have been proposed to be used as a dynamic compensation strategy to balance the reactive power resources in the grid.

(Mnguni and Tzoneva, 2019) Investigating the stability of voltage in an electrical power system, the authors demonstrated how increasing load consumption can affect the safe operation of the electrical power system. Voltage instability in this regard is caused by the inability of the generators to supply adequate reactive power to meet the shortage of reactive power caused by the increase in load demand. To improve the operation of the grid and restore voltage stability, the authors proposed and developed a strong and effective Under-Voltage Load Shedding (UVLS) scheme for real-time application in the power system networks. A new multi-stage adaptive UVLS scheme is implemented in real-time using the RSCAD software environment of the Real-Time Digital Simulator (RTDS). Contrary to the traditional method of shedding a bulk number of loads to stabilise the electrical power system, the proposed UVLS method differs in approach in that it develops a load shedding strategy based on equal sharing of the percentage of the load to be shed among all loads of the electrical network taking into consideration their prioritization. The criteria used to determine the priority of load are pre-defined for the participating loads. The feasibility of the UVLS method is dependent on the continuous comparison between the setpoint value of 0.95 p.u. which is the voltage stability for the load shedding and the measured voltage at the load buses. The difference between the two voltages is sent to the controller, which then calculates the percentage of increase in load consumption and sends the collected data to the actuator intelligent electronic device to take remedial action which is achieved by tripping the breaker and shedding the loads. The operation of the controller is uninterruptedly active until the process variable matches the setpoint value of 0.95 p.u. By establishing the UVLS scheme in the power system, the authors managed to restore voltage stability.

The developments of the different voltage stability algorithms for the electrical network system without microgrids as shown in Table 2.1

Table2 1: **A review of papers on voltage stability without a microgrid**

PAPER	Aim of the paper	Method of Voltage Stability	Structure of the system	Used hardware/software	Advantages / Drawbacks	Achievements
(Bongiorno and Svensson, 2006)	To develop a cascade control for voltage dips in the power system.	Voltage source converter (VSC) coupled in shunt with the grid to control voltage dips.	Power system Grid with one source.	A simulation-based project using PSCA.	The method provides a clear technique for voltage control et reactive power compensation.	Robust control of voltage dips has been achieved.
(Yue, Xuehong and Kejun, 2007)	To find a control approach to improve power system voltage stability after disturbance	Control voltage stability based on real power flow tracking	IEEE 118 -bus system.	A simulation project in DIgSILENT power factory.	The method can provide fast restoration of voltage stability	A controller for voltage stability based on power flow tracing is achieved.
(Radman et al., 2007)	To develop a fast voltage collapse recovery method.	Power system voltage stabiliser method (PSVS).	IEEE 14 bus system.	MATLAB is used as a simulation software tool.	The technique used a method that enhances dynamic reactive power for a specific part of the power system grid.	A new method for voltage stability called Power System Voltage Stability is achieved.
(Yue, Xuehong and Kejun, 2007)	To develop a new preventive method to monitor the collapse of voltage.	Preventive and corrective controller for voltage Stability.	168-bus real power system.	A mathematical approach corrective model for voltage stability.	Improve stability of the power system.	An engineering practice for preventive voltage control has been established.
(Ri et al., 2007)	To analyse the impact of induction motor on grid voltage profile.	The enhanced relation between voltage and rotor angle.	Investigation of Shanxi power grid.	Simulation-based project.	Control the influence of the induction motor on the voltage grid for	A consideration of the effect of the induction motor as a factor of

					better voltage stability.	voltage stability has been proved.
(Phadke,Bansal and Niazi, 2008)	To introduce a voltage stability method based on the best location of the shunt capacitor.	Shunt FACTS controller at the weakest bus.	IEEE 14 bus system.	Simulation project using MATLAB.	The method allows identifying the weakest bus of the grid	A strategy for placement and sizing of the shunt controller has been achieved.
(Sreejaya and Rejitha, 2008)	To develop a technique of reactive power control by dispatching reactive power monitoring devices through the power system.	Reactive power control at each bus.	Kerala(India)171 buses power system with 2 generators.	Simulation project based on power flow variation.	The method takes into consideration of load behaviour at each bus.	The Genetic algorithm method proves to be a good platform for solving voltage instability problems.
(Reddy and Manohar 2012)	To analyse voltage collapse in the power system and provide a solution.	Voltage sensitivity methods and methods of modal analysis including participation factor.	IEEE 14-bus system.	Simulation-based project.	The method improves voltage sensitivity and stability.	A new algorithm for voltage stability demonstrates a fast response time.
(Lin, Wang, and Gao, 2012)	To investigate the load power flow.	Analyse of load power factor to determine the voltage characteristic of the power system	A 2200KV distribution network.	Research-based project.	The method focuses on the load demand to determine the system's stability.	A regulation controller for reactive power consumption at loads has been established.
(Karidza and Anderson, 2013)	To demonstrate the impact of the introduction of capacitor banks on various bus	To determine the active and reactive power flows in the power system.	15 bus Morupule Power Station in Botswana	Power World software has been used to simulate the results.	The method uses the effect of a capacitor bank to determine a better voltage profile.	The busbar with a capacitor bank shows a better voltage profile.
(Müller et al., 2017)	To establish a power loss optimization in the power system.	Novel Method of optimization of losses.	30-node scheme IEEE with 6 generators.	Simulation project in MATLAB.	The method presents a STATCOM as a source of needed	FACTS devise such as STATCOM has been described as an

					active and reactive power.	application for voltage control and active power optimization.
(Tahboub, Alaraifi, and Elmoursi, 2017)	To reduce the time of the fault-induce delayed voltage recovery	The method presents a dynamic VAR planning strategy for rotor angle and short	IEEE New England 39-bus system	Simulation-based project in MATLAB	The hybrid method uses a generic Algorithm interfaced with dynamic VAR	Optimum installation control has been achieved through a hybrid voltage stability controller
(Ahire, 2018)	To manage the voltage stability issues in the power system.	Dynamic compensation in the system to mitigate voltage sag.	Western India high voltage of (400 kV) and ultra-high voltage (765 kV) level power grid system.	Design related project	The method allows the use of different compensation methods at once at diverse locations of the power system	The method has shown that the Dynamic compensation is appropriate in dealing with high chronic voltage at the busbar,
(Hu, 2019)	To control the reactive power in the power system.	Reactive power control by STATCOM.	ZX (China) station with a load level of 16000MW.	Simulation based project.	The method uses the reactive power and voltage characteristics of STATCOM to analyse the voltage profile of the network.	The STATCOM influence the voltage stability of the power grid.

2.12.2 Review of theory of voltage stability in power system with integrated microgrids

Diverse algorithms for control of power system stability exist worldwide and depend on different researchers and their interest in power system stability. In the interest of our thesis, we can briefly name the following algorithm:

(Munkhchuluun and Meegahapola, 2018) described how the size and location of the PV plant can affect the operation of the power system. Bearing in mind that the penetration of PV power in a power system may increase the voltage stability of the grid, it is therefore critical to emphasize that connecting a PV plant can create unwanted situations like overvoltage, distribution losses, harmonics, and flickers appearing during the operation of the power system. Analysing the influence of the PV on the IEEE 14 bus system, the researchers demonstrated that the size of the PV in grid-tied mode may have the possibility of negatively influencing the parameter of the grid when not carefully regulated. A downsized PV plant integrated into the grid may contribute to more overloading troubles, whereas an oversized PV supplying active and reactive power can negatively affect the operations of the grid by creating overvoltage and more instability. While the size matters, it is important to also consider the position of the PV plant since this may positively influence the magnitude of the voltage when placed closer to the problematic area of the network.

(Lipták, 2021) although renewable energy is regarded as an appropriate solution to the global energy crisis; the importance of PV energy security and reliability when integrating with power systems still needs to be considered carefully. The researcher goes on to explain how the power supplied by solar panels can result in uncontrolled power, this may in turn cause significant network disruption. To avoid the disturbance of the power system, the researcher proposed a central controller algorithm located at the microgrid level to improve and boost the attributes functions. The role of the controller is to determine the rentability of the microgrid based on the condition of the load on the grid side. The well-defined mechanism for the safe operation of the grid is implemented by synchronising the transmitted grid signal with the set parameters of the microgrid controller. By so doing, the proposed control ensures that the energy exchange through the microgrid and the grid is equally balanced between load consumption and microgrid energy production.

(Dusa *et al.*, 2019) proposed a synchronous algorithm method that deals with the uncontrolled injection of reactive power from the PV microgrid to the power system. The Impact of the uncontrolled PV power plant is known in some conditions to have an unwelcomed impact on the safe operation of the grid. When the electrical grid is subjected to uncontrolled flow of PV power, its operation is disturbed to an extent of producing voltage instability in the power system. The researcher demonstrated that an uncontrolled flow of active and reactive power to the grid has a diminishing effect on the voltage profile. To solve the problem caused by the uncontrolled injection of reactive power into the electrical grid, the researchers proposed a method of active power filtering which is controlled by the synchronous algorithm method based (d_q) frame. The d_q frame is used to compare the phase angle between the voltage and the current of the PV plant with those of the Grid. Once synchronisation is achieved between the PV plant and the grid, the inverter of the solar plant can then positively regulate the amount of power needed to restore the voltage profile of the power system.

(Mills-price *et al.*, 2014) Explained the importance of regulating PV penetration in the power system. The researchers described a PV plant control system that can aid in solving various challenges related to the interconnection of large PV power plants with the utility grid. The proposed control strategy consists of monitoring the overall operations of the generation plant at the point of common coupling and based on the conditions adjusts the PV plant operation to meet the grid performance requirements. The proposed architecture is based on the implementation of strong control communication to be integrated into both the PV plant and the power system.

To achieve a reliable and efficient control system, it is recommended that the use of communication protocols such as SCADA and others be made available as part of grid architecture. These control systems provide a reliable communication monitoring system that ensures the power system voltage stability remains monitored at any given time of the operation of the grid. By doing so, the utility continuously maintains a safe and reliable electrical grid integrated with renewable energy.

(Muhammed Y Worku and Abido, 2016) proposed an efficient configuration and real-time implementation of a comprehensive model and control of a grid-tied photovoltaic (PV) system. The proposed algorithm is called Adaptive Neuro-Fuzzy Inference System (ANFIS) based MPPT controller, which is an integration of the fuzzy inference system (FIS) based MPPT method with the Artificial Neural Networks (ANN). The design of a P-Q control is proposed and implemented to transfer the power from the PV to the grid using a Voltage Source Converter (VSC). The technique to transfer the PV power to the grid is based on the function of two independent controllers, which respectively control the buck converter and the VSC. Using Adaptive Neuro-Fuzzy Inference System-based MPPT, the duty cycle on the side of the buck converter is uninterruptedly regulated depending on the varying irradiation and temperature to track the maximum power available. On the other side, a P-Q control is designed to interact with the VSC for the transfer of power from the PV to the grid. the algorithm integrates an independent active and reactive power control using a synchronous rotating reference frame. In the current control technique, the component $\mathrm{I_D}$ controls the active power while the reactive power flow is controlled by regulating $\mathrm{I_Q}$.

Furthermore, by controlling the magnitude and angle of the inverter output voltage in the $\mathrm{D-Q}$ frame, the technique allows to independently control the reactive and active power respectively.

The inverter in this regard keeps the DC voltage unchanged for active power delivery to the electrical network. A phase-locked loop is applied to track the grid angle θ and the grid frequency $(\omega = 2\pi f)$, which are used for ABC to DQ conversion.

(Mohamed Usama et al 2017) share a view that permanent and instantaneous voltage stability is the main requirement for any power system. This is because any disturbance within the power grid could lead to power instabilities and imbalances with consequences that can lead to power cuts across wide areas of the network or even entire the entire network. They proposed a Machine learning technique, that uses a smart technology alerting system and a programmed manoeuvre system able to deal with the power failure through a voltage stability index. The machine learning technique as proposed repose of three steps to follow with respect to allowing the indicator of the voltage stability and the capability to indicate the level of instability in the power system. Such steps are determined by a set of machine learning algorithms called predictors. The predicator concept is to analyse the machine learning algorithm based on numerous input data with their matching outputs data and then to organize a relation that led to the development of new inputs needed for power stability. The three sets for the machine learning technique are:

- Linear regression

In the process of machine learning algorithm, the first machine is described as linear regression. This is a statistical method that permits the discovery of the relation between the dependent variable named labelled characteristic and a sequence of other varying variables. In Voltage Stability Automatic Manoeuvre Algorithm (VSAMA), the projected variable is the index of the stability of the voltage, and it is a constant variable from 0 to 1. A comparison between a set of three indicators had been performed to determine the suitable index with the linear regression algorithm (Usama et al., 2017).

- Neural Network

  After the linear regression, a second machine called an artificial neural network is used based on the method of a reverse feedback neutral network initiated by a controlled learning algorithm, for training Multi-layer Sensitivities. Here again, a comparison between three indices is done to determine the accurate index for the algorithm associated with a neural network.

- Decision tree

In the final step of the machine learning algorithm, the third machine used is called the decision tree. As previously stated, that the predictor's output is varying between ranges from zero to one. During the step of the decision tree, the machine algorithm is presented in form of a flowchart based on a model of a tree structure that displays the predictions that result from a sequence of feature-based splits which start with at root level up to the top of the tree where the decision is made by leaves.

From the image of the tree, a predictor is a group of rules that can be represented in the form of a graphic. The researchers managed to develop a learning machine that understands the operation of the grid in line with the voltage stability indices. This technique helps to generate a warning system that alerts the electrical power grid operator of a possible malfunction in the power system.

(Panda, Mohapatra and Srivastava, 2018) An Effective Inertia Control Scheme for Solar PV Systems with Conventional d_q Controller is proposed to deal with voltage issue in power system with PV inverter connected. The algorithm applies a traditional d_q controller scheme. The role of the d_q the controller is to provide virtual inertia to the PV system by affecting its Phase Locked Loop (PLL) parameters. The relationship between the power mismatch and phase angle of the inverter is derived in terms of the inertia constant. As a result of this relation, a comparable inertial constant representation is achieved. In another way by varying the parameters of the PLL, the existing d_q controller of the power system can be enhanced by virtual inertia. No additional circuit is required with this method as the proposed d_q only affect the existing PLL parameters of the PV system inverter to add virtual inertia. This makes the algorithm effective and simple.

(Isha and Jagatheeswari, 2021) develop an algorithm for the best allocation of DSTATCOM and PV array in the distribution system. The fuzzy-lightning search algorithm is dealing with power losses that affect the operation of the power system. Fuzzy-lightning search algorithm focuses on the placement of the static compensator (DSTATCOM) as distributed FACTS device and the photovoltaic (PV) array unit as DG**.** The algorithm proceeds by performing a load flow analysis using the Newton-Raphson method. Data from the load flow are used to determine the base case values of active and reactive as well as the bus voltage values of the entire power system. From the result of the load flow analysis where the best case has been revealed, the optimal location of the DSTATCOM and PV system can be obtained.

Figure 2.13 below describes the best placement of the STATACOM in distribution based on the fuzzy logic algorithm.

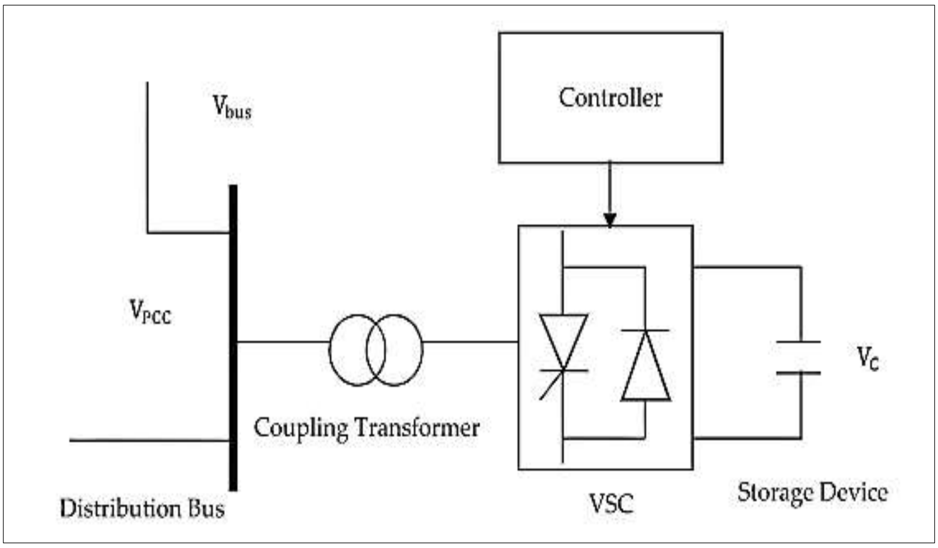


Figure 2.13: DSTATCOM configuration diagram in distribution network (Isha and Jagatheeswari, 2021)

The placement of the STATCOM, as well as that of the PV system, are load flow analysis's results dependent. The Fuzzy logic algorithm as presented reduces the power loss in the power system, assists in voltage recovery after disturbance, and increases the voltage stability value of the power system.

(Rubeša and Mandi, 2019) proposed a volt/var control strategy for a transmission grid with a microgrid wind power generator. The necessity to implement the VVC function in the 220 and 400KV transmission networks is justified by the high ratio of the fluctuation of the voltage during some period of the operation of the grid. For this reason, the implementation of a control strategy is necessary for the optimization of the reactive power in the transmission network.

The Volt/vars control function in this regard is executed by the function of the (Supervisory Control and Data Acquisition (SCADA) for the optimization of the optimal power flow by reducing the active power losses in the transmission network while observing the predefined threshold for safe operation, for example, voltage and power flow limits as set by the utility operator. The proposed VVC control is set to adjust the voltage limit in a case where there is an over-voltage in the system.

(Gubert *et al.*, 2021) an Adaptive Volt-Var Control Algorithm control for voltage stability scheme is prosed to deal with voltage instability in a power system with DER penetration. The volt-Var function is characterised by five parameters, which are considered in the application of the algorithm. Parameters $Q_{max}inv$ and $Q_{min}inv$ are used to represent the inverter's reactive power ability;$u_{min}PCC$ and $u_{max}PCC$ represent the dead-band where the reactive power from the inverter is not exchanged, and d is the droop parameters to the slope of the curve. The remaining parameters are u_{meas} and S_{nom} which are respectively the voltage as measured at the PCC and expressed in p.u and the total apparent power of the smart inverter status is considered (PV penetration, voltage instability) by adjusting its control ability to ensure an optimal response to voltage stability.
The application of the volt-var scheme considered the interference of these parameters where voltage stability is a concern. The ability of the volt-var control has proven that the control is adequate in a power system where the PV inverter is interconnected and the power grid. The developments of the different voltage stability algorithms for the electrical network system with microgrids as shown in Table 2.2

Table2 2: **A review of papers on voltage stability without a microgrid**

PAPER	Aim of the paper	Method of Voltage Stability	Structure of the system	Used hardware/software	Advantages / Drawbacks	Achievements
(Chowdhury and Fieee, 2005)	To analyse the reliability of PV power responsible for grid stability.	Load modification method to assess the impacts of PV power.	Unit power system with the three-generation unit.	Mathematical design of power variation in power system.	The method is based on the energy consumption of the loads.	A new method of evaluating the capacity and reliability of PV has been achieved.
(Pereira et al., 2006)	To study the reactive power injection for dynamic voltage stability.	Numerical integration scheme of PV power.	A power network with 5 busbars and on a generator of 380Kv.	Simulation project using transient software EUROSTAG.	Injection of PV power is based on each Busbar power consumption	A voltage collapse has been resolved by a numerical integration scheme
(Majumder et al., 2008)	To analyse power system stability during load sharing for system stability.	Droop controller gains method.	Basic power system with 2 Microgrid sources.	PSCAD software was used for simulation.	The method allows smooth transfer between islanded, and grid-connected modes.	A modular controller structure has been established for better load sharing.
(Majumder et al., 2010)	To design a back-to-back controller for active and real power flow in a hybrid environment.	Back-to-back converters for power flow control.	Simple power system with microgrid load and two DG sources.	Simulation-based project using PSCA/EMTDC software.	The method allows the excess power from the microgrid to be shared by the DGs.	A load sharing and power flow controller have been verified for voltage stability.
(Sakthi Suriya Raj *et al.*, 2015)	Develop an effective design algorithm for tracking the maxim power of the PV	Intelligent MPPT Control algorithm for photovoltaic System	The solar PV system is connected to a	MPPT control techniques in MATLAB/Simulink.	The method has the advantage of tracking the total power	The Neural Network-based MPPT control

			Resistive load through Boost converter with LC filter		produced by the PV system	technique can track the maximum power
(Zhang, Yang, and Zhu, 2016)	To investigates the power regulation method of PV generation during transient events for enhancing the grid.	A novel integrated control method.	A typical power system with two synchronous generators and two aggregated loads.	Simulations using MATLAB/Simulink.	The presence of the battery allows a double control of active and reactive power for improving system damping.	The system damping characteristic has been improved.
(**S**eritan et al., 2016)	To address the impact of distributed generation on the distribution system as well as on the energy management system.	Load flow simulation as a method.	A hybrid system of PV and wind power connected to the 250KV grid.	The simulation was done using ETAP software,	The characterisation of the electrical loads for a future microgrid.	SVC integration has been recommended to improve harmonic distortion and reduction in reactive power.
(Muhammed Y Worku and Abido, 2016)	Presents an effective strategy and real-time implementation of a comprehensive design and control of grid-connected PV system	Adaptive Network-Based Fuzzy Inference System (ANFIS)	A PV with a booster converter DC-DC converter is connected to a grid	executed in Real-Time Digital Simulator (RTDS)	The algorithm combines two different methods in response to voltage instability in the power system	Integrating FIS with ANN results in a robust Artificial Intelligence algorithm for voltage stability
(Refaat et al., 2017)	To design a maximum power point tracking control	Adaptive fuzzy logic controller.	Simple grid-tie PV power system.	Simulations-based project.	The control is intended to upgrade the efficiency of PV	A maximum point of tracking of active and reactive power has been achieved.

	scheme for voltage stability.				and diminish the outpower oscillations.	
(Meng and Guerrero,2017)	To custom the power quality of the power system.	An optimization method-based strategy.	7 bus microgrid with 3 DG units.	Generalized mathematic model built in Simulink.	Compensation by utilizing a microgrid converter.	Power quality regulation has been achieved.
(Han et al., 2017)	To achieve proper power-sharing between active and reactive power.	Method of Hierarchical control of power.	Two parallel hybrid DGs are connected to the grid.	Simulation-based project.	Improve the dynamic stability of active power-sharing.	A control strategy for active and reactive power-sharing has been achieved.
(Refaat et al., 2018)	To investigate and report on the dynamic of the grid-tie PV power system.	Dynamic stability analysis method.	IEEE 30-bus network with PV and six synchronous generating units.	Simulation project using ETAP power system analysis software.	The method focuses on the weakest bus bar of the network.	The method shows that the generator recovers its stability.
(Wang and Ren, 2018)	To investigate a new control structure for power flow in grid-tied PV.	A disturbance estimator-based current-mode controller.	The typical grid-tie PV system is used.	A simulation-based project.	Two-stage converters one DC/DC and the second one DC/AC are used in the method.	The DC bus voltage regulation for PV is achieved.
(Wang et al., 2018)	To verify the effect of STATCOM on reactive power flow control and voltage stability.	Synchronous compensator (STATCOM) method.	Grid-connected microgrid system.	MATLAB/Simulink software is used for simulation.	The use of a shunt reactive compensation device technology.	The STACOM can control reactive power flow and voltage stability at PCC.

2.13 Discussion

To achieve the safe operation of an electrical network power grid, the stable operation of the system needs to be addressed and attended to. The stability of the power system is affected by various situations like increased load consumption, faults in the system, and other environmental burdens on the distribution side. At the point of the abnormal operating condition of the electrical power system grid, the stability of the power grid needs to be restored accordingly (Jeyapriya and Chockalingam, 2018).

The literature review scrutinizes several techniques used for voltage stability in power systems with or without microgrid PV. Research on power algorithms for voltage stability schemes in terms of rapidity, reliability, security, and stability has placed a huge burden and accountability on power system engineers who starve for a better algorithm to monitor the voltage stability in a power system where disturbance is a concern.

The different voltage stability schemes presented in the review are grouped into two classifications. Classification one focuses on the investigation of voltage collapse in a power system without a microgrid while classification two in the review focuses on the stability of voltage in a power system with a microgrid. An emphasis was put on the PV microgrid as well as on the hybrid microgrid where others DGs were considered. For both classifications, all the different algorithms investigated focus on the stability of the voltage and the quality of power in the power system using different methods that regulate either the flow of active and reactive power separately or the flow of the active and reactive power at load side or at generation side or again at both sides.

In a power system without a microgrid, various researchers have proposed numerous techniques for dealing with voltage stability. These techniques involved the use of electrical components such as capacitor banks, STATCOM, or other voltage regulator techniques. With the integration of the microgrid in the power system, the researcher has shown a sharp improvement in dealing with voltage stability. Smart grid technology brings control algorithms more accurate, especially when used in real-time technology. With modern technology, it is important and recommended to consider algorithms than can constantly monitor the grid vulnerability and propose fast voltage stability recovering margin to prevent the total collapse of the grid. Few of the algorithms proposed in the past investigated the voltage collapse in real-time simulation with regards to digital communication schemes as well as the possibility of combining different algorithms for better control of power flow in power systems, particularly those with microgrid-tied. The volt-var algorithm or the Adaptive Neuro-Fuzzy Inference System (ANFIS) respectively presented by (Gubert et al., 2021) and (Muhammed Y

Worku and Abido, 2016) describe a better recovery method of voltage stability compared to other methods used for voltage stability in power system.

The two scheme promotes comprehensive monitoring of the variability of the power on the grid side of the system. By considering combining the two algorithms in a Real-Time Digital Simulation (RTDS), a more efficient volt-var-based MPPT algorithm can produce a better result for voltage stability in the power system considering the disturbance.

2.14 Conclusion

This chapter gave an overview of the basics of the power system in both structures of traditional electrical power systems power grids and smart grids. A description of the mechanism of voltage stability tools available for study and factors to be taken into consideration for the integration of renewable energy in the electrical power system grid has been highlighted.

Furthermore, this chapter presented a literature review of different algorithms that deal with voltage collapse in the traditional grid as well as in the smart grid. The selected algorithms focus on the method used, the hardware for voltage stability, and the technical environment for testing. These algorithms in most cases did not make use of online testing with a Real-Time Digital Simulator for accurate voltage deviation and recovery. For the real-time voltage stability control to estimate the voltage stability margin, it is imperative to regulate the active and reactive power on both sides of the loads and the generators or again on both grid and the microgrid.

This thesis focuses on developing a control scheme that will address voltage instability in the power system. The control scheme will facilitate a smooth integration of the photovoltaic system to assist the recovery of voltage stability after any disturbances without affecting the safe operations of the electrical grid. The control scheme is an advanced control loop designed to regulate the flow of power injected into the grid. This is achieved by utilizing the advanced control loop to monitor any variation in the magnitude of the voltage at the point of common coupling.

Chapter three covers the theoretical aspect of photovoltaic technology. Various components of the photovoltaic plant as well as the impact of the integration of the photovoltaic in the power system are covered.

CHAPTER THREE
THEORETICAL ASPECTS OF PHOTOVOLTAIC TECHNOLOGY

3.1 Introduction

A healthy electric power system is the backbone of modern civilization. However, the means of electricity generation have experienced a significant change during the 21st century because the rapid increase in demand for electricity puts immense pressure on the Power Utility. As a result, the power system is more likely to face repeated failures that may lead to a blackout that negatively impacts consumer's everyday lives (Alhelou et al., 2019).

The impact of the increase in power demand can be managed by using integrated microgrid energy into the power system. Microgrid energy sources such as photovoltaic (PV) are used in the power system to provide extra power that can improve the electric power system. With the rapid erection of PV power plants and the need for grid-tie electric power systems, it has become crucial to develop a safe and effective mode of interfacing the power system and the PV power plant (Tran et al., 2018).

This chapter provides a literature review on the technology behind the photovoltaic power plant. It also explains the necessity of some factors associated with the integration of PV power plants into the power system. Therefore, the importance of preventing large disturbances due to diverse PV challenges becomes crucial and needs constant monitoring of the power system. This will pave the way for the implementation of a fast, effective, and reliable control scheme. Section 3.2 examines the electrical components of PV. In this section detailed composition of PV, the mathematical model that constitutes a PV, and the power characteristic of PV is presented. Section 3.3 discusses the PV inverter's topology.

The inverter is described as an electronic component that transforms the direct current (DC) of PV into an alternative current (AC). The Section deals with the modelling and influence of the DC-link capacitor, the Three-phase VSI, the harmonic filter, and the power transformer in the integration of the PV into the power system. Section 3.4 discusses the theoretical aspects of the PV technology and closes off in section 3.5 with a conclusion.

3.2 Electrical components of PV

In this section, a review of each component is presented considering their operating principles and influence on grid tie technology of solar power. The electrical components of the photovoltaic power plant have three tasks, which are:

- To convert the light from solar into electricity.

- To inject the power from the PV into the grid.
- To ensure the safe and adequate performance of the power system grid.

The basic electrical components involved in these tasks are photovoltaic modules, photovoltaic inverters, and transformers. These components are today subjected to the power control system, which regulates their functions in the power system.

3.2.1 PV modules

Solar power is the greatest existing form of energy and is used globally. Photovoltaic systems convert solar power into electric energy. Solar power is converted into electrical energy through PV modules. The power output of the solar system depends on the quantity of energy incident on the surface of the PV modules and the temperature of the photovoltaic cell. The efficiency of the photovoltaic modules depends on the laminating materials used on the PV modules, as well as on the efficiency of the cell that composed the module (Zekry, Shaker, and Salem, 2018)

Three cell technologies are categorised in power system:

- Monocrystalline: These types of cells are grown on a single crystal. They are more efficient and more expensive.
- Polycrystalline: This type shows multiple crystalline structures developed in one cell. They are cheaper than monocrystalline and have lower efficiency.
- Thin film: These types use less silicon in the production of cells. They are less expensive and lower in efficiency (Benda and Černá, 2020).

Regardless of their difference in conception, PV modules use the same standard testing condition (STC) to determine the module's rating. The variation of these conditions determines the output power of the PV modules. The STC set up the total irradiance of 1000W/m^2 and the ambient temperature of 25℃ as standard operating values.

The PV module is a nonlinear source of energy. In large-scale PV plants, PV modules are arranged in series and parallel configurations where series alignment is providing the voltage of the system. On the other hand, the parallel determines the current out of the PV system. This arrangement formed what is described as a PV array in a power system (Zekry, Shaker, and Salem, 2018)

Figure 3.1 shows the difference between cells, modules, and arrays for a better explanation of PV technology.

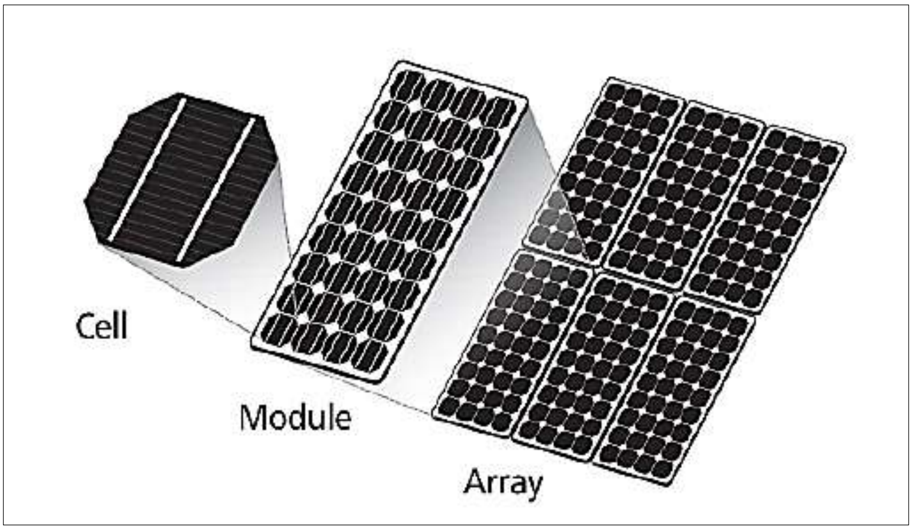


Figure 3 1: **Cell-Modules-Array for PV technology (Nabipour Afrouzi et al.,2013)**

The primordial element is the solar cell. Solar cells can be connected in series configuration or parallel configuration or again in both configurations at the same time to form a PV module. A suitable module will have 36 to72 cells tied in series. The PV modules are merged in series and parallel to shape a PV array.

3.2.2 Mathematical model of PV arrays

In figure 3.2 below, an analytical model of the PV system's arrangement to model the behaviour of the output current and output voltage is presented.

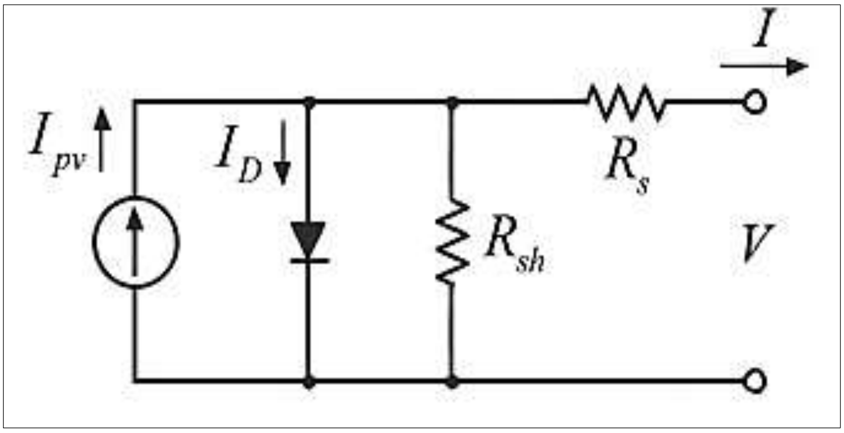


Figure 3 2: Equivalent circuit of a solar panel (Cubas,Pindado and De Manuel,2012)

The mathematical presentation of a PV is built on an equivalent circuit of the solar power plant where:

I_{pv} represents the photocurrent delivered by the constant current source.

I_0 implies the reverse saturation current related to the diode.

R_s represents the series resistor that reflects the losses in cell solder connections.

R_{sh} represents the shunt resistor that considers the current leakage via the high conductivity shunts across the p-n junction.

α is the ideal factor that considers the variation of the diodes from the Shockley diffusion theory.

V_T implies the thermal voltage of the diode and depends on the charge of the electron, q, the Boltzmann constant,

k is the number of cells in series,

n is the temperature,

V is the output voltage of the PV arrays.

As mentioned above, the current-voltage characteristic depends on the radiation level and temperature of the cell. Applying Kirchhoff's current law on the circuit presented in figure 3.2, the equivalent relation between current and voltage through the PV is obtained as follows:

$$I=I_{pv} - I_s[exp\left(\frac{V+IR_S}{\alpha V_T}\right) - 1] - \frac{V+IR_S}{R_{sh}} \quad (3.1)$$

$$V_T= n\frac{kT}{q} \quad (3.2)$$

The parameters I_{pv}, I_s, R_s and R_{sh} required to use in Equation. Subsequently, to plot the PV panel I-V characteristics, these parameters are defined in the equations below:

$$I_s= (I_{sc} - \frac{V_{oc}}{R_{sh}})\exp(-\frac{V_{oc}}{mV_t}) \quad (3.3)$$

$$R_s=R_{s0}(-\frac{mV_t}{I_s})\exp(-\frac{V_{oc}}{mV_t}) \quad (3.4)$$

$$I_{pv} = I_{sc}(1 + \frac{mV_t}{I_s}) + I_s(\exp(\frac{I_{sc}R_S}{mV_t})-1) \quad (3.5)$$

$$R_{sh}=R_{sh0} \quad (3.6)$$

Where:

I_{sc} is the short circuit current (A),

V_{oc} is the open-circuit voltage (V),

R_s is the series resistance (Ω),

R_{sh} is the shunt resistance (Ω),

V_t represents the diode thermal voltage (V) and m is the ideal factor of the diode(Nguyen and Nguyen, 2015)

The expression of the output power of the PV results from the above equations. The parameters used in the equations are subjected to environmental conditions such as irradiation variation and temperature variation. Figure 3.3 below describes how the alteration of the environmental condition affects the output power of the PV.

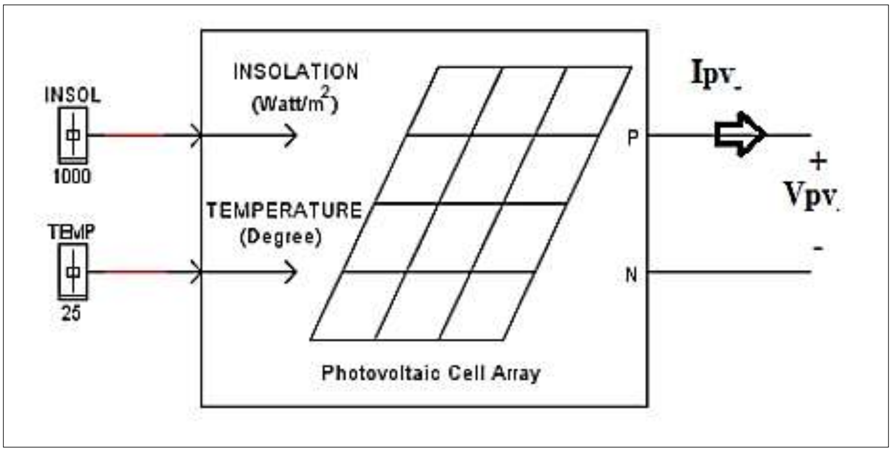


Figure 3 3: PV output power dependency on the impact of environmental conditions on PV array (Muhammed Y. Worku and Abido, 2016)

The RTDS model of the PV array shows how the environmental condition affects the output characteristic of the PV, the alteration of the environmental condition may affect the boundary conditions of the equations and, consequently lead to the amount of power that the PV can provide a non-linear.

3.2.3 Intensity versus Voltage characteristic curve for photovoltaic

The characteristic of the current-voltage curve I-V for the photovoltaic module is derived from the complex mathematical formulation shown in equation 3.1. The I-V characteristic is used to determine the curve between the current and the voltage of the PV module (Ali et al., 2018). Figure 3.4 below describes the relationship between the current and the voltage at standard test conditions (STC).

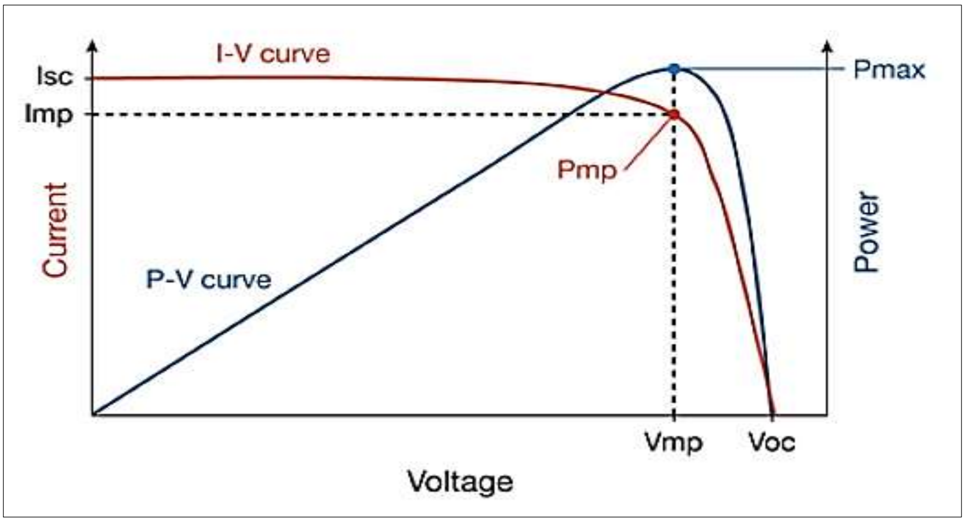


Figure 3 4: I-V characteristic curve of a PV module at the standard test of 25℃ of temperature and 1000W m^{-2} of irradiation (Khatib,et al., 2017).

PV modules do not generate much voltage. The illustration in Figure 3.4 shows a PV module with a short circuit current I_{Sc} for an open voltage V_{oc}.For a specific load, the simulated PV module in figure 3.4 is working at the maximum power point P_{mp} and P_{max}. I_{mp} and V_{mp}represent respectively the current and voltage at the maximum power point.

The I-V curve provides vital operating information about the PV module such as short circuit voltage, current, maximum current, maximum voltage, maximum power, and efficiency. The I-V curve allows tracing the overall performance of the PV. The output power of the PV modules can be described in the event of the curve where the interference of change between the current and the voltage is visible. Thus allowing the effectiveness of the maximum power tracking (Li *et al.*, 2020).

3.3 PV inverters Topology

The task of the PV modules is to convert the solar light to DC power. To feed the power system, an inverter is required between the PV modules and the electric power system. Hence an inverter is an electronic solid-state used to convert electric power from DC to AC (Merza, 2019).

For precise control of power factor, power quality, and voltage stability the choice of inverters is very crucial in a power system. Depending on the design of the PV power plant. An inverter can be modelled in a single stage or double stage. Single-stage inverters convert DC to AC directly while double-stage inverters first convert DC to DC to an amplified DC then at the second stage the new DC is converted into AC power, which is fed into the grid. Inverter application in PV power plants goes beyond the above-mentioned. The inverter in PV integrate power plant is also used for:

- Performing maximum power point tracking (MPPT) to maximise the output power of the PV system.
- Connecting the PV power plant system to the electric grid in accordance with the grid code.
- Providing full monitoring of the power transfer.

Figure 3.5 describes the overall three-phase inverter topology of the integrated PV power plant into the electric power system. The grid-tie inverter with an inductor capacitor-filter has a DC-link voltage V_c that is presumed to be constant. V_c is connected to a voltage system source with six transistors and six freewheeling diodes. The LCL filter consists of the inverter side and the grid side inductors L_{cJ} and L_{cg}, together with their internal resistances. The capacitor C_f and the capacitor resistance R_d which are connected in a star configuration. The role of the LCL filter is to filter the harmonics caused by the inverter before their injection into the power system.

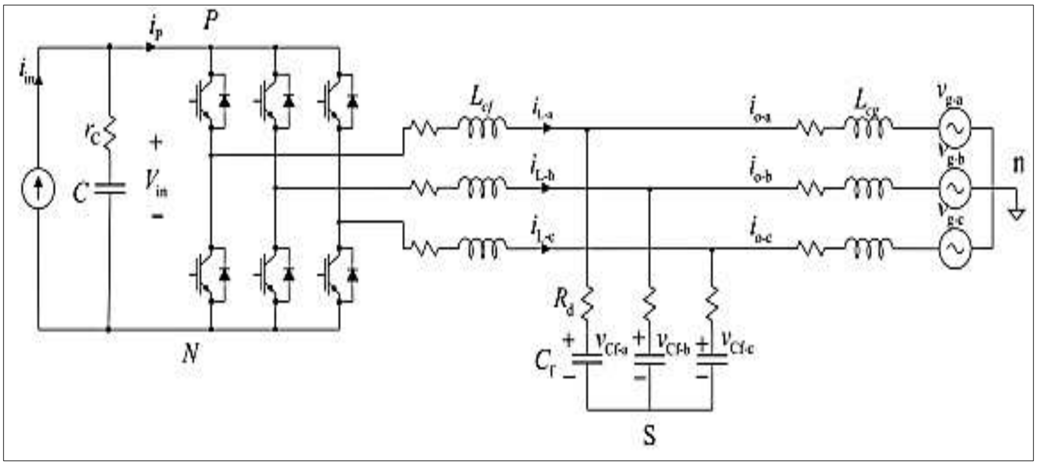


Figure 3 5: Voltage-sourced inverter connected to the grid through an LCL filter (Wang, et al., 2014)

The voltage generated by the PV system is fed across the inverter into the grid. The inverter is set as a voltage source inverter, which is crucial in the study of voltage stability. In the event of voltage instability, the PV inverter is expected to provide reactive power compensation to the electric grid. This is expected in a scenario where the load demand increases beyond the stability margin of the power system. Usually, in a power system, most of the reactive power compensation techniques make use of electrical components such as static var compensator (SVC), static synchronous compensator (STATCOM), and other technology such as shunt capacitor. However, current studies in power systems have promoted the use of grid-connected photovoltaic inverters for reactive power generation (Vlahinić et al., 2019).

3.3.1 Modelling of the DC-Link Capacitor

The DC-link capacitor is the link between the PV array and the input power of the inverter. The capacitor's role is to minimize the ripple in the DC voltage and is controlled to keep the DC voltage $(V_{dc}(t))$ constant. (Memon, 2020). Considering the constant lumped capacitance, the current passing through the capacitor is expressed by the below equation :

$$I_{cap}(t) = c\frac{dv_{dc}(t)}{dt} \tag{3.7}$$

Integrating both sides of equation 3.7 over one time-step (δt):

$$\int_{t-\delta t}^{t} dv_{dc}(t) = \frac{1}{C}\int_{t-\delta t}^{t} i_{cap}(t)dt \tag{3.8}$$

Solving equation 5.5 by applying the trapezoidal rule leads to the discrete approximation of

$$i_{cap}(t) = \frac{2C}{\delta t}[v_{dc}(t) - v_{dc}(t-\delta t)] - i_{cap}(t-\delta t) \tag{3.9}$$

3.3.2 Modelling of the Three-Phase VSI

Photovoltaic modules generate DC, which needs to be transformed into AC to match the requirement of the power system. The inverter is an electronic device that transforms DC into AC. The performance requirement of the inverter is crucial in delivering the required power into the grid. Poor choice of the inverter can lead to poor performance of the microgrid. Photovoltaic inverters are classified into various topologies. The choice of topology determines the connections link between the PV modules and the inverter and their required applications for the inverter. Below figure 3.6 describes different types of inverters used in photovoltaic microgrid technologies

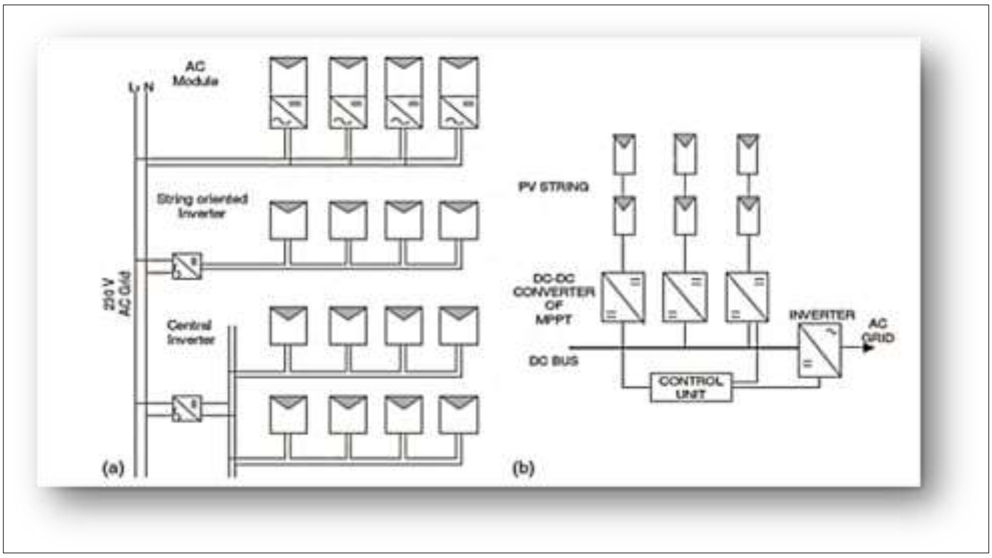


Figure 3 6: **PV inverter configuration. (a) Central inverter, string inverter, AC module. (b) Multi-string inverter (Nema and Agnihotri, 2011)**

- Central PV inverter

  A centralised configuration required a huge number of modules, which are normally tied up to one inverter. Central PV inverters aim to produce a large amount of high voltage. The power range in a centralised configuration can be rated up to 100 MW with a three-phase topology.

- String PV inverter

  In this configuration, each module is connected to the individual inverter. The string name is related to the absence of a blocking diode. The advantage of this configuration is mixed as the inverter can be used in both central and string configurations. This type of inverter is commonly used for small roof-top PV systems with panels connected in one string range between 0.4 to 10 kW of power.

- Multi-string PV inverter

  The configuration represents a mixture of central and string configurations. Many PV strings with their DC_DC converter are connected in parallel to form a PV array. The PV array is further connected to a single inverter. The configuration is used for a medium-large roof-top PV system rated between 10KW to 30 kW of power.

- AC module PV inverter

  For each PV module, there is an individual micro-inverter. This configuration is known as AC-module/microinverter.AC module inverter is known to be the smaller and most complex inverter in PV technology. The inverter type is recommended for a very small PV plant power rating estimated at 500 W(Nema and Agnihotri, 2011).

The above classification of the inverter does not reveal any specific information about the topology and control employed therein. Topology and inverter control are based on the number of stages used in power processing. The technology behind the stage in power processing is classified as a single-stage inverter and multiple-stage inverter (Kolantla et al, 2020). For grid integration under consideration, the centralised configuration will be used for simulation. The inverter is known for its high-rating power capability. The inverter is a two-level voltage source inverter, which is a three-phase legs two-level inverter shown in Figure 3.7.

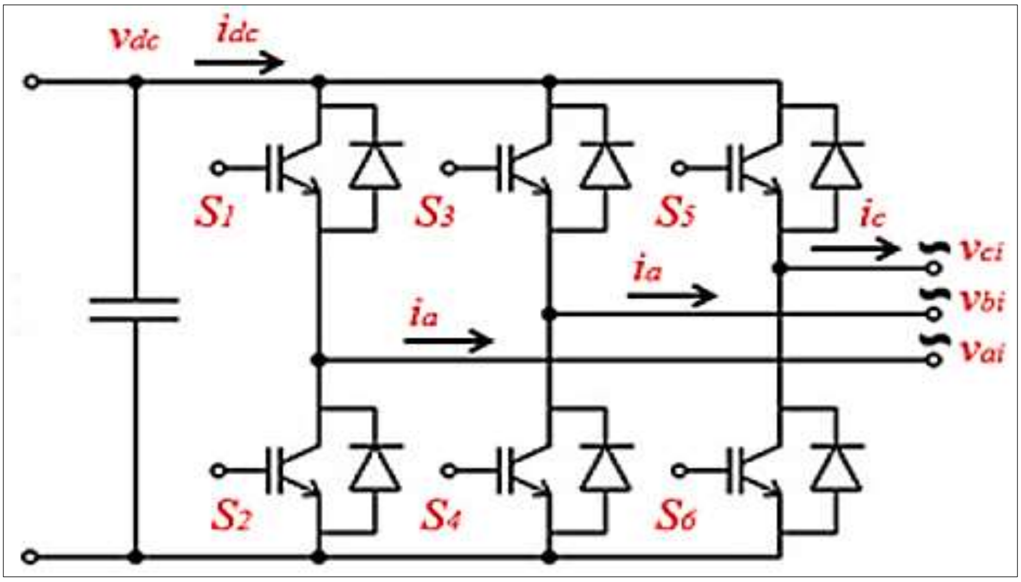


Figure 3 7: **General configuration of three-phase two-level inverter circuit diagram (Hariri, 2017)**

The three-phase two-level inverters are built-in upper and lower levels modes each with a capability switching component having opposite states where if one is open, the other is closed. The switching component is made up of a gate turn-off switch (Gate turn-off (GTO) thyristor, insulated gate bipolar transistor (IGBT)), and an anti-parallel diode. The inverter switching function relates the output AC voltage to the DC voltage and the switching states.

The switches are assumed to be ideal, i.e., they have zero “ON” resistance and infinite “OFF” resistance and have zero turn-on and turn-off times. Both the DC bus negative terminal and the AC system-neutral can be used to calculate the output voltage of the inverter. The output Phase voltage relative to the DC bus negative terminal is expressed as :

$$v_{kN}=S_k \text{x } V_{dc};\ k = a, b, c \qquad (3.10)$$

Where:

S_k correspond to the switching state of the k switch. The switching state is either 1 for the ON state or 0 for the OFF state.

V_{dc} is the input voltage from the PV; and V_{kN} the expression of the total output voltage of the inverter times the number of switches.

If in equation (3.10) $k = a, b, c$;than S_a will correspond to S_1 as respectively S_b to S_3 and S_c to S_5. This correlation between the switches assumes the balanced AC voltage relative to the AC system neutral point, resulting in the equation below :

$$v_{an}+v_{bn}+v_{cn} = 0 \quad (3.11)$$

Moreover, by using simple vector algebra as in the below equation, the output voltage of the inverter can be expressed in terms of the DC negative terminal and the AC neutral point as follow :

$$v_{kn}=v_{kN}-v_{nN} \; ; k = a, b, c \quad (3.12)$$

By combining equations (3.11) and (3.12), we have

$$v_{nN} = \frac{1}{3} (v_{aN} + v_{bN} + v_{cN}) \quad (3.13)$$

Lastly, substituting (3.13) into (3.12) and expressing v_{kN} in terms of equation (3.10) results in the inverter three-phase line-to-neutral AC voltage representations in equations (3.13) to (3.15) below :

$$v_{an}=V_{dc}[\frac{2}{3} S_a-\frac{1}{3}(S_b+S_c)] \quad (3.13)$$

$$v_{bn}=V_{dc}[\frac{2}{3} S_b-\frac{1}{3}(S_a+S_c)] \quad (3.14)$$

$$v_{bn}=V_{dc}[\frac{2}{3} S_c-\frac{1}{3}(S_a+S_b)] \quad (3.15)$$

The current from the DC side can be expressed in terms of the switch states and the AC phase currents according to equation (3.15)

$$i_{dc}= \sum_{k=a,b,c} S_k \times i_k \quad (3.16)$$

From the above equation, the inverter AC voltage can be determined regardless of the AC loads connected to it because of their dependence on DC voltage and the state of the inverter switches. However, the inverter output It is noticed that the inverter AC voltages are calculated regardless of the AC loads since they only depend on the DC voltage and the states of switches. However, the inverter output AC currents i_a , i_b , i_c depend on the AC load linked to the inverter.

3.3.3 The RTDS inverter modelling

The grid-connected PV plant is linked to the power system via a suitable inverter since the PV module delivers only DC power. The RTDS inverter modelling can simulate sub-networks containing IGBTs and additional devices, which are ideal switches. The component as modelled is described as a Voltage Source Converter (VSC). The VSC circuit in RCAD/RTDS is referred to as a sub-network and it is the ability to be interfaced with the main network. The sub-network is solved with a time-step size of 50μs while the VSC is solved and requires a time-step of 1.4 to 2.5 μs.

The Voltage source converter (VSC) switching frequencies are mostly in the scale of 1 to 4kHz. Due to these, the two level VSC is developed in RSCAD within a small timestep sub-network known as BRDG1 in Figure 3.8. This sub-network is solved within a time frame of 1.4 to 3 $\mu secs$, making possible the simulation of the high switching frequencies of the voltage source converter in RSCAD/RTDS. A further key characteristic of these smaller timestep networks during simulation is that they can outstand a broad variety of power system components which allow the user to perform different kind of simulation of the entire power systems in the smaller timestep environment. The simulation can include large transmission lines, machines, subnetwork with their complexity and size.

The transfer of voltage and current between the sub-network and the VSC is done through the bridge interface between the large and small time-step portions for the simulation. The bridge interface allows voltage and current information to move from the large time-step side to the small time-step side and vice versa. The PV array in RSCAD/RTDS is first connected to the DC bus, and later to the AC grid via a DC/AC power inverter. During real-time simulation in RTDS, the firing pulses action on the switching device of the inverter are subject to the comparison between the Controlled Sinusoidal Reference (CSR) and a triangular wave supplied by the firing pulse generator component (Pinheiro et al., 2016).

Figure 3.8 shows the design and function of a 2-level small steps VSC in RTDS. The AC output power from the inverter goes through a filtering stage before going through the single-phase interface transformer, which connects the main power system to the small time-step sub-network. An additional setup transformer may be required to furthermore set up the voltage to the grid requirement.

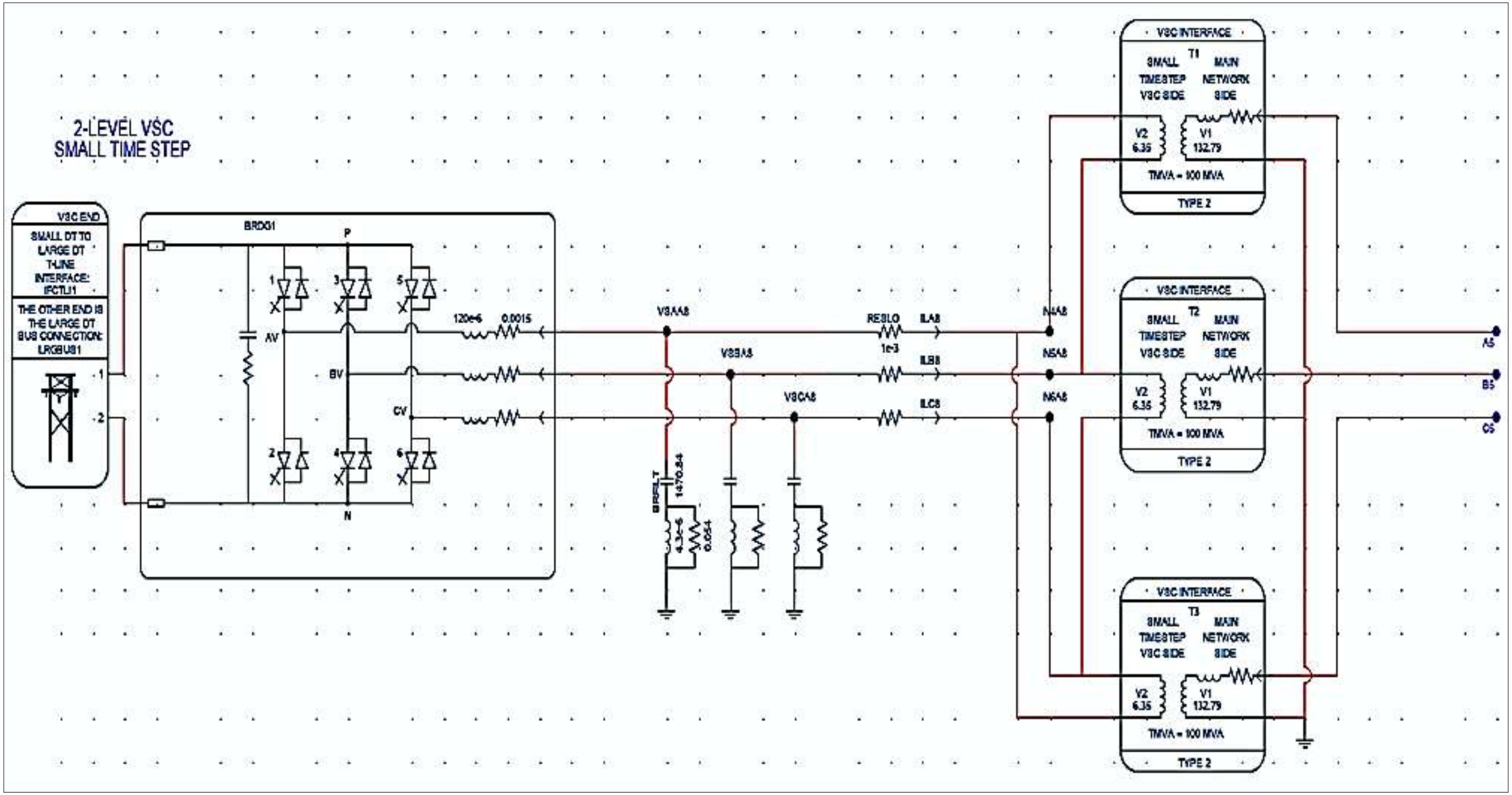


Figure 3 8: Small Time-step Subnetwork interface settings in RSCAD/RTDS (RTDS hardware manual, RTDS Technologies,2009)

The small time-step circuit constructed in RSCAD for the interface of the PV system with the main network consists of the small-time step VSC T-line branch, the 2-Level VSC bridge, three-phase reactor in series with resistance, high pass filter-branch, and the VSC interface transformer branch. Furthermore, the small time-step has a feature that makes it easy to interconnect and adapt to any size of the power system.

The small-time step VSC interface transformer which connects the AC side of the inverter to the grid has a scale factor to increase the amount of current injected from the PV generator to the power system grid. Therefore, opting for the option to 'include scaling influence on large DT' in the configuration menu shown in Figure 3.9 shows the scale factor of the transformer can be used to control the outpower generated by the solar plant without changing the array and control parameters of the PV. If only update the VCS interface transformer to a grid level and in some cases the number of series and parallel modules. Figure 3.10 shows the scale factor slide used in the RSCAD/RTDS configuration is presented.

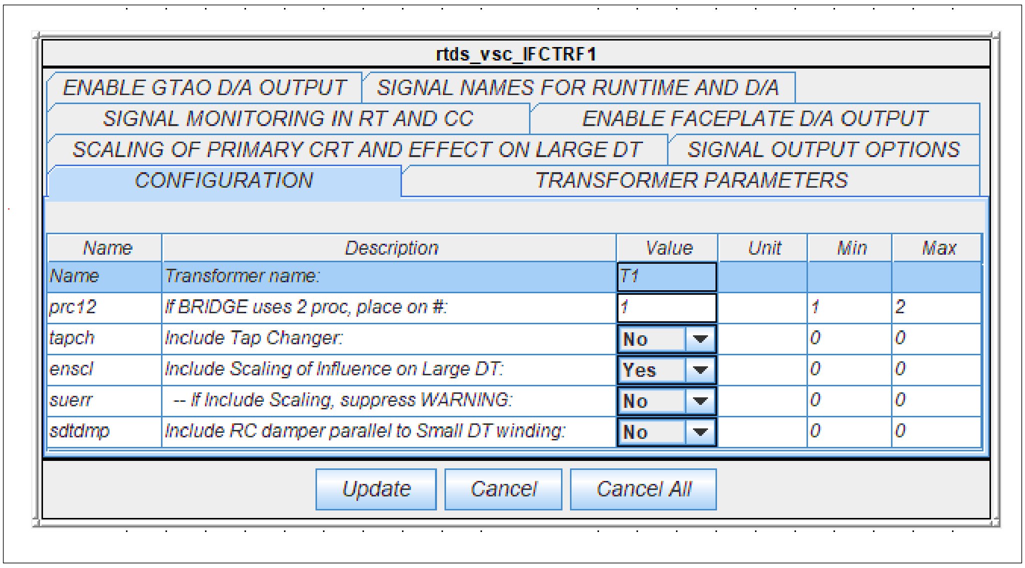


Figure 3 9: **Scale factor configuration setting for VSC interface transformer (Gbadamosi, 2017)**

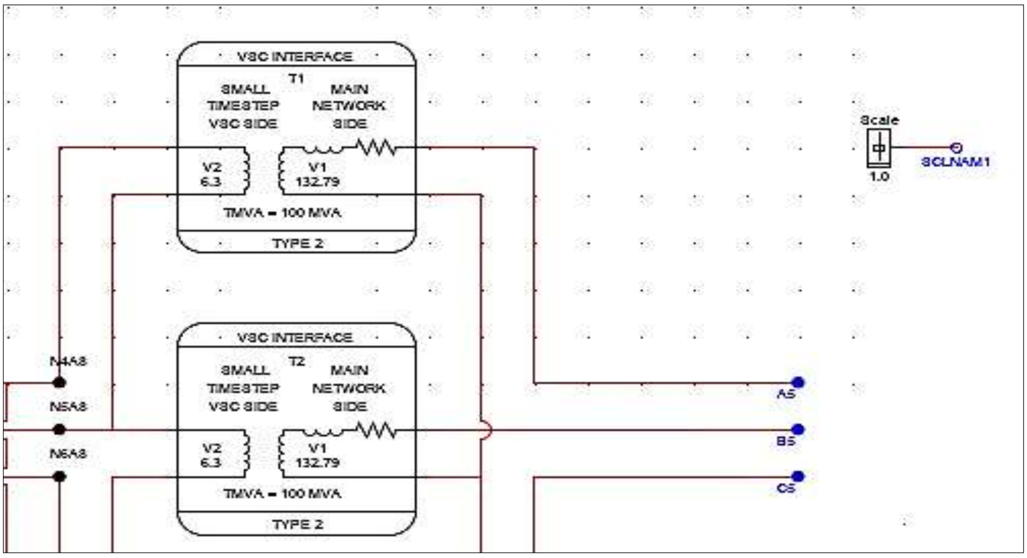


Figure 3 10: **VSC Interface Scaling Slider for power tuning. Available: https://erigrid.eu/wp-content/uploads (2018)**

The scale factor slide used in the RSCAD/RTDS is important during simulation when a scenario on the impact of variation of PV power is needed to be investigated. Using the scale factor, the user can create different scenarios of simulation that can lead to Over voltage or undervoltage at the point of common coupling and in some areas of the power system. All without changing the initial parameters of the PV system.

3.2.4 The efficiency of the inverter

The efficiency of the inverter, which is known as the ratio of the utilizable AC output power to the amount of the generated DC input power determines the loss of power from the PV modules.

The expression of the inverter efficiency is determined by :

$$\eta_{\mathrm{Inverter}} = \frac{P_{out}}{P_{in}} \times 100\% \quad (3.17)$$

Where

η_{Inverter} is the inverter efficiency in %

P_{out} is the AC output power from the inverter

P_{in} is the DC input power from the PV modules.

By converting DC to AC some of the DC power is lost in the process of transformation. The losses are caused by the heat loss dissipation from the inductance and ohmic resistance of the inverter or again by the inverter's ability to keep some standby power for its standby operational mode. The loss of power is therefore estimated between 20% to 30% in many cases (Literski et al., 2016). The loss in the conversion of DC to AC determines the efficiency of the inverter (Mertens, 2014).

Characteristically, the inverter efficiency curves in figure 3.11 show that the efficiency of the PV is less when the PV output power is below 10-15% of the total output power, and this efficiency is accordingly increased when the output power is greater than 15%. The inverter load ratio is one of the most important factors in PV plant design. The load ratio of the inverter determines how much the inverter will deliver into the grid after the DC power is transformed into AC power.

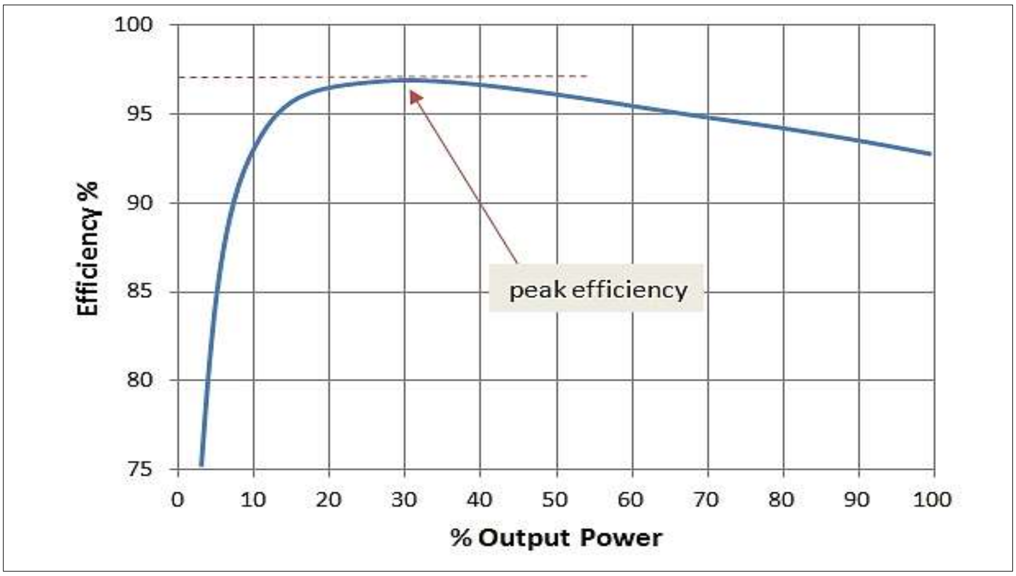


Figure 3 11: Basic generic inverter efficiency curve. Below 10 to 15% of the output power, the efficiency is quite low. For high output power, the efficiency is steadily high (Literski et al., 2016)

The ratio of the DC PV plant and the AC output. The DC input power of the inverter is expected to be about between 20% and 30% of the AC output power rating. This corresponds to the inverter load ratio (ILR) of 1.30. Based on the ratio of the ILR, the inverter DC input is not expected to be above the AC output of the inverter, A 30% less power is expected to be rated AC power of the PV plant. Therefore the inverter load ratio is a metric of inverter operation (Literski et al., 2016).

3.2.5 Harmonic LC filter

Because the photovoltaic system delivers DC power, which is then pass-through electronic devices that convert the DC signal to AC signal by using Pulse Width modulation switching (PWM). The interference of PV to the electrical grid can cause some power quality issues, such as residual DC, harmonics, or unbalance. High penetration of solar power into the electrical network may cause harmonic distortion. Harmonic distortion much as voltage instability constitutes a danger to the stability of the grid. Just like any other power generation unit, large solar power can be a source of harmonics that affect the power quality when connected to the power system. Because solar inverters produce high-frequency harmonics, and even they are usually limited to a tolerable level for the interconnection to the grid. The power system grid needs to be equipped with harmonic filter devices that reduce harmonic distortion in the power system (Fritz, 2019). Figure 3.12 below describes a design model of harmonic filter in RSCAD/RTDS

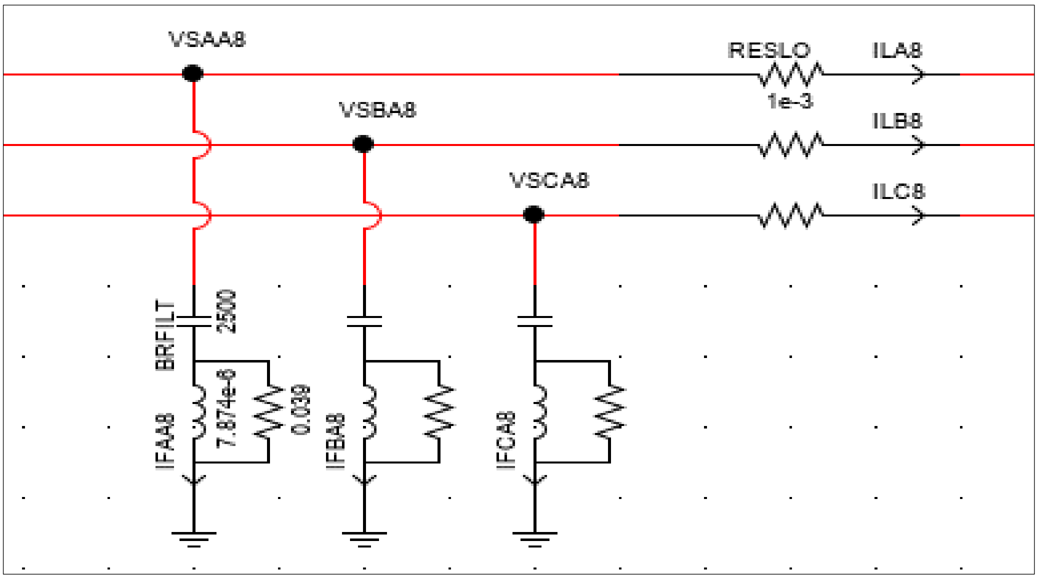


Figure 3 12: **Modelling of updated harmonic filter for RSCAD testbench. (2016). available:https://www.rtds.com/technology/modelling-library**

LC type filter in RSCAD/RTDS in Figure 3.12 is made of the capacitor, resistance, and inductance. These devices are built in parallel with the inverter AC output power. The harmonic filter regulates the total output harmonic distortion (THD) to an acceptable level for Grid integration.

3.2.6 Power Transformer

The integration of the PV power plant into the electric grid is done via a power transformer. Unlike the inverter, the transformer in the power system is crucial mainly when the PV inverter has a reactive power control system. Having in mind that the winding of the transformer is either star-start or start-delta with both having a neutral earthed, the configuration of winding is very important when dealing with integrated PV into the grid, particularly in the case where the reactive power controller of the PV support the voltage regulation of the grid (Tumbelaka et al., 2018).

The choice of the connection winding of the transformer may affect the inverter control capability of delivering the appropriate reactive power into the grid. Because some winding connections may create a phase shift in the line current passing through both sides of the transformer. There is a possibility of injecting incorrect output power than the recommended reference values of power by the inverter controller (Plants *et al.*, 2020).

Hence the appropriate winding connection of a step-up power transformer is star-delta where the delta winding is connected to the high voltage of the power system and the star winding to the output terminal of the PV inverter, which is the lower side of the voltage. For the efficiency of the system, the delta winding provides a better current balance and phase shift for the grid. It also prevents the zero-sequence current from flowing into the grid (Tumbelaka et al., 2018).

3.4 Discussion

The primary objective of the PV module is to produce electricity either in island mode or integrated mode into the power system. Photovoltaic modules are described as solid-state devices that convert sunlight into electricity without any intervention of a heat engine or rotating mechanism. The electricity produced by PV is a direct current that needs to be converted into an alternating current using appropriate technology to ensure its integration into the power system. The technology surrounding the conversion of PV energy into a suitable current for the power system is facing many challenges that require a proper understanding of the problem of PV applications. One of the key problems to consider when integrating the PV into the power system is the absolute efficiency of the PV. The efficiency of the PV plant is regarded as a backbone upon which the reliability and delivery of the integrated PV into the power system is relied on. By considering all the implicated components in the realisation of the PV plant, an efficient and reliable PV plant is achievable to be implemented in the power system.

3.5 Conclusion

This chapter has presented a comprehensive theory of the photovoltaic technology as integrated into a power system subjected to load increase is presented. A detailed description of the photovoltaic system is proposed. From cells, and modules to arrays solar power are crucial in energy generation where there is a shortage of electricity and a need for clean energy.

Additionally, the chapter discussed the integration of PV in power systems. The benefits and various effects of their integration into the power system have been detailed. Voltage stability is one of the various problems, which was discussed. Considering their high penetration in cripple grids with voltage issues. PV systems may have detrimental effects on the system if the amount of power is not regulated to meet the need of the power system. To regulate the output power of the inverter, a Volt-Var controller scheme was proposed. The control aim is to match the amount of active and reactive power from the inverter to the reference amount at the point of common coupling. The control strategy is to inject only the amount of power needed. The control ability allows the inverter to intervene when the power failed below the threshold as set by the grid code.

Considering the grid code requirements which define voltage stability in a power system with a microgrid, it can be stated that a PV inverter with Volt-Var control capability is adequate to solve the issue of voltage stability in a power system with integrated PV.

CHAPTER FOUR
SYSTEM ANALYSIS OF IEEE-9 BUS

4.1 Introduction

The IEEE 9 bus transmission network is under consideration. The analysis of the power system in DIgSILENT power factory software and RSCAD/real-time digital simulator (RTDS) allows the power system to be tested for grid performance. This chapter addresses two different approaches to power system modelling and simulation. The first approach relates to the implementation of the 9-bus system in the DIgSILENT power factory.

The aim is to perform a load flow analysis, the contingency analysis, and a disturbance of voltage by increasing the load consumption by 35% with an increment of 5% every 2 seconds until the voltage reaches a point of instability. The second approach in this chapter relates to the modelling and simulation of the 9-bus system in RSCAD/RTDS for validation of the non-real model of DIgSILENT in real-time simulation. The results for both simulations provide a deep understanding of the power system performance under disturbance due to an increase in load demand.

The key point in the validation of non-real-time simulation results (DigSilent) in real-time simulation (RSCAD/RTDS) is to determine the degree to which the simulation design and its related data are an accurate interpretation of the actual word (Sargent, 2020). Section 4.2 discusses the design and analysis of the power system under investigation. In this section, an introduction to the modelling of the IEEE 9 bus system is presented. The power flow analysis in both software DigSILENT and RSCAD/RTDS is summarised.

Section 4.2 focuses on the test benchmark investigation of the IEEE 9 bus in the DigSILENT power factory. In this section, the load flow analysis, the contingency analysis, and the impact of the load consumption are discussed. While the load flow is used to establish the state of the operation of the power system, the contingency analysis on the other end is used in the power system to investigate system vulnerabilities and possible remedial solutions to consider when such vulnerabilities occur in the power system. The section concludes with the impact of increased load consumption on the power system. The aim of increasing the load consumption is to demonstrate how the variation of load consumption may lead to voltage instability if the power consumed by the load exceeds the grid capability to generate the appropriate amount of power to be consumed by the load

In section 4.3, the focus is to investigate the IEEE 9 bus system in real-time simulation using RTDS. In this section, the load flow analysis of the IEEE 9 bus system and the impact of disturbance on the voltage profile are investigated in real-time simulation. The chapter comes in section 4.4 to an end with the discussion of the results of both simulations in DigSilent and RTDS. A conclusion of the chapter is also presented in section 4.5.

Network design and IEEE 9 bus system analysis: The network represents a transmission network made of 9 buses, six lines, three generators, three loads, and three transformers. The different parameters for all individual elements of the network are detailed in Appendix A. Figure 4.1 below is the representation of the One-Line Diagram illustration of the IEEE 9 Bus Power System. Because of its radial structure and the ideal placement and sizing of the generators, the network is likely to develop a deteriorate voltage profile, which is ideal for a perfect test benchmark for voltage stability study.

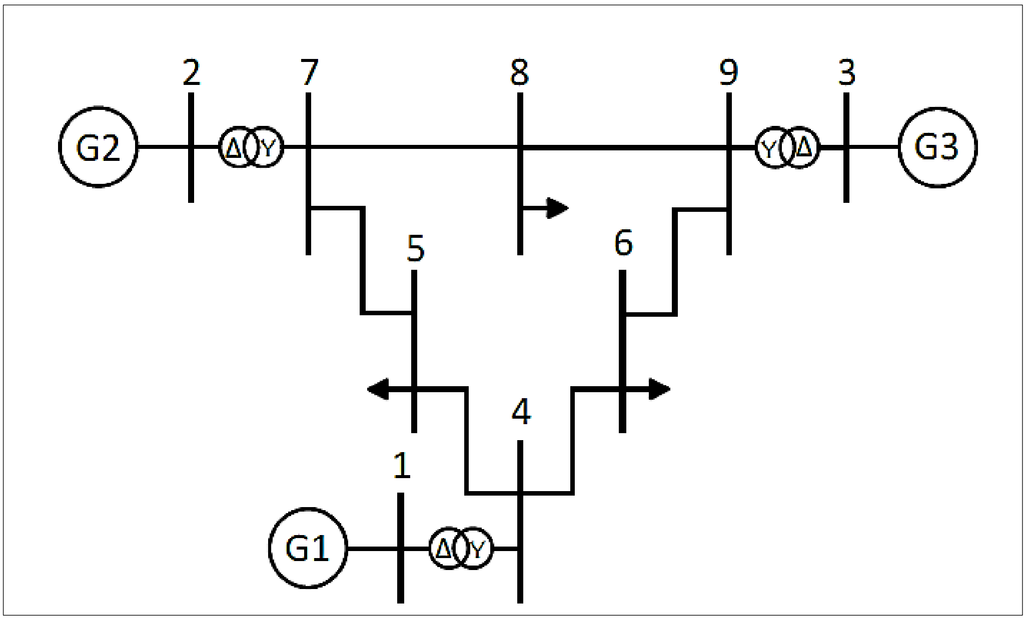


Figure 4 1: **IEEE 9 bus power system**

4.2 Test Benchmark Investigation in DIgSILENT

The investigation of the system stability is carried out using the DigSILENT power factory. In this section different steps of the investigation of the system performance and voltage stability study are presented with the aim to understand the system performance under normal and abnormal conditions. These steps are crucial in establishing the suitability of the IEEE-9 bus system as a reliable benchmark test for the impact of a microgrid on voltage stability considering the disturbance.

4.2.1 Load Flow Analysis

Load flow analysis is the most crucial method for investigating problems in electrical power system operating and design. The Based-on IEEE 9 bus system explains the steady operation state with bus voltages and power flow in the grid. The load flow analysis in DIgSILENT is used to confirm that each component of the system runs at the optimum operating point; demand will be met without overloading the power system. The grid code set the normal operating voltage range between 0.95 p.u to 1.05 p.u. Figure 4.2 shows the busbars voltages as measured, the lines loading, and generated power as a color-coding index, which helps to determine the violation of voltage in the system.

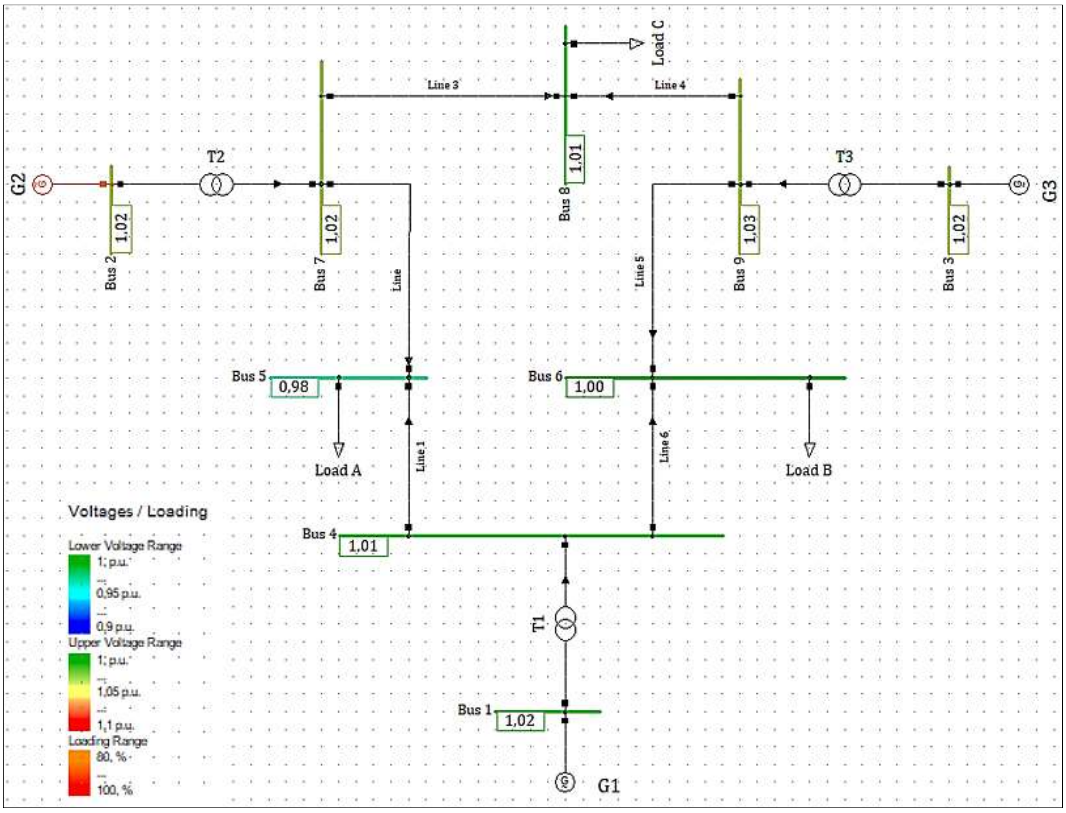


Figure 4 2*:* Simulation outcome of the IEEE 9 bus system in DIgSILENT

The results of the load flow simulation show that the power system is stable since all voltages in the system are within the acceptable range of voltage as per the grid code. Below in table 4.1 on the next page are the result of the load flow analysis of the IEEE

9-bus system in DIgSILENT in power factory software. These results are compared to the results provided by the IEEE 9 bus data sheet of the system under investigation.

Table 4 1: **Load flow results from IEEE 9 bus compared to load flow results from DIgSILENT**.

Bus number and Type		Bus u, Magnitude [p.u.] profile from IEEE 9 bus datasheet	Bus u, Magnitude [p.u.] profile from simulation in DIgSILENT power factory
Bus	**Type**		
1	P-V	1.040	1.040
2	P-V	1.025	0.998
3	P-Q	1.025	1.025
4	P-Q	1.026	1.017
5	P-Q	0.996	0.974
6	P-Q	1.013	1.004
7	P-Q	1.026	1.00
8	P-Q	1.016	0.992
9	P-Q	1.032	1.023

In table 4.1, the IEEE result of the load flow analysis of the 9-bus system is compared to the experimental result in DIgSILENT. Results show that experimental results using the software DIgSILENT are identical to the IEEE 9 bus data sheet. Figures 4.3 and 4.4 show the load flow result performed in DIgSILENT. The result proves that the magnitudes of the voltages at all buses in the system are stable and within the permissible voltage index for a stable power system. Figure 4.3 describes the voltage profile per bus in the entire system. The bar chat shows the average voltage of a steady system under consideration.

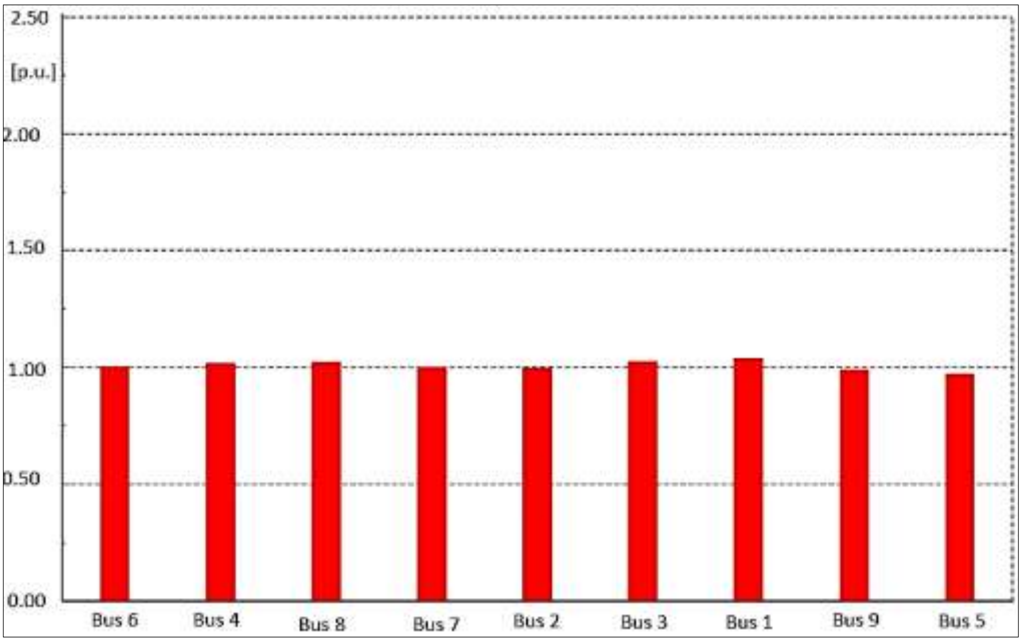
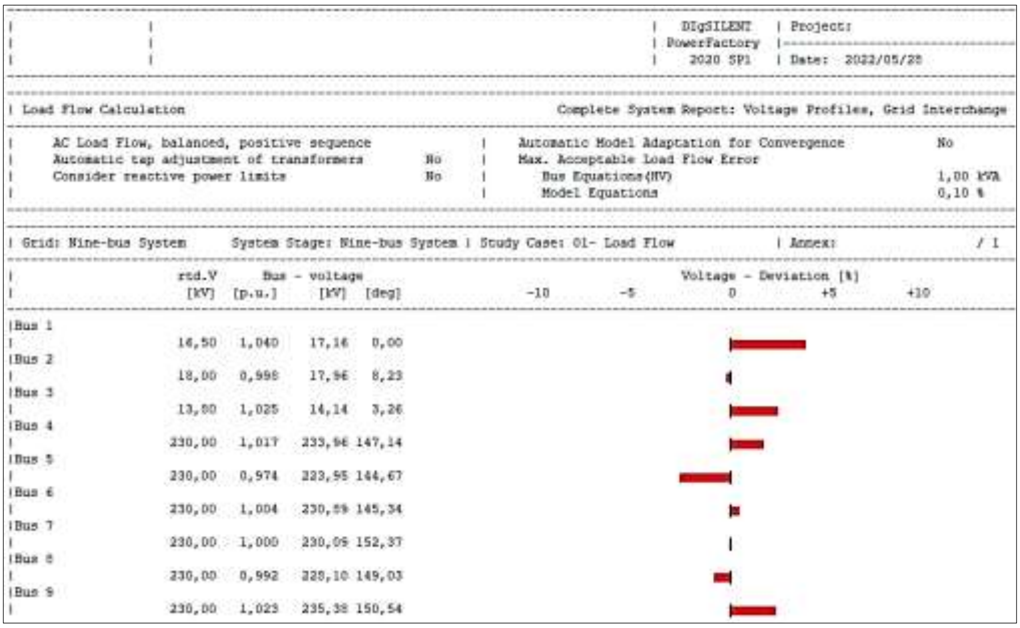


Figure 4 3: **Bar diagram showing voltages magnitude of each bus bar in DIgSILENT**



DIgSILENT PowerFactory 2020 SP1 | Project: | Date: 2022/05/28

Load Flow Calculation — Complete System Report: Voltage Profiles, Grid Interchange

AC Load Flow, balanced, positive sequence		Automatic Model Adaptation for Convergence	No
Automatic tap adjustment of transformers	No	Max. Acceptable Load Flow Error	
Consider reactive power limits	No	Bus Equations(HV)	1,00 kVA
		Model Equations	0,10 %

Grid: Nine-bus System | System Stage: Nine-bus System | Study Case: 01- Load Flow | Annex: / 1

	rtd.V [kV]	Bus - voltage [p.u.]	[kV]	[deg]
Bus 1	16,50	1,040	17,16	0,00
Bus 2	18,00	0,998	17,96	8,23
Bus 3	13,80	1,025	14,14	3,26
Bus 4	230,00	1,017	233,96	147,14
Bus 5	230,00	0,974	223,95	144,67
Bus 6	230,00	1,004	230,89	145,34
Bus 7	230,00	1,000	230,09	152,37
Bus 8	230,00	0,992	228,10	149,03
Bus 9	230,00	1,023	235,38	150,54

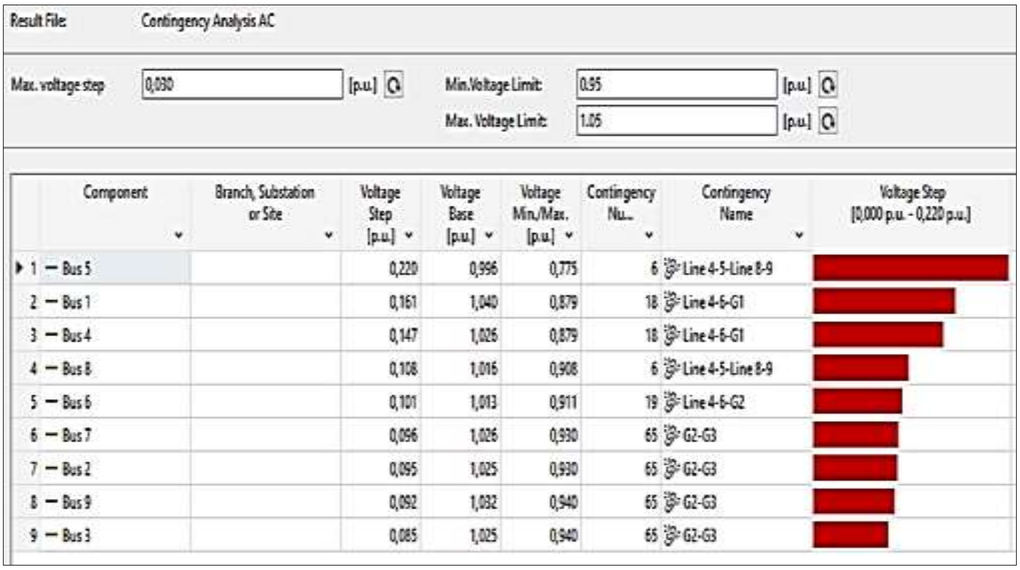
Figure 4 4: **The results of the load flow calculation performed in DIgSILENT**

4.2.2 Contingency analysis

Contingency analysis is described as a crucial task in modern Energy Management Systems (EMS). The purpose of the contingency analysis in the power system is to provide the operator with information about the static security of the grid (Chen, 2011). By performing a contingency analysis, the power system discloses accurate information about potential violations that lead to system instability or total system collapse. It also gives remedial action to remove such violations.

Using the DIgSILENT power factory, the contingency analysis is carried out by defining a fault case for all lines and buses bar of the system. In this research, for instance, an analysis of line fault is executed by selecting all the lines of the system and subsequently running an analysis using the option contingency analysis in the DIgSILENT tab. The result of the analysis is automatically compared to the threshold of the voltage level set to 0.95 p.u for lower voltage and 1.05 p.u for upper voltage. This voltage limitation can be defined according to the utility grid requirements.

The analysis displays the base case of the capability loading of each line and busses in the system. Further reports for severe violations can be requested to emphasize the cause of the violation that led the voltage to collapse at a certain point in the system. Not only, does the contingency analysis describes the type of fault involved in voltage collapse but also provides a remedial situation. Figure 4.5 below describes the results of the contingency analysis of the IEEE 9 bus system performed in DIgSILENT.


Result File: Contingency Analysis AC

Max. voltage step: 0,030 [p.u.] — Min.Voltage Limit: 0.95 [p.u.] — Max. Voltage Limit: 1.05 [p.u.]

	Component	Branch, Substation or Site	Voltage Step [p.u.]	Voltage Base [p.u.]	Voltage Min./Max. [p.u.]	Contingency Nu...	Contingency Name	Voltage Step [0,000 p.u. - 0,220 p.u.]
1	Bus 5		0,220	0,996	0,775	6	Line 4-5-Line 8-9	
2	Bus 1		0,161	1,040	0,879	18	Line 4-6-G1	
3	Bus 4		0,147	1,026	0,879	18	Line 4-6-G1	
4	Bus 8		0,108	1,016	0,908	6	Line 4-5-Line 8-9	
5	Bus 6		0,101	1,013	0,911	19	Line 4-6-G2	
6	Bus 7		0,096	1,026	0,930	65	G2-G3	
7	Bus 2		0,095	1,025	0,930	65	G2-G3	
8	Bus 9		0,092	1,032	0,940	65	G2-G3	
9	Bus 3		0,085	1,025	0,940	65	G2-G3	

Figure 4 5: **Contingency analysis results of the 9-bus power system**

Bus 5 is the critical bus with maximum voltage and minimum voltage of 0.996 p.u. and 0.775 p.u., respectively. The contingency analysis is performed for the outage level of the “n-1” case where an outage of generator 3 or a loss of lines 4-5 triggers the collapse of voltage at bus 5. The lower the voltage is at bus 5, the rise of voltage at the same bus is likely to be larger once the microgrid is integrated into the power system. This will likely allow all parts of the power system to operate at a steady state.

The contingency analysis leads to the detection of the weakest bus in the power system. Power system engineers also use the method of the Power-Voltage (P-V) curve to detect the critical bus in the system. The method of the P-V curve is achieved using sequences of load flow iteration for incremental power allocations at a constant power factor to find the relationship between voltage and power transfer in the system (Chary et al., 2017). The above-mentioned relationship between power and voltage is used to plot the P-V curve of the 9-bus power system under investigation. Figure 4.6 below describes the voltage curve of bus 5 of the IEEE 9 bus power system.

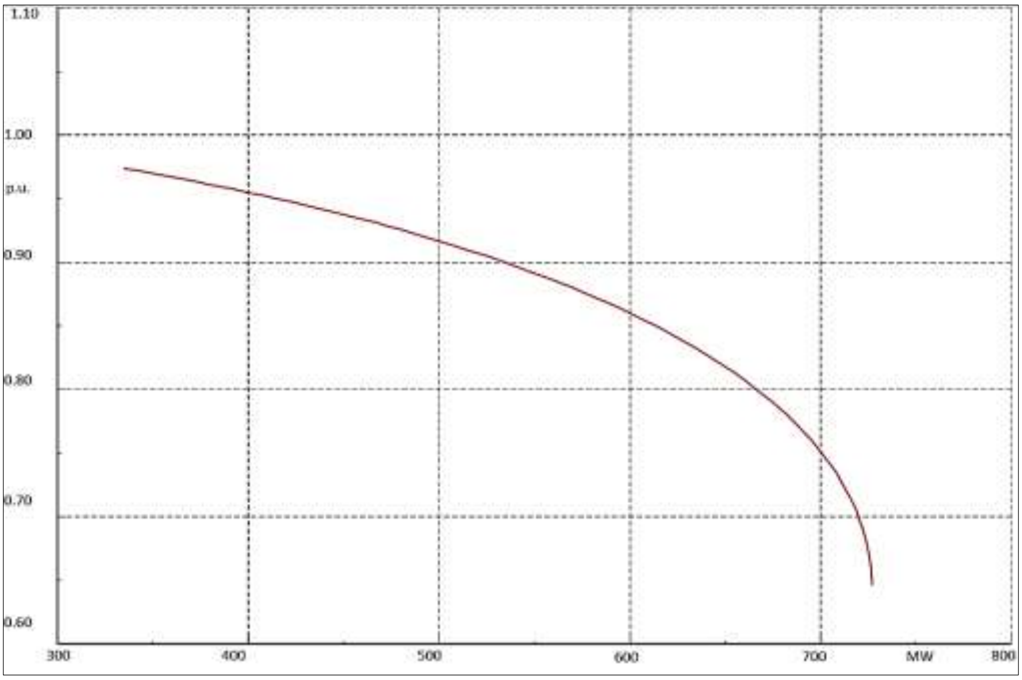


Figure 4 6: **As per the PV curve method bus 5 is the critical bus in the system.**

The method of acquiring P-V Curves requires a sequence of load flow results by adjusting the real power (MW) transfer from supply toward the load and consequently, a variation of voltage at various buses is observed. Because of the impact of electrical phenomena such as power transfer across the electrical network, power factor of the load, and the reactance of the line the voltage at a specific bus may be increased or decreased its magnitude. While the load demand is increased voltage supply declines and gets to a nose point, any additional escalation in load demand leads to the instability of the power system.

A demonstration can be made by taking into consideration a simple electrical system involving a voltage source $E\angle 0$ and load at voltage $V\angle\delta$ fed by an infinite bus as a transmission system. If the resistance of the transmission line is not considered, the active and reactive powers are presented by Equations (4.1) and (4.2).

$$P = \frac{EV}{X}\sin\delta \quad (4.1)$$

$$Q = \frac{EV}{X}\cos\delta - \frac{V^2}{X} \quad (4.2)$$

P-V curves display the link between the load in MW in a specific section and the bus voltage for various power factors (where. $\tan ø = \frac{Q}{P}$) as the load angle is not considered for this study it can be eliminated.

Let $p = \frac{PX}{E^2}, q = \frac{QX}{E^2}\ and\ v = \frac{V}{E}$

By regulating the Equations (4.1) and (4.2) in consideration of the short circuit power.

$$s = \frac{E^2}{X}$$

Then we get.

$$p = v\sin\delta \quad (4.3)$$

$$q = \cos\delta - v^2 \quad (4.4)$$

To preserve the voltage stability of the power system, Power dispatch from the generator to the loads needs to be regulated to the capacity of load demand to avoid the bus voltages to operate close to the critical voltage point at the PV curve.

4.2.3 Load event as disturbance

The power system grid is constantly dealing with the increase in load consumption. A load increase in the power system can affect the normal operation of the system by creating a disturbance. To simulate the disturbance in the power system, a case study was implemented by increasing the load consumption by 35% with an increment of 5% every two seconds on the simulation until the voltage collapsed. DIgSILENT power factories offer a possibility to execute such disturbance through a simulation called load event.

Figures 4.7 and 4.8 describe the configuration steps to follow when creating a load event in the power factory. The parameters in figure 4.7 consist of the type of graph expected, which can be ramp or step, the time of the start of the simulation which corresponds to the number of stages, and lastly the increment percentage of both active and reactive power.

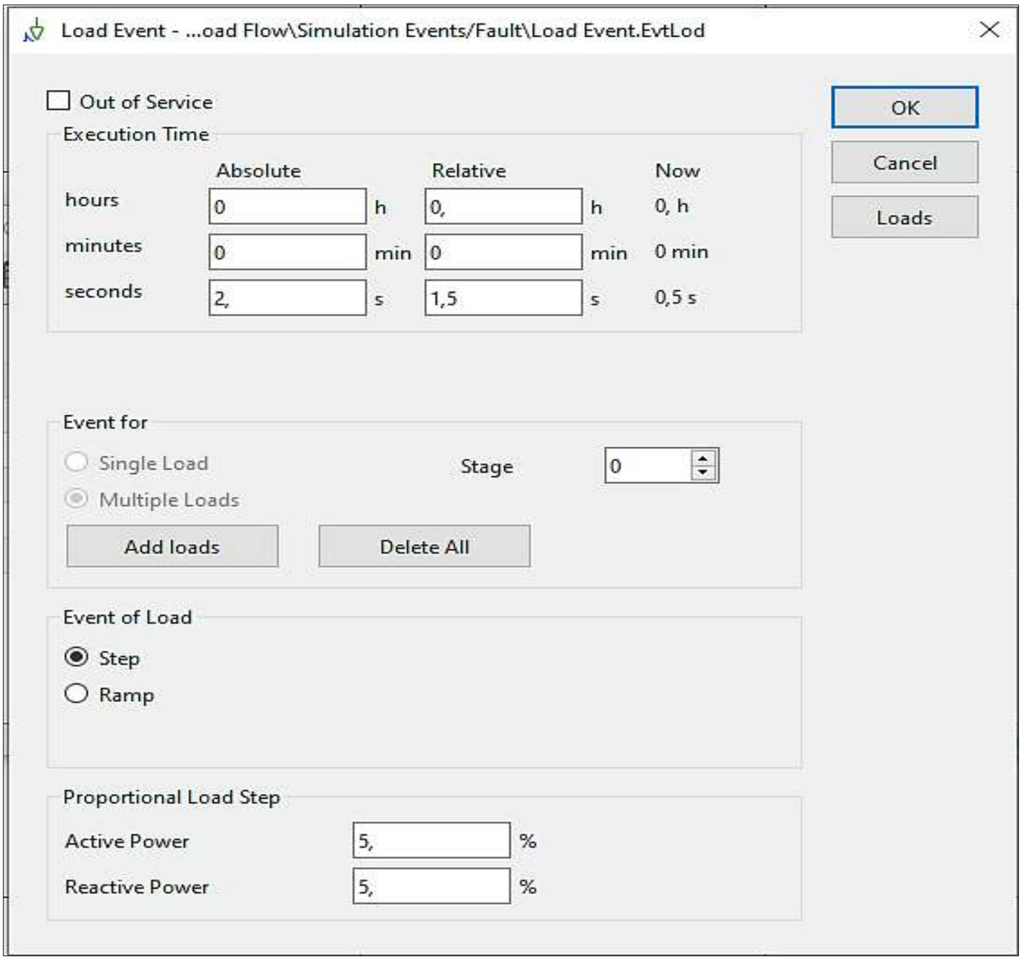


Figure 4 7: **parameters configuration of load event in DIgSILENT**

Figure 4.8 shows the number of stages, and their respective time of start are computed. These parameters are used to show the increment pattern on the output graph when a load event is requested. The dynamic change of the load, which is caused by the increase in power demand can be presented through a graph using these parameters.

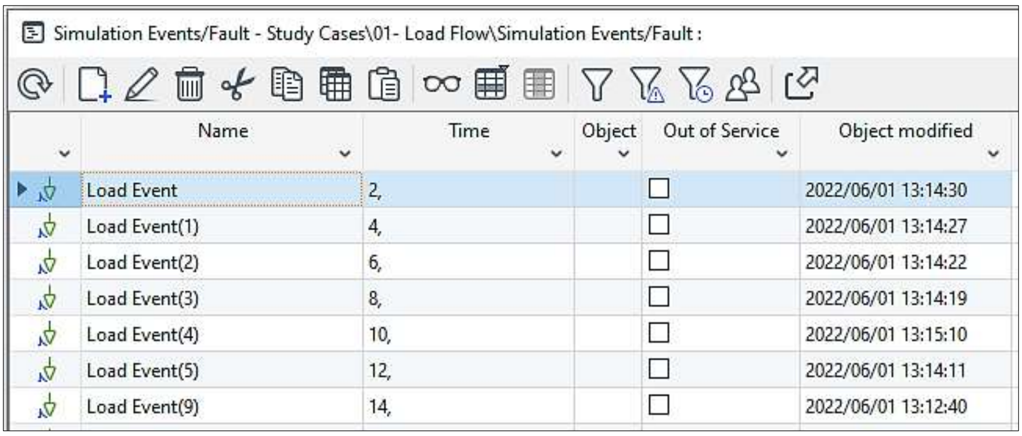


Figure 4 8: **Configuration stage of load event for dynamic load change in DIgSILENT**

Figure 4.9 below shows the results that describe the impact of the disturbance on the voltage magnitude of bus 5, bus 6, and bus 8 when the consumption of the loads is subject to an increase of 35% from their initial value. The graph shows a dynamic increment in the stages of 5% every 2 seconds of the event. The dynamic change of load consumption pushes the system to operate beyond its stability. Thus, creating voltage instability.

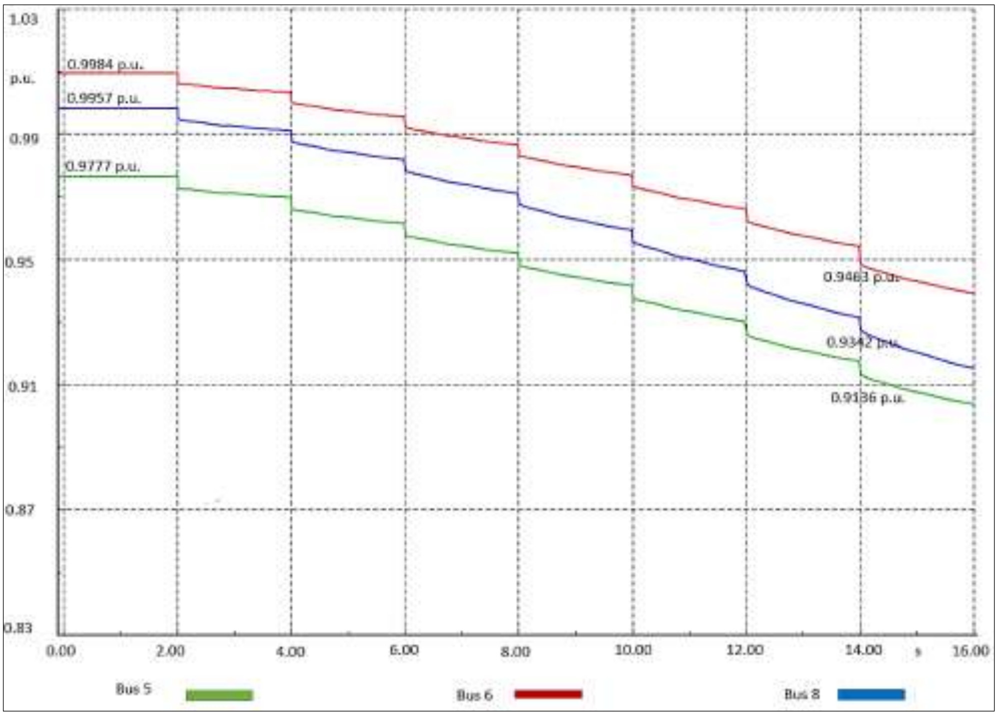


Figure 4 9: **Voltage variation at bus 5, bus 6, and bus 8 due to a 35% increase in load demand**

The illustration shown in figure 4.9 above consists of increasing the consumption of the load until the entire system or one part of it becomes unstable. When the disturbance is induced in the power system at the start of the simulation until eight seconds, the voltage magnitude at bus bar nodes of the electrical network remains within the acceptable range for safe grid operation, but after eight seconds of the simulation time, the voltage starts dropping beyond the threshold of 0.95 p.u. with bus 5 being the first to be affected. At 35% load consumption increase, after 16 seconds of the simulation, the voltage magnitude in the rest of the network is affected with bus 5 dropping from 0.980 p.u to 0.9126 p.u. bus 6 from 1.005 p.u to 0.9455 p.u. and lastly bus 8 from 0.921 p.u. to 0.933 p.u.

Consequently, the voltage at these buses becomes unstable. Table 4.2 below presents the result of voltage drop on each bus of the system when all the loads demand are increased by 35% from their initial value.

Table 4 2: System disturbance result compared to a base case result in DIgSILENT shows the deviation in voltage

9-bus base case simulation results in Power Factory		9- bus system results after disturbance due to load event in Power Factory		
Bus	**u, Magnitude [p.u.]**	**TYPE**	**Bus**	**u, Magnitude [p.u.]**
1	1.040	SLACK	1	1.003
2	0.998	P-V	2	0.950
3	1.025	P-V	3	0.96
4	1.017	P-Q	4	0.967
5	0,974	P-Q	5	0.9126
6	1.004	P-Q	6	0.9463
7	1.	P-Q	7	0.9440
8	0.992	P-Q	8	0.9342
9	1.023	P-Q	9	0.962

The result shows that the disturbance creates in the power system due to a 35% load increase in the stage of 5% every two seconds managed to drop the voltage beyond its stability threshold of 0.95 p.u. Consequently, creating a scenario of voltage instability in the power system. The purpose of the voltage stability threshold is to reveal just how close a specific point of voltage magnitude is within the range accepted of the steady-state voltage stability margin. The simulation results are detailed in Table 4.3 on the next page.

As per the grid code, the power system is expected to operate continuously within the range of 0.95 p.u to 1.05 p.u, which makes a 5% deviation acceptable for voltage stability. Beyond the threshold of 0.95 p.u, the voltage becomes unstable (Juliana and Mwale, 2015). The table below is a description of the minimum and maximum threshold for voltage stability as described by the National Energy regulator of South Africa (NERSA)

Table 4 3: **Minimum and maximum acceptable operating voltages in the power system in South Africa(NERSA,2020)**

Nominal Voltage,U_n[KV]	**U_{min}[p.u.]**	**U_{max}[p.u.]**
765	0.95	1.05
400	0.95	1.05
275	0.95	1.05
220	0.95	1.05
132	0.90	1.0985
88	0.90	1.0985
66	0.90	1.0985
44	0.90	1.08
33	0.90	1.08
22	0.90	1.08
11	0.90	1.08

4.2.4 Discussion and Conclusion of the results

This section covers the analysis of the IEEE 9 bus power system analysis in Dig Silent the simulated findings carried out on the IEEE 9-Bus system have been presented step by step to easily understand every single stage of the project. The first subsection discusses the existing IEEE 9-bus system without disturbance. However, the second subdivision investigates the effect of disturbance on the voltage stability of the IEEE 9 bus system.

The IEEE 9 bus system is simulated in two scenarios. The load flow is performed to confirm the stability of the network and a comparison is made with the results provided by the IEEE 9 bus data sheet. A contingency analysis carried out on the electrical network shows the possible vulnerability of the system and remedial solution. Bus 5 in the system is critical because of its lower voltage magnitude. Thus, making it a perfect point for connecting the PV.

The second subsection focuses on the influence of increasing load consumption in the power system. The disturbance in the power system is created by a dynamic increase of the load consumption by 35% with an increment of 5% every 2 seconds until the voltage collapse. The load event as performed in this chapter shows the disturbance caused by the load demand increase is a challenging task that required adequate response for the safe operation of the power system.

4.3 Development of the test bed using RTDS

The Real-Time Digital Simulator (RTDS) is an efficient engineering tool for modelling and simulation power and control systems. RTDS hardware uses high-speed digital signal processor chips, operating in parallel, to computer simulation resulting in step sizes small as two microseconds. Large electrical power systems such as the IEEE 9 bus can be modelled and simulated in real-time using RTDS. In the present subsection, RTDS is used for real-time electromagnetic transient analysis of voltage stability to validate the results of the simulation run in the power factory DIgSILENT.

The reason for using RTDS is justified by the fact that the electromagnetic transient solution algorithm gives additional detail and consequently better accuracy than the transient stability algorithm used in the power factory DIgSILENT (Vargas, 2021).

The use of RTDS is to develop an advanced algorithm that meets the demand for higher reliability and efficiency. A simulation test bench to investigate the algorithm of voltage stability in a power system imperatively needs to be modelled under a real-time scenario before it can be installed in a real power system environment.

In the previous section load flow analysis and a dynamic study were conducted to evaluate the performance of the 9-bus system under normal conditions and disturbance in DIgSILENT. This section focuses on the stability analysis of the 9-bus system in the Real-Time Digital Simulator (RTDS). The variation of power due to an increase in load demand is presented. The results from DIgSILENT are analysed for validation. Figure 4.10 represents the modified 9-bus system modelled in RSCAD.

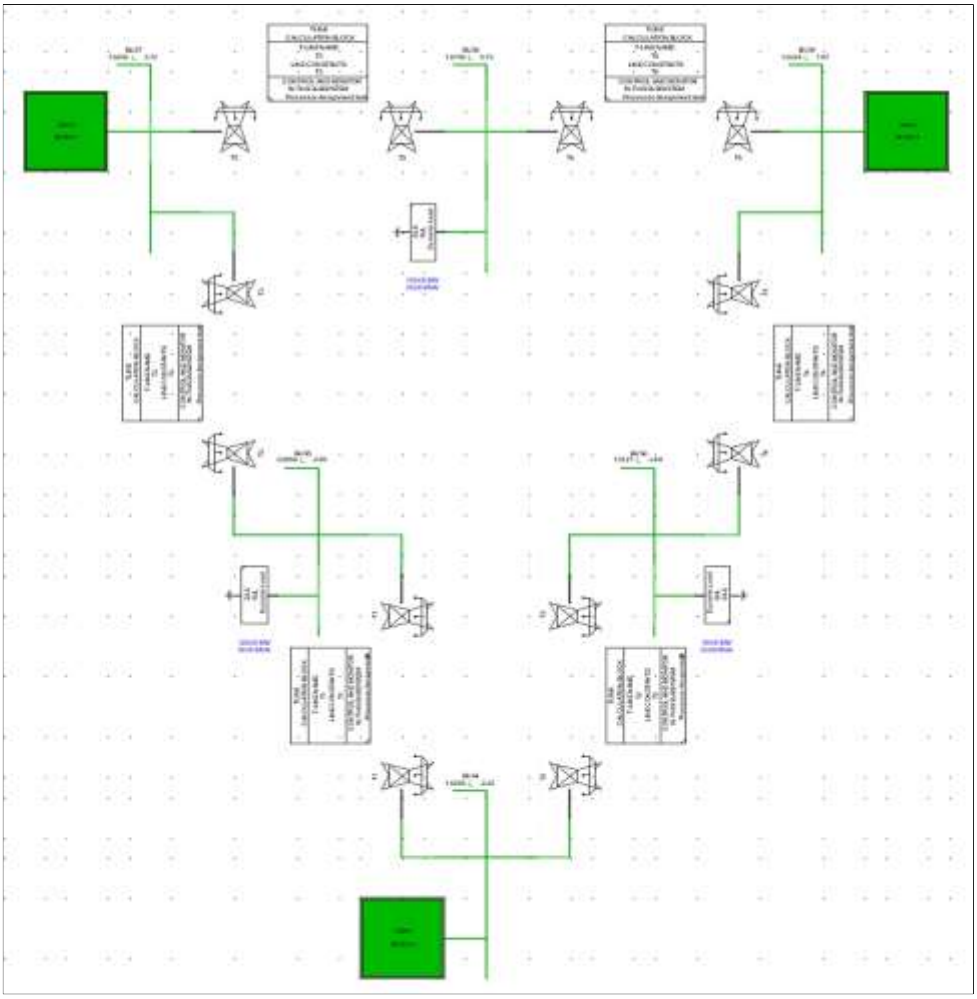


Figure 4 10: Single line diagram of 9 -bus system in RSCAD/RTDS (IEEE 9 bus system from RSCAD tutorial file)

The network configurations in Figure 4.10 are made of, three generators, three transformers, six lines, 9 buses, and three loads. The related nominal voltage of the power system is 230KV for a frequency of 60Hz. The different parameters for all individual elements of the network are detailed in Appendix A. The network is adequate for voltage stability study because of its diversified power generation sources and radial configuration which allow a multipart sharing of power among the different component of the power system.

4.3.1 Real-time digital simulation

A real-time simulation is performed using real-time digital simulation (RTDS). The simulation provides real-time conditions of the 9-bus bar power system. Voltage magnitudes and disturbance are investigated for the reliable and accurate study of voltage stability. A load flow analysis is performed on the IEEE 9 bus system to investigate the normal operation state of the electrical power system.

The simulation of the base case in RTDS provides accurate performance of the power system network, which provide a depth analysis than the traditional load flow analysis programs like DIgSILENT, which is not sufficient for the future of power system because of much complex dynamic communication between new electrical component with different dynamic time constants. Hence the use of RTDS, which offers electronic transient simulation tools to analyse the dynamic response of electrical power systems in great detail (Chou et al, 2019).

Table 4.4 below describes the results of the real-time simulation in RSCAD under normal operational conditions. The summarised results of the real-time simulation of the 9-bus system are recorded and compared to the results provided by IEEE data.

Table 4 4: **Real-time simulation result in RSCAD/RTDS compared to IEEE 9 bus system data**

IEEE data of 9 bus systems from RSCAD/RTDS data.			Base case results of the modified 9 bus system in RSCAD/RTDS.	
Bus	**u,Magnitude [p.u.]**	**TYPE**	**Bus**	**u,Magnitude [p.u.]**
1	1.040∠0.0°	SLACK	1	1.030
2	1.025∠9.3°	P-V	2	0.9946
3	1.025∠4.7°	P-V	3	1.020
4	1.026∠-2.2°	P-Q	4	1.012
5	0,996∠-4.0°	P-Q	5	0.9777
6	1.013∠-3.7°	P-Q	6	0.9884
7	1.026∠3;7°	P-Q	7	1.001
8	1.016∠0.7°	P-Q	8	0.9957
9	1.032∠2.0°	P-Q	9	1.020

In Table 4.4, the results of the IEEE 9-bus power system are presented and compared to the simulation results of the case study in RSCAD/RTDS. For the stability analysis approach, Data from the standard IEEE model are investigated using RSCAD/RTDS. The simulation in RSCAD/RTDS is performed to check for any variation in results provided by the IEEE data. Figure 4.11 below represents the voltage magnitude at different nodes of the IEEE 9-bus system.

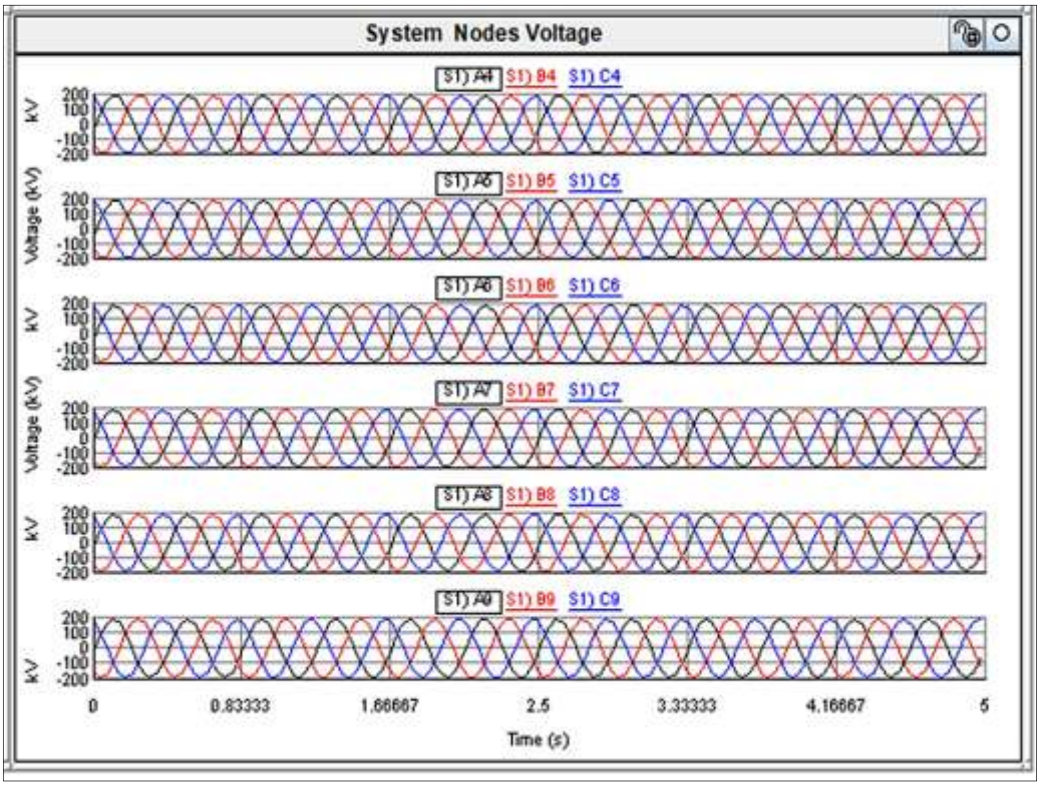


Figure 4 11: **Voltage wave of the modified 9 bus system in RTDS**

The vibration of the voltage waveform in figure 5.6 remains constant on each node of the power system. The sinusoidal expression of the waves helps to understand the stability of the voltage in the power system

4.3.2 Real-time Disturbance

As in DIgSILENT, the voltage stability study in RSCAD is performed using the load event mechanism. Voltage stability has been previously described as the ability of the power system to preserve or regain voltage magnitudes to an adequate level after a contingency event. Instability would cause the increase or decrease of voltage levels in part of the power system.

In the RSCAD environment, dynamic loads can be adjusted by turning a build control logic, where P and Q setting inputs are fully set for the external logic for tuning. Figure 4.12 below shows the dynamic load control logic in RSCAD

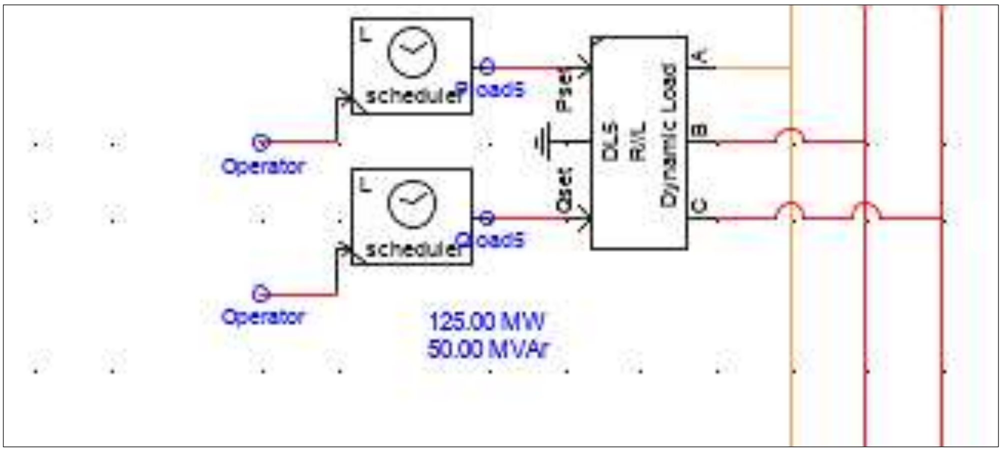


Figure 4.12: **Control logic for dynamic load engineering of the laboratory test bench**

In the above figure 4.12, the signal names Pload5 and Qload5 represent the active and reactive power respectively. These are used to control the consumption of load 5 (DLoad5). The signal called Operator is used to control the state (ON/OFF) of the scheduler component. The component “scheduler” in the RSCAD plays the role of increasing the load consumption by multiplying the given multiplier percentage with the initial values of power. The load scheduling settings and multiplier values of each load are shown in Appendix B.

Voltage stability is investigated using a disturbance describes as a load event, where the demand of the load has been increased from the initial value by 35% during 10 seconds in the step of 5% every 2 seconds. The result of load events following the disturbance in the power system is presented in Table 4.5 and figure 4.13 below.

Table 4 5: **Real-time results under disturbance compared to results under normal conditions.**

Modified 9 bus system base case simulation results in RSCAD/RTDS			Modified 9 bus system results after disturbance in RSCAD/RTDS	
Bus	**u, Magnitude [p.u.]**	**TYPE**	**Bus**	**u, Magnitude [p.u.]**
1	1.030	SLACK	1	1.025
2	0.9946	P-V	2	0.9704
3	1.018	P-V	3	0.9878
4	1.012	P-Q	4	00.9872
5	0.9777	P-Q	5	0.9199
6	0.9984	P-Q	6	0.9463
7	1.001	P-Q	7	0.9598
8	0.9957	P-Q	8	0.9442
9	1.020	P-Q	9	0.9744

Table 4.5 summarises the results of real-time simulation of the 9 IEEE bus system under the disturbance of a 35% increase of load demand for 14 seconds. The disturbances in the electrical power system create a voltage drop in the network with bus 5, bus 6, and bus 8 dropping beyond the threshold limit of 0.95 p.u.

Figure 4.13, figure 4.14 and figure 4.15 next page show the voltage collapse of bus 5, bus 6and 8 which respectively dropped from 0.9777 p.u. to 0.9199 p.u. for bus 5,0.9984 p.u. to 0.9463 p.u for bus 6 and 0.9957 p.u. to 0.9442 for bus 8.

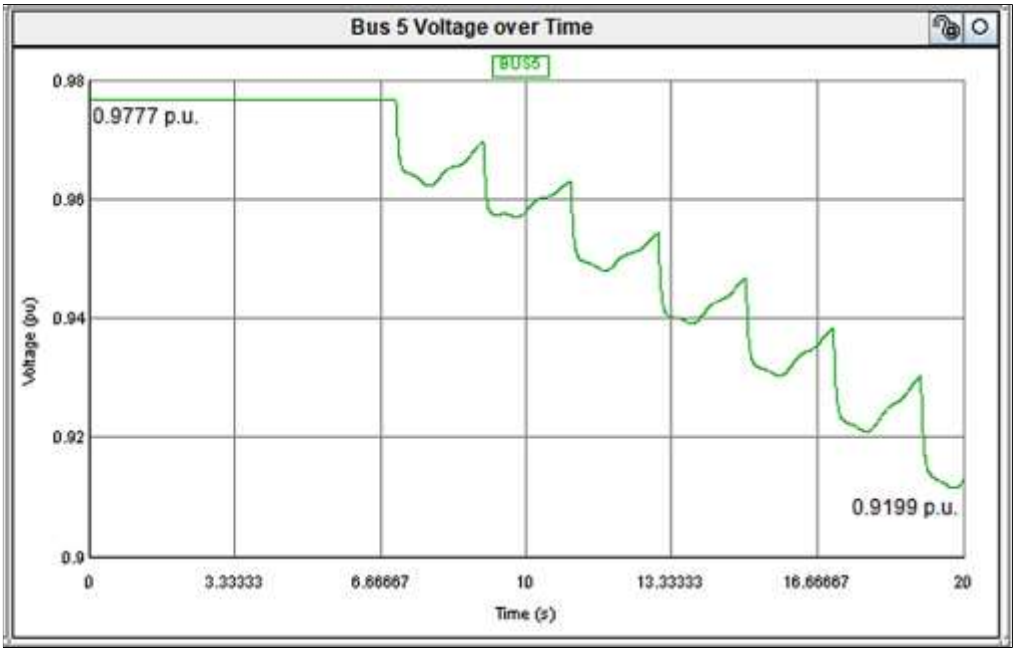


Figure 4 13: Voltage drop at bus 6 due to disturbance caused by 35% increase of load demand

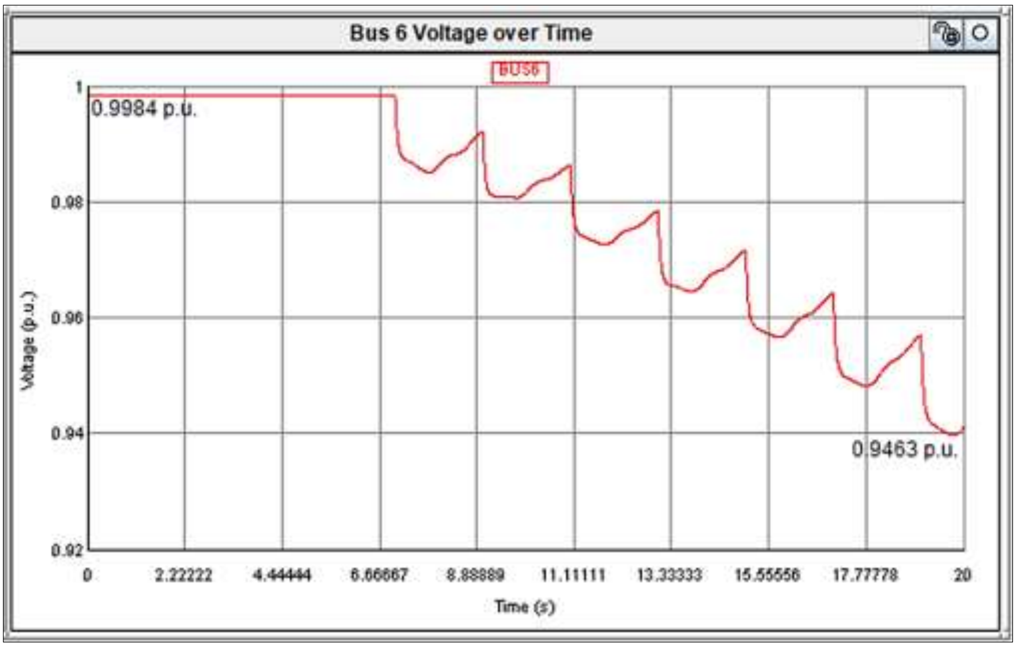


Figure 4 14: Voltage drop at bus 6 due to disturbance caused by 35% increase in load demand

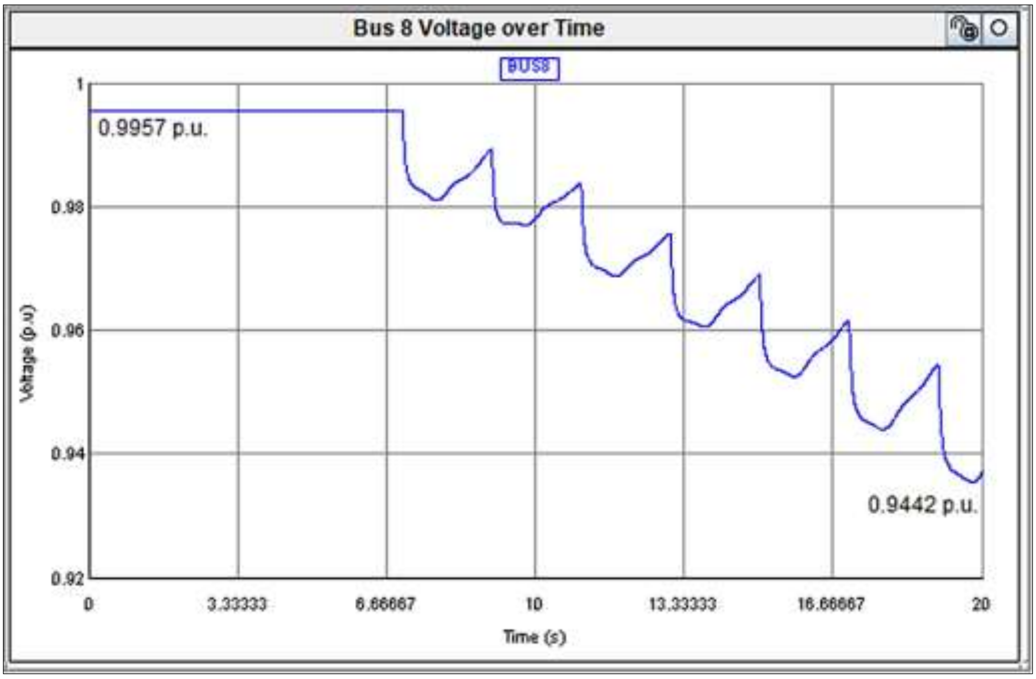


Figure 4 15: **Voltage drops at bus 6 due to disturbance caused by a 35% increase in load demand**

The recorded violation at these 3 buses indicates that the permissible voltage post contingency at these buses exceeded the standard limit of 0.95 p.u of the nominal voltage. Furthermore, the simulation shows that the induced disturbance increases in load consumption are stabilised once the increase reaches 35%. This is observed hen the network is simulated for 50 seconds indefinitely as shown in figure 4.16 below.

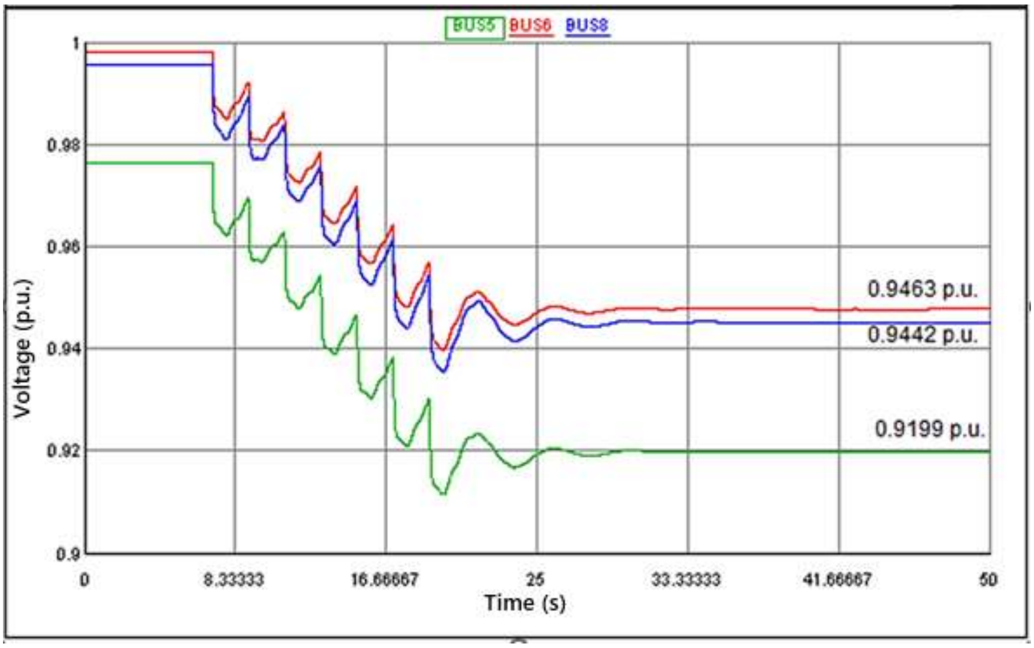


Figure 4 16: **The induced disturbance increases in load consumption are stabilised once the increase reaches 35%.**

Figure 4.16 shows how the disturbance in the power system is subject to the amount of power the load consumed. The reason for such observation helps not only to investigate the impact of excessive load consumption but also to determine the amount of power needed from the microgrid to restore the voltage of the power system to its normal operating level.

When a voltage violation happened after contingency, meaning the voltage in the power system or part of it is driven beyond the threshold of 0.95 p.u which determines the steady nominal voltage, a spike in the reactive power is about to happen as more of it will be injected in the power system.

The reactive power is expected to restore the voltage profile to an acceptable voltage magnitude. The same scenario is required in case of voltage rise above the limit of 1.05 p.u., and a drop in reactive power is expected to occur. More reactive power will be absorbed by the power system to maintain the nominal voltage acceptable for the buses (Juliana and Mwale, 2015).

4.4 Discussion of the results

Investigation into voltage stability and voltage collapse has been carried out using real-time digital simulation. The various analyses performed on the 9-bus system in RTDS reveal that the network is compatible with an in-depth analysis of voltage stability studies in the power systems.

To validate the result from DIgSILENT, a disturbance has been created by increasing the load consumption of the system. The dynamic increase of load was performed in the stage of a 5% increase from the initial load value every 2 seconds for 14 seconds. The results show that the voltage magnitude of all buses in the power system is decreased when a disturbance was stimulated by increasing the load consumption in the power system. Figure 4.17 shows the voltage magnitude of the entire system when the power system is subject to disturbance.

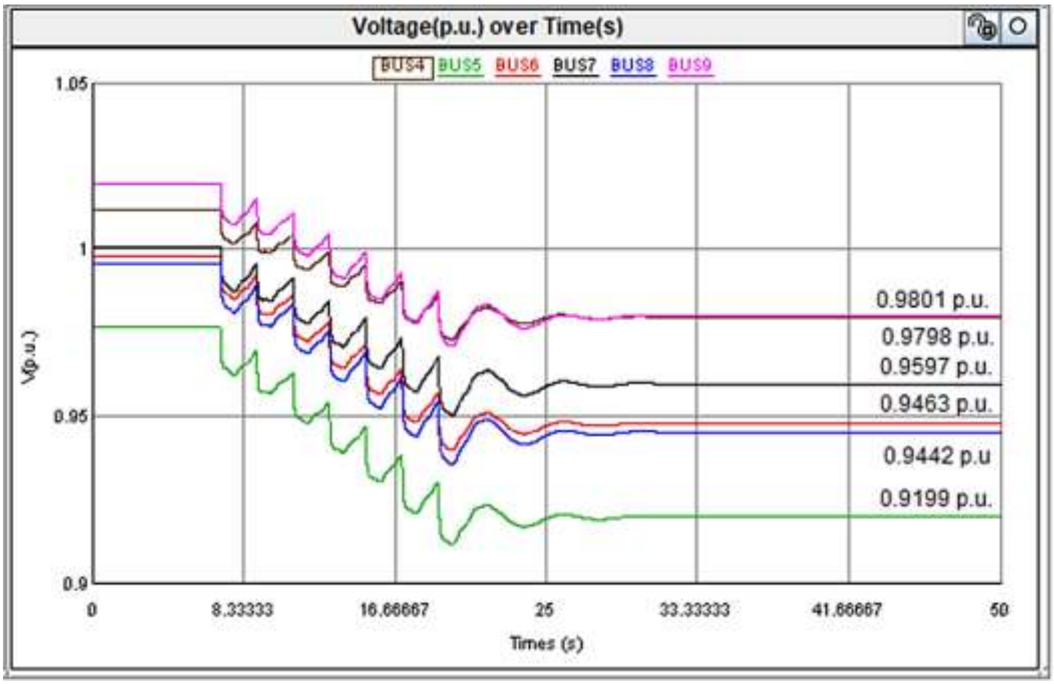


Figure 4 17: **Overall voltage dropped for all buses in the power system due to a 35% load demand increase.**

Bus 5,6,7 and 8 of the system are severely affected when the increase of load consumption reaches 35%. the respective rated voltage initially at 0.9777 p.u ,0.9984 p.u. and 0.9957 p.u. before disturbance dropped to 0.9199 p.u.,0.9463 p.u.,0.9455 p.u., and 0.9445 p.u. after the power system was subject to the disturbance. On the other hand, the power loss of the system is also considerably affected by the disturbance.

4.5 Conclusion

The chapter focused on the modelling and simulation of the IEEE 9 bus system. Load flow analysis was performed in the DIgSILENT simulation environment, and the real-time simulation was done in RSCAD/RTDS On the other hand by comparing the result on RTDS and DIgSILENT to validate the results of simulation in Real-Time Simulation. The contingency analysis in DIgSILENT was investigated to identify the factor that influences the stability of the power system. From the contingency analysis, bus 5 in the system was found to be the weakest bus in the system. Furthermore, a load event was carried out in both cases as a preferred disturbance to understand how an increase in load demand affects the instability of one part of the power system. The results obtained in this chapter will be used in chapter five as a reference for further voltage stability analysis in a power system with an integrated photovoltaic microgrid. Chapter five will focus on the integration of microgrids in power systems. The impact of such integration is addressed considering the absence of an ideal controller for the microgrid.

CHAPTER FIVE
INTEGRATION OF SOLAR PHOTOVOLTAIC SYSTEM INTO A GRID

5.1 Introduction

Over the last couple of years, the influence of Embedded Renewable Energy Resources (ERER) has considerably increased. Most countries have opted to increase their energy production using renewable energy. Consequently, several technical challenges are being faced by power utilities concerning the planning and operations of the smart power system.

These challenges are mainly attributed to effort leading to control of the penetration of renewable energy into the power system, which in this research it is affected by the instability of voltage caused by the increase of loads demand. This chapter presents the operation of the microgrid in grid-connected mode, where the PV system with a non-ideal controller is used to respond to the voltage instability after the power system is subject to the disturbance caused by a total of 35% increase in load consumption in the stage of 5% every two seconds of the simulation.

The modified IEEE 9-Bus transmission system is used as a test benchmark model for voltage stability studies in a real-time digital simulation (RTDS) environment. A Solar Power generation plant from the RSCAD library is used to represent the microgrid system wherein, an increase in load consumption is simulated as disturbances leading to voltage instability.

This chapter covers the investigation of the voltage stability study in a power system with PV as a microgrid. In section 5.2, the modelling of a large-scale PV microgrid is presented. In this section, the calculated design parameters of the microgrid PV are computed. In section 5.3, a case study of the Grid-tied photovoltaic with no optimized PI controller is presented.

The simulation of the modified IEEE 9 bus system with an integrated photovoltaic system is implemented considering a non-ideal control system. The influence of the PV-microgrid on the modified bus system power is investigated and evaluated. The focus is to demonstrate how the integration of PV microgrids with non-ideal control affects the state operation of the transmission network. The RTDS simulator hardware and software features are used as simulation tools. The chapter also includes in section 5.4, a discussion of the result, and a conclusion of the chapter is accordingly presented in section 5.5.

5.2 Modelling of large-scale PV microgrid

Microgrid modelling is generally known as the representation and implantation of a power generation unit, either islanded or connected to the power system. Such representation is usually mathematical, circuit-based, or physical-based, which described the parameter of the microgrid, and rated voltage and power (Shahgholian, 2021). The microgrid under consideration in this research is a photovoltaic plant with a description in the section below.

5.2.1 Input parameter of PV system

When modelling a microgrid solar plant, the only known parameters of the PV system is the desired outpower, the nominal voltage of the power system, and the DC voltage expected. The rest of the parameters in most cases are computed at the time of modelling. PV system engineers have provided various software that makes it easy to determine the parameters required in designing the solar power plant.

Using the already-built model of PV in RSCAD, the number of series modules has been set to 253 and those of parallel at 870.With a total number of 220110 modules for the PV array under consideration. The designed model of the PV system can deliver an estimated DC output power of 90MW and 11KV at Standard Test Conditions (STC) of the solar intensity of 1000 $W/m2$ and 25℃ for temperature.

5.2.2 Validation of Input parameter of PV system

Below calculation steps are considered to validate the input parameter of the PV system used in RSCAD/RTDS :

Number of modules required in series

$$\text{N-number series} = \frac{V_{OCA}}{V_{oc}} \tag{5.1}$$

Where

V_{OCA} is the estimated DC output open voltage expected to be delivered by the solar system.

V_{oc} is the open-circuit voltage per single series module.

V_{OCA} = 11 kV (estimated)

V_{oc} = 43.5 V

N-number series = $\frac{V_{OCA}}{V_{oc}} = \frac{11000}{43.5} = 252.88$ non-integer value of N-number of series PV modules.

The next higher integer of the N-number of series PV modules is 253 modules.

The current is determined from the below formula :

$$P = VI \qquad (5.2)$$

Where

P is the DC output power expected from the PV array

V is the DC voltage of the Solar plant

I is the total intensity of the solar plant

The calculated total current of the PV system is

$I_T = \frac{90e6}{11e3}$ =$8.182\ KA$ (Computed not simulated)

The number of modules in parallel is determined by :

$$\text{N-number parallel} = \frac{I_T}{I_{MP}} \qquad (5.3)$$

Where

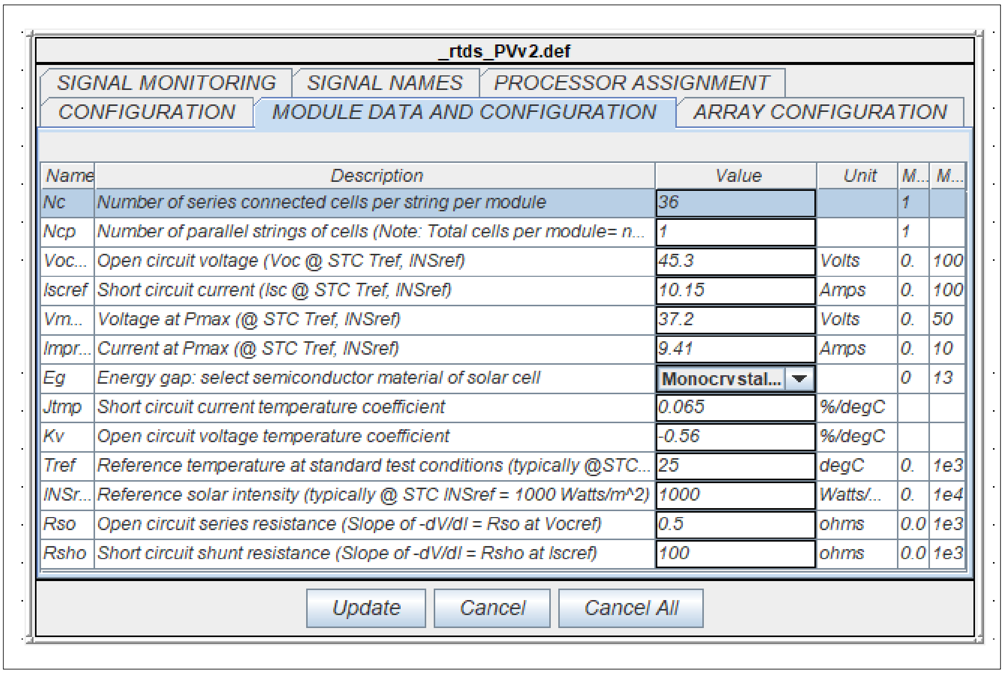
N_{pp} is the number of parallel modules

I_T is the total intensity of the solar plant

I_{MP} is the current of the solar plant at Maximum power

N-number parallel = $\frac{I_T}{I_{MP}}$ = $\frac{8182}{9.41} = 869.5$ non-integer value of N-number of parallel PV modules. The next higher integer of the N-number of series PV modules is 870 modules

Therefore, by connecting 220110 panels,870 in parallel, and 253 in series, the overall power of the PV power plant is expressed by the total number of all modules. Thus allocated an estimated 410W per panel, which is like the highly efficient monocrystalline panels as per the datasheet. In RSCAD/RTDS the above results are not always accurate. Figure 5.1 next page represents the parameters of the monocrystalline module used for simulation in RSCAD.



Name	Description	Value	Unit	M...	M...
Nc	Number of series connected cells per string per module	36		1	
Ncp	Number of parallel strings of cells (Note: Total cells per module= n...	1		1	
Voc...	Open circuit voltage (Voc @ STC Tref, INSref)	45.3	Volts	0.	100
Iscref	Short circuit current (Isc @ STC Tref, INSref)	10.15	Amps	0.	100
Vm...	Voltage at Pmax (@ STC Tref, INSref)	37.2	Volts	0.	50
Impr...	Current at Pmax (@ STC Tref, INSref)	9.41	Amps	0.	10
Eg	Energy gap: select semiconductor material of solar cell	Monocrystal...		0	13
Jtmp	Short circuit current temperature coefficient	0.065	%/degC		
Kv	Open circuit voltage temperature coefficient	-0.56	%/degC		
Tref	Reference temperature at standard test conditions (typically @STC...	25	degC	0.	1e3
INSr...	Reference solar intensity (typically @ STC INSref = 1000 Watts/m^2)	1000	Watts/...	0.	1e4
Rso	Open circuit series resistance (Slope of -dV/dI = Rso at Vocref)	0.5	ohms	0.0	1e3
Rsho	Short circuit shunt resistance (Slope of -dV/dI = Rsho at Iscref)	100	ohms	0.0	1e3

Figure 5 1: PV modules configuration menu for testbench in RTDS at Standard Test Condition ('R t d s p s u m', 2012)

The projected output DC voltage of the PV plant computed from the N-number of the modules in series configuration is 11KV. The PV is designed as a large-scale plant for high penetration of power into the electrical grid. The advantage of high output power is to minimize losses of power in the transmission line, which connect the PV plant to a 230KV node of the transmission network.

The controller of the PV under investigation is a prebuild model of PV controller found in the RTDS library, The non-ideal controller design and parameter are described in Appendix B.

5.3 Case study: Grid-tied photovoltaic with no optimized PI controller

This section focuses on the impact of the penetration of the PV-microgrids n the power system considering the load demand disturbance. Voltage magnitude of the system network, power losses of the grid, and PV performance were also considered.

5.3.1 The preamble of the case study

In chapter 4 the simulation result from the load flow analyses of the IEEE 9 bus system before disturbance shows that the voltage at all nodes of the electrical network is stable and within the acceptable range of ±5% tolerance rated voltage value between 0.95pu and 1.05pu as per the grid code for a healthy electrical network.

However, after the power system was subject to some disturbance, the voltages in the system were negatively affected with the voltage magnitude at bus 5, bus 6, and bus 8 dropping beyond the acceptable level of voltage stability indicators in the power system. The lower magnitude of the voltage at these buses trigged the necessity of integrating the microgrid PV to support the grid in restoring the voltage stability. But the integration of the microgrid to a grid is also known for its possibility to create over-voltage when proper regulation for integration is not followed.

Figure 5.2 and Figure 5.3 describe the impact of the PV penetration on bus 4 and bus

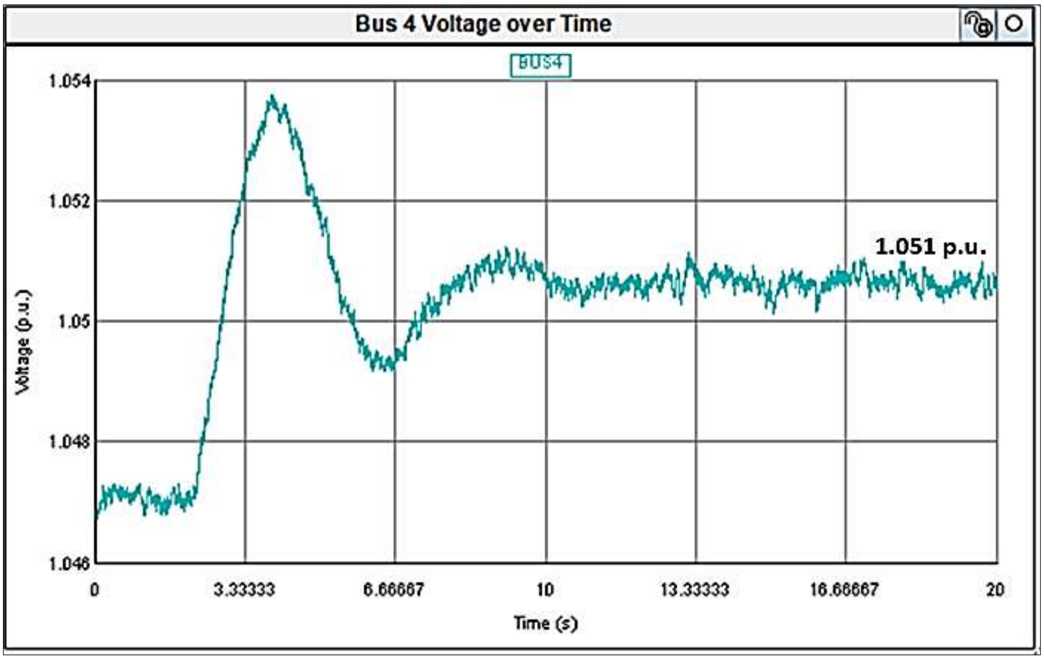


Figure 5 2: **Over-Voltage at bus 4 caused by the impact of PV penetration due to the absence of an ideal control scheme.**

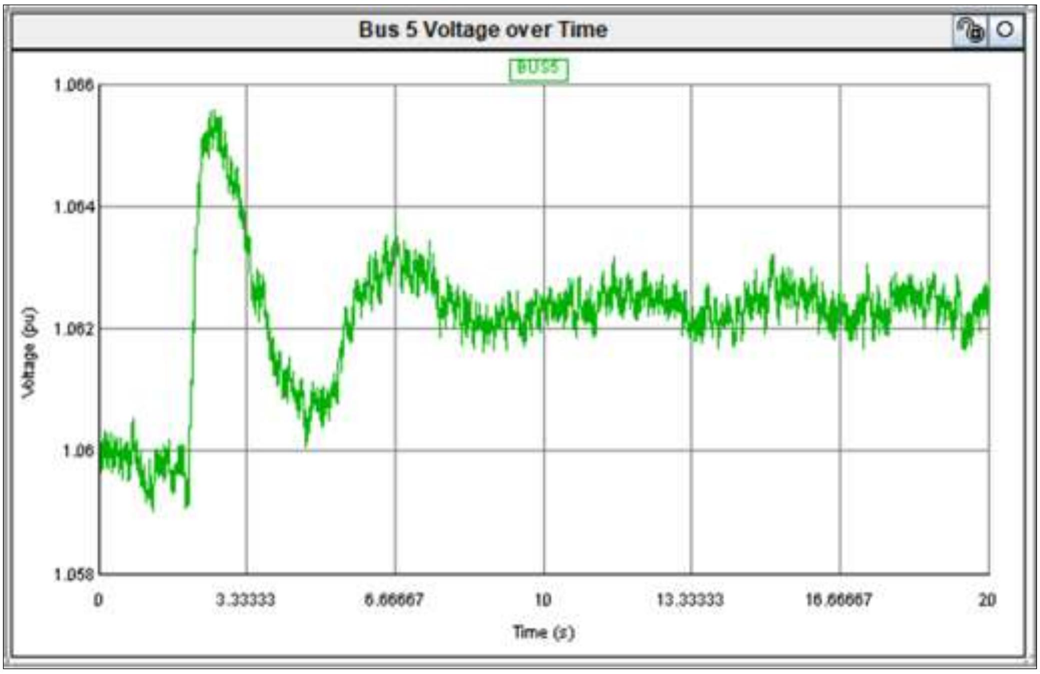


Figure 5 3: **Over voltage at bus 5 caused by the impact of PV penetration due to the absence of an ideal control scheme.**

The voltage profiles presented in Figure 5.2 and figure 5.3 shows a surge in the magnitude of the voltage when the PV is integrated without an ideal control strategy. The rise of the voltage represents the poor quality of power at the point of common coupling and some parts of the power system. Additional results for the voltage magnitude along different bus bar is presented in table 5.1.

Table 5 1: **Voltage magnitude of the base case versus the voltage magnitude of the grid when integrated with the PV system**

9 bus system base results in RSCAD/RTDS			9 bus system results due to uncontrolled PV impacts RSCAD/RTDS	
Bus	**u, Magnitude [p.u.]**	**TYPE**	**Bus**	**u, Magnitude [p.u.]**
1	1.030	SLACK	1	1.044
2	0.9946	P-V	2	0.9976
3	1.018	P-V	3	1.022
4	1.012	P-Q	4	1.052
5	0.9777	P-Q	5	1.062
6	0.9984	P-Q	6	1.025
7	1.001	P-Q	7	1.067
8	0.9957	P-Q	8	1.015
9	1.020	P-Q	9	1.033

Table 5.1 describes the voltage deviation between the base case and the modified IEEE 9 bus system when a PV system with no control is integrated. The integration of the microgrid to the power system has the potential to cause an alternation of the system parameters beyond or below the operation limit fixed by the utility power. This concern leads to the common term of hosting capacity of a power system, which is defined as the measure of how much renewable energy a power system can accept for it to stay stable(*Sam et al., 2021*)

The acceptable capacity is the safe amount of Solar PV power allowed to be supplied to an existing power system. Such an amount of power can be determined by software simulation and system monitoring to establish when a voltage violation occurred in the system.

The hosting capacity of the power system also depends on the capability of the inverter to regulate the correct amount of power needed to flow to the grid. Unfortunately, due to the lack of a proper control algorithm, the flow of power from the inverter is not related to the dynamic change of the voltage within the power system. The exchange of power between the PV system and the power system is continuous rather than reliant on the dynamic change of the load consumption. Figure 5.4 below shows the ON state of the inverter which does not wait for the voltage at the point of common to drop below 0.95 p.u. but the ON state of the inverter is constant because of the lack of proper control algorithms to determine when mode ON and OFF of the inverter valve is needed.

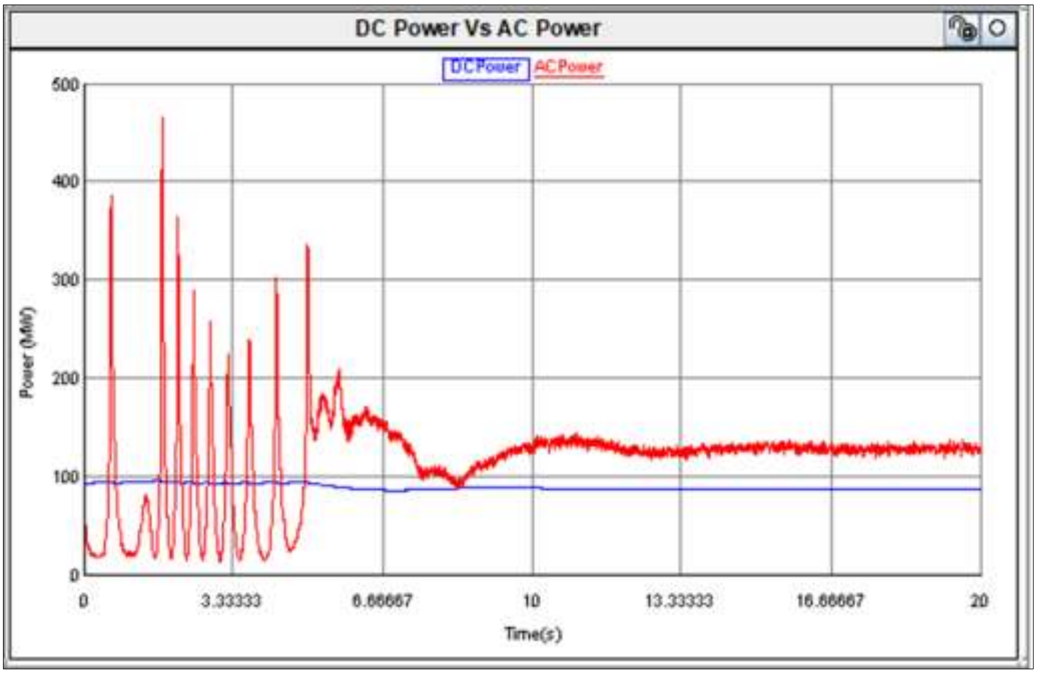


Figure 5 4: **Simultaneous ON state of DC power and AC power at inverter level**

As seen in Figure 5.5 above, the injection of power from the inverter is not controlled by any regulator. The flow of the power is consequently related to the time of the simulation and not to the change of the operation state of the grid. Because of the missing adequate controller for the integration of the PV. The inverter valve delivers excessive and disorganized power to the grid. Even though the flow of the power stabilized itself after 10 seconds of the simulation, the considerable power send to the grid is above the host capacity of the grid. The transfer of power between the grid and the microgrid PV as shown in figure 5.4 demonstrates that the controller from the RTDS library which has been used to integrate the PV to the grid shows that the valve for the inverter is constantly in ON mode by allowing the power of the PV to be injected to the grid. Because of this, there is an overvoltage at bus 5. Consequently, violating the standard for grid code for the integration of renewable power into the grid. In grid tied mode, proper power flow at inverter level and correct communication sharing strategies to adjust the inverter role are essential to achieve adequate and reliable operation of the power system.

5.4 Discussion

The negative impacts of the integration of the PV system in the power system include voltage rise and voltage unbalance. Such a voltage violation may depend on the capacity of the photovoltaic system, on the hosting capacity of the grid, or again and most of all on the absence of an appropriate control mechanism to regulate the flow of power from the microgrid to the electrical grid. In this chapter, the investigation carry out with a PV control shows that the absence of proper control can create further voltage unbalance in the network by injecting the full amount of power produced by the PV into the grid.

The importance of having a gradual injection of power is to prevent damage to the power system. Unfortunately, with the absence of an adequate control mechanism, the flow of the power from the PV is correlated to the start of the simulation and not to the need for the grid. The behaviour of the PV system violates the grid code of safe integration of the microgrid into the power system. Thus, these violations refrain us from further experimentation on the impact of disturbances on such systems, especially knowing that an increase in load demand will reduce the voltage surge at bus 4 and bus 5. The critical point here is to acknowledge that the leads overvoltage that happens at the point of common coupling and another bus close to the PV system is a very serious and dangerous violation of voltage stability that needs an appropriate control scheme that can keep the voltage level to an acceptable limit rather than create further disturbance to the safe operation of the electrical grid.

5.5 Conclusion

This chapter presented the effect of the integration of microgrid PV into the power system. The focus was to reveal the impact of such integration when a photovoltaic system is integrated into the grid without adequate control schemes. The investigation in the chapter shows that integrating a PV with no ideal control into the power system can be caused more harm to the grid than resolve the voltage stability.

The simulation results show that the penetration level of the microgrid PV creates an uncontrolled voltage surge that disturbed the power system. Such overvoltage led to voltage instability in power systems even though the level of voltage in part of the grid remains within the acceptable level for voltage stability.

The focus on the impact of the PV system during disturbance was not addressed because the voltage rises at bus 4 and bus 5 violated the grid code for voltage level in the power system. The disturbance will decrease the voltage magnitude to a safe level, but the research does not consider further simulation as the violation of voltage already occurs at bus 5 and bus 6 with a respective magnitude of 1.052 p.u. and 1.063 p.u.

The key founding of this chapter paves a way for chapter six." Proposed controller developed for integration of microgrid into the grid.". The chapter focuses on the control algorithm for an integrated microgrid system in a power system. The modelling and design in RTDS of the algorithm for voltage stability in a power system with a microgrid will be achieved.

CHAPTER SIX

THE DEVELOPED CONTROLLER FOR INTEGRATION OF MICROGRID INTO THE GRID TO MITIGATE VOLTAGE STABILITY

6.1 Introduction

The weight of the transmission network is increasing at a considerable speed due to the increasing power demand. Since the issue of power shortage which affects the electrical network has become a major concern with economic implications, microgrids have grown to become an effective alternative way when it comes to power shortage.
In a smart grid, microgrids are commissioned with the idea that power can still directly flows from the traditional generators to the load without having to disturb the operation of the transmission network. Microgrid in this regard serves as a palliative solution to alleviate the burden on the transmission network when generators can no longer able to supply the amount of power needed.

The integration of PV into power systems is generally a major concern for the various power utility. Connecting distributed generation to the power system brings some challenges that need to be addressed for the safe operation of the electric grid. One of those challenges is described as voltage stability, which is defined in the power system as the potential of the electric grid to re-establish the initial working voltage level after being exposed to a disturbance (Hosseinzadeh *et al.*, 2021) The integration of the photovoltaic (PV) as microgrid into the transmission network require adequate control strategy to assure that the operation of the grid remains safe and the quality of the power increase to the permissible index for stability as per grid code. An adequate voltage drop versus reactive power controller for the safe operation of the microgrid is presented in the present chapter.

The chapter presents the implementation of the algorithm that endorses complete the synchronization of the PV to the transmission network. The overall control strategy of the algorithm is to monitor the operation of the grid for any variations in power due to disturbance and be able to react instantly once the voltage in the transmission network or part of it drops beyond the permissible index of 0.95 p.u. The overall concept of the algorithm is based on the functionality of the adaptive Volt-Var technology which consists of monitoring any variation of the magnitude of voltage between the voltage of the transmission network and the voltage set index by the controller.
For any difference in the voltage set, the controller will send a signal command to the inverter through a proportional-integral controller to supply power from the PV gradually in line with the dynamic change of power consumed by the load. The controller

regulates in stages, not at once the power flow from the PV to the power grid. Hence it restores the voltage stability in the power system to an acceptable voltage magnitude of above 0.95 p.u. based on the maximum power point tracking. The chapter is devised into three sections. Section 6.2 the Adaptive Volt-Var controller used in Power Systems describes the operational function of the adaptive Volt/Var Control algorithm in Power Systems and the description of the controller for PV synchronization to the grid. Section 6.3 "Case study: Simulation of grid-tied photovoltaic considering disturbance " focuses on the simulation of the IEEE 9 bus system in Real-Time Digital Simulation considering the disturbance. Section 6.4 of the chapter, "Discussion of results" is dealing with the appreciation of the results collected from the simulation when a PV with an ideal volt/var control algorithm is applied to the system. The chapter closes with the final section 6.5 which is the conclusion.

6.2 Adaptive Volt-Var controller used in Power Systems

The integration of large-size photovoltaic systems into the power system requests the application of an adequate controller to manage the output power of the PV plant. Thus, the amount of active and reactive power needs to be monitored in line with the requirement of the grid code for PV integration.

The proposed controller is defined to keep adequate power within the grid by considering the characteristics of the PV as well as the demand for the amount of power needed by the power system. Photovoltaic adaptive Volt-Var control scheme delivers reactive power (Var) output to the power system as a response to voltage measurements index (Almeida *et al.*, 2020).

The capability function of the volt-var control scheme depends on the inverter's reactive power (Q) available to be injected into the power system. The equation below describes the relation including the injected reactive power and the available inverter capability:

$$Q_{inv}^{max}(t)=\sqrt{S_{inv}^2 - P_{inv}^2(t)} \tag{6.1}$$

Where

S_{inv}^2 is the inverter-rated power.

P_{inv}^2 implies the inverter-generated power.

Q_{inv}^{max} represents the reactive power limit of the inverter when supplying active power.

Equation (6.1) proves that the Volt-var function is used to keep the injection of the power from the inverter in line with the required power of the power system. The controller guides the inverter to respond to voltage variation at the point of common coupling. By doing so, the inverter of the PV responds to the command of the adaptive

Volt-Var control setpoints as predefined by the utility in line with the grid code, which is expected to keep the voltage of the grid within the threshold of ±5% of the p.u. value. For a given voltage index setpoint, the inverter will deliver extra reactive power or absorbs the extra power depending on the prospective difference at the point of common coupling.

6.2.1 Operational function of adaptative Volt/Var Control algorithm used in Power Systems

Below are some of the contributions of the volt -var control algorithm in mitigation of voltage stability in Microgrid Solar PV integrated with the power system.

- The proposed control algorithm can provide controller stability and set-point tracking performance at the same time by providing simultaneous functions without compromising the stability of the power system. Thus, eradicating the challenge of droop control.
- The proposed control allows the feasibility of a self-sensitive control algorithm, which updates automatically to voltage fluctuation in the grid operating system and external disturbance. The control algorithm allows the Solar PV to compensate only when needed to do so.
- The proposed algorithm maximizes the inverter's capability to operate beyond overvoltage mitigation in accordance with the integration standards and utility practices under IEEE1547, rule 21 (CA) which stipule the grid-interactive with DER's inverters.

The PV system connects to the grid at the point of common coupling (PCC). The injection of the PV ~~power~~ into the power system may lead to voltage instability at the PCC. Thus, the power operator should limit the penetration of PV power with the use of the adaptive Volt-var algorithm.

The control function of the Volt-Var algorithm regulates the inverter output power needed to improve the stability and reliability of the level of voltage in the power system. The overall operational function mode of the Volt-Var controller is based on the electrical grid characteristics. A power meter is set on the grid side to sense the variation in voltage magnitude. The control algorithm has a unique optimization mode that considers the magnitude of the deviation of the voltage and lines current at the point of common coupling. Consequently, sending an order to the inverter to provide an adequate amount of power is needed for voltage stability on the grid side (Gubert et al., 2021).

A voltage sensitivity in form of a mathematic matrix is used as a representation of an approximation of the grid's topology. Power flow. Equation(6.2) and (6.3) is used to derive the voltage sensitivity matrix.

$$P_i = U_i \sum_{j=1}^{n} U_j \left(G_{ij} \cos\left(\theta_i - \theta_j\right) + B_{IJ} \sin(\theta_I - \theta_J)\right) \quad (6.2)$$

$$Q_i = U_i \sum_{j=1}^{n} U_j \left(G_{ij} \sin\left(\theta_i - \theta_j\right) + B_{IJ} \cos(\theta_I - \theta_J)\right) \quad (6.3)$$

Where:

P_i, Q_i, U_i, represent the active, reactive, and voltage as seen at node i by the controller set level,

G_{ij} represents the real part of the admittance of the line connecting node i to node j,

B_{ij} is the imaginary part of the admittance,

θ_i is the voltage phase of node i

The added value of going from a mathematical model to real-time simulation is demonstrated in section 6.3, which focuses on the simulation of the adaptive Volt-var algorithm controller in Real-Time Digital Simulations (RTDS).

6.2.2 The proposed Adaptive Volt-Var Controller topology used in RTDS

The interference of power electronic-based microgrid integration into the transmission system has shown the ability to impact voltage regulation and performance. Previously the traditional grid, Volt-Var Control was conducted by various techniques and equipment such as voltage regulators, transformer load tap changers, and capacitor banks.

The presence of power electronics in the Electric Power System (EPS) has increased the level of interest in other Volt-Var control methods, such as STATCOM and the inverters that interface photovoltaics (PVs) and Battery Energy Storage System (BESS) to the grid. Nowadays as per the new IEEE 1547 standard, smart solar inverters are required to remain connected to the electric system during disturbances rather than disconnecting from it from the system. The inverter in this regard became a major component with the control capability to inject or absorb reactive power based on the deviations in voltage magnitude observed at the side of the grid (Johnson *et al.*, 2021). This research proposed a technique to establish the optimal dynamic reactive power injection from the microgrid to the grid. An algorithm that enhances the reactive power injection when there is a disturbance in the grid side due to a dynamic step-by-step

increase of 35% increases load consumption in the stage of 5% every 2 seconds of the simulation. A case study based on a modified IEEE 9 Bus system with microgrid PV connected to bus 5. The algorithm is implemented in an environment of centralized dispatch. The research proposes an adaptive volt-var algorithm to mitigate the voltage collapse as identified by the controller using RSCAD/RTDS technology.
Figure 6.1 describes the block diagram of the full control algorithm implemented in this thesis while the modelling of various control blocks in RTDS is presented in Appendix B. The MPTT controller block is served to monitor the current and voltage from the PV side. The controller is used to provide maximum power tracking from the PV to the grid. The output AC voltage current from the inverter is transformed by the dq reference frame into DC signals to simplify the tuning parameter process and the controller ability design.

By tracking the voltage and the angle of the grid side using a phase-locked loop (PPL) mechanism at the point of common coupling, which is bus 5. A transformer angle "angPLL8" is obtained and used to transform the output AC voltage and current from the inverter to dq reference frame. The decoupled current controllers are used to provide a modulation signal ($mdA8$ and $mqA8$) as output. These reference outputs are transformed to three-phase sinusoidal signals $\mathrm{ES2Va8}$, $\mathrm{ES2Vb8}$, and $ES2Vc8$ using a $\mathrm{dq/abc}$ transformation block and serve as the modulation waveform in the (SPWM) control block. Thus, the Sinusoidal pulse width modulation (SPWM) control block generates the firing pulse of the voltage source converter (VSC) valves. The signal of the valve to allow the transfer of power from the PV to the grid is controlled by a second proportional integral derivative (PID) controller block.

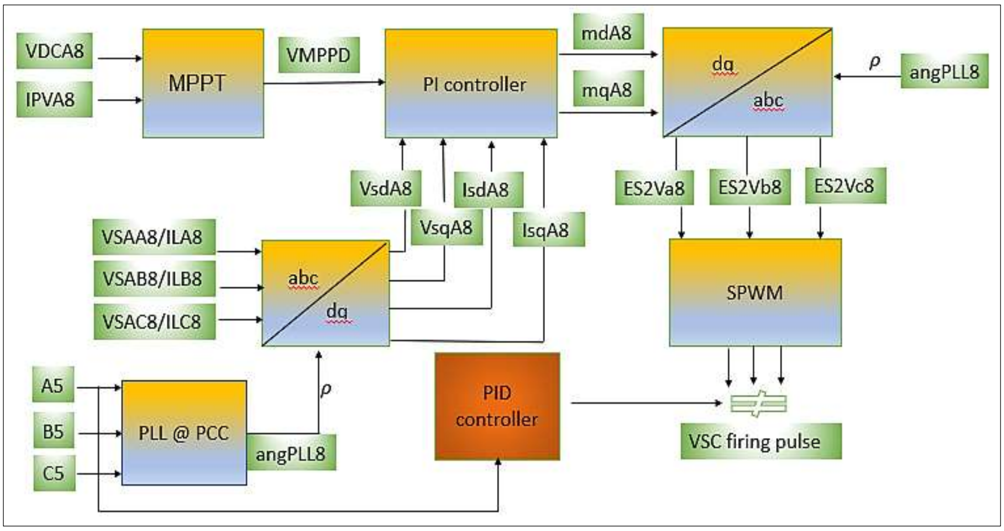


Figure 6 1: Modified block design of the proposed controller for PV integrated into the transmission power system (Gbadamosi, 2017)

These function blocks formed the control unit which allows the PV to be connected to the power system. The role of the secondary controller block is to monitor the behaviour of voltage at bus 5, compared it to the reference voltage $Vset,$ and issue an error $Vsetref.$

To achieve the aim of the thesis, the developed secondary controller consists of the following:

- a measurement unit to regulate the voltage at bus 5 in a normal operating state and under disturbance.
- A voltage regulator unit, which compares the measuring unit of bus 5 to the reference set by the utility.
- a Synchronization unit with a signal generator to the firing pulse unit.
- And a PI controller to set the ON/OFF state of the inverter valves for power transfer

These elements are required for proper control of the Photovoltaic system to respond to the voltage stability in the grid considering the disturbance caused by the increase in load consumption. Figure 6.2 shows the part of the PV control model in RSCAD, which monitors the voltage at bus 5 of the power system.

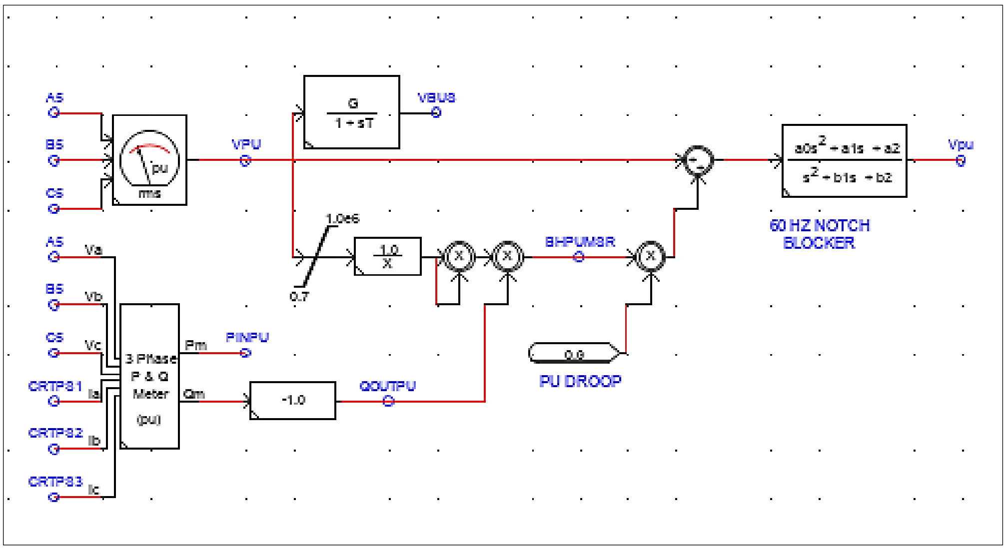


Figure 6 2: Power logic control at the Point of Common Coupling. The grid voltage is compared to VSET1 for any variation in voltage magnitude.

Figure 6.2 describes the control unit for voltage and current measurement on the grid side. The bus 5 RMS voltage per unit is processed through a filter circuit to obtain a clear input voltage per unit (VPU).

The current of the output side of the delta-wye (Dy) transformer is also measured in per unit value and later compared to the clear value of the bus 5 per unit voltage to obtain an accurate per unit voltage stability (Vpu) at bus 5 of the power system.

In figure 6.3 next page, the voltage, Vpu is compared to the reference voltage (VSET1) to obtain an error for further processing. The error is processed through a PI controller to obtain the susceptance (Vsetref). The susceptance gained from the voltage monitor is used to differentiate the ON state from the OFF state of the inverter. By comparing the susceptance value to the pre-set VSET1 value, the PI controller will then send a control command to the inverter to allow the flow of power to the grid.

For a VSET1 less than the susceptance the valves of the inverter will operate in an ON state for the power to flow. For a VSET1 greater than the susceptance, meaning the voltage at bus 5 is within the acceptable range of safe operation of the grid, the valve of the inverter will remain in the OFF state. Therefore, no power will be injected into the grid.

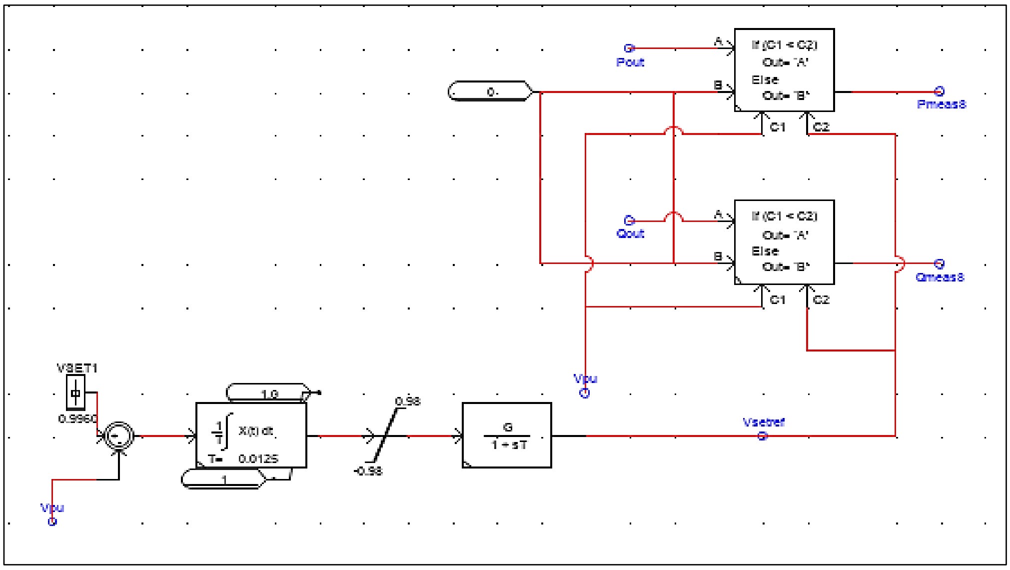


Figure 6 3: **PI controller command for ON/OFF state of the inverter valves**

The function of the inverter depends on the difference margin between the threshold of power as determined by the utility and the magnitude of voltage when the power system is subject to disturbance. The inverter function to inject both active and reactive power is subject to a drop of voltage level beyond the safely permitted index for voltage stability.

The inverter is also regulated to inject power in a gradual sequence as determined by the adaptive volt/var algorithm. Figure 6.4 next page is the synchronization logic at the point of common coupling. The logic is served to measure the angle of the AC voltage at the grid side.

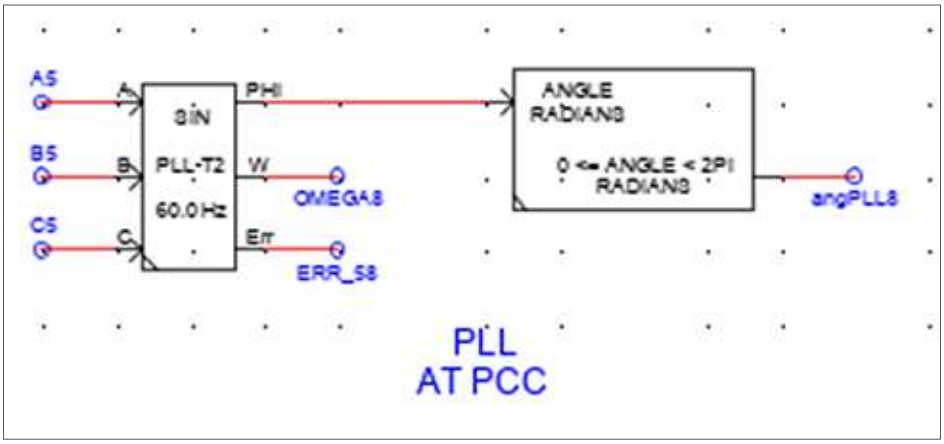


Figure 6 4: **phase-locked loop for grid-side synchronization**

The three-phase voltage from the power system at bus 5 is processed through a Phase-Locked Loop (PLL) to obtain a firing angle, which is the same as the firing angle of the voltage source converter (VSC). The angle as obtained from the grid side together with the output signal of the PLL is used to activate the firing pulse generator which regulates the flow of power through the inverter.

6.3 Case study: Simulation of grid-tied photovoltaic considering disturbance

The benchmark case study focuses on the development and implementation in RTDS of an algorithm for voltage stability in a power system considering the disturbance. The case study aims to design an algorithm capable of supporting the power system to recover voltage stability after disturbance. The disturbance under consideration is described as a load consumption increase of 35% in the stage of 5% every two seconds of the real-time simulation. The method used in this regard is the adaptive volt/var algorithm, which is used as theoretical background in building a controller that will consider the dynamics change in power consumption.

The controller shall be able not only to monitor the variation of voltage magnitude at the point of coupling but also be able to command appropriate action to the inverter once the voltage at bus bar 5 fails beyond the threshold of 0.95 p.u. The proposed algorithm is dynamic and adaptive to voltage variation. The PV power as displayed on the meter display in figure 6.5 below shows that the inverter is not transferring any power to the grid at the time of no disturbance in the system.

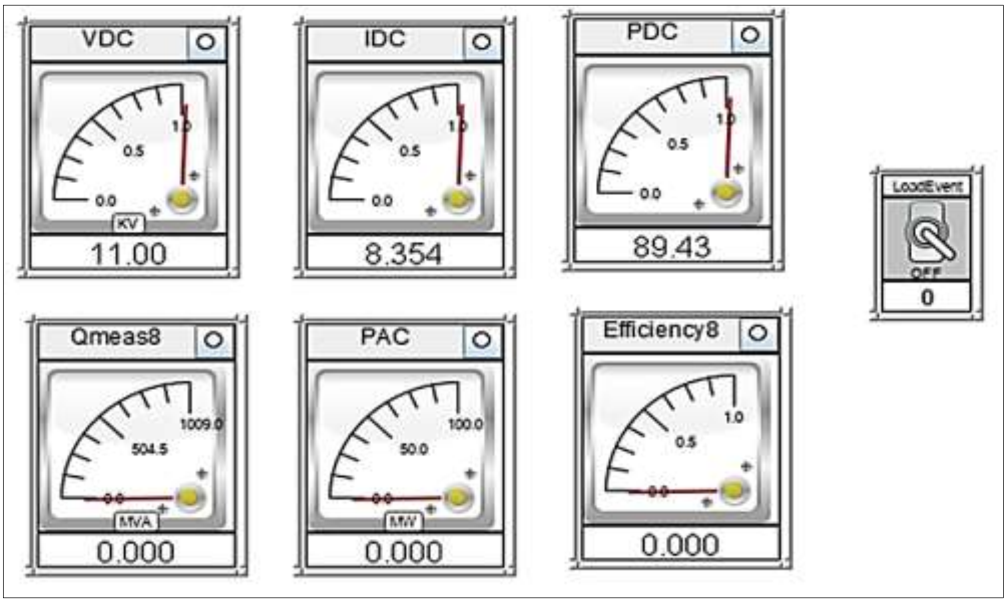


Figure 6 5: **Signal metering of the inverter before disturbance in the power system**

The reading of the meter (VDC) or voltage DC shows the generation voltage of the PV system, IDC is the current of the PV, which was obtained from the (N number of the parallel panel of the photovoltaic plan, PDC or power DC is the total power produced by the PV, Qmeas8 and PAC represent the active and reactive power of the PV on the inverter side and the efficiency meter is the actual reading of the efficiency of the PV, which is obtained from the relation of the PAC and PDC respectively Dc power and AC power of the PV system. The power from the microgrid PV is expected to be supplied to the grid gradually when the voltage at the point of common coupling drop beyond the permissible voltage magnitude for a stable grid.

The supply of power to the grid will flow frequently to keep the voltage recovering as long the consumption of the load remain increased. Hence the adaptive function of the volt/var is justified. During the entire simulation, the voltage of bus 5 is monitored before and after the interference of the microgrid by considering further disturbance.

6.3.1 Performance assessment of the modified IEEE 9 bus system with developed controller

In chapter four, a load event based on load consumption increase was implemented to create a disturbance on the transmission grid. As a result, of the increase in the load demand, the voltage at bus 5, bus 6, and bus 8 of the system dropped beyond 0.95

p.u. leading the voltage of those parts of the network in a state of instability. A strategy was proposed in chapter five to assist in the recovery of the voltage by integrating the photovoltaic system. Unfortunately, the proposed strategy did not restore expected voltage stability but instated created an overvoltage at the point of common coupling.

The simulation result in chapter five shows that the integration of the PV system with no ideal controller did not assist the grid to achieve a safe voltage recovery but instead create over-voltage and voltage fluctuation in the power system. Figures 6.6 and 6.7 below show the stage of power increase for load 5, load 6, and load 8 when the power system is subject to a disturbance caused by an increase of 35% in load consumption in the stage of an increment of 5%. The simulation in real-time is done on a time limitation period of 50 seconds which can also be considered as an indefinite time of the simulation.

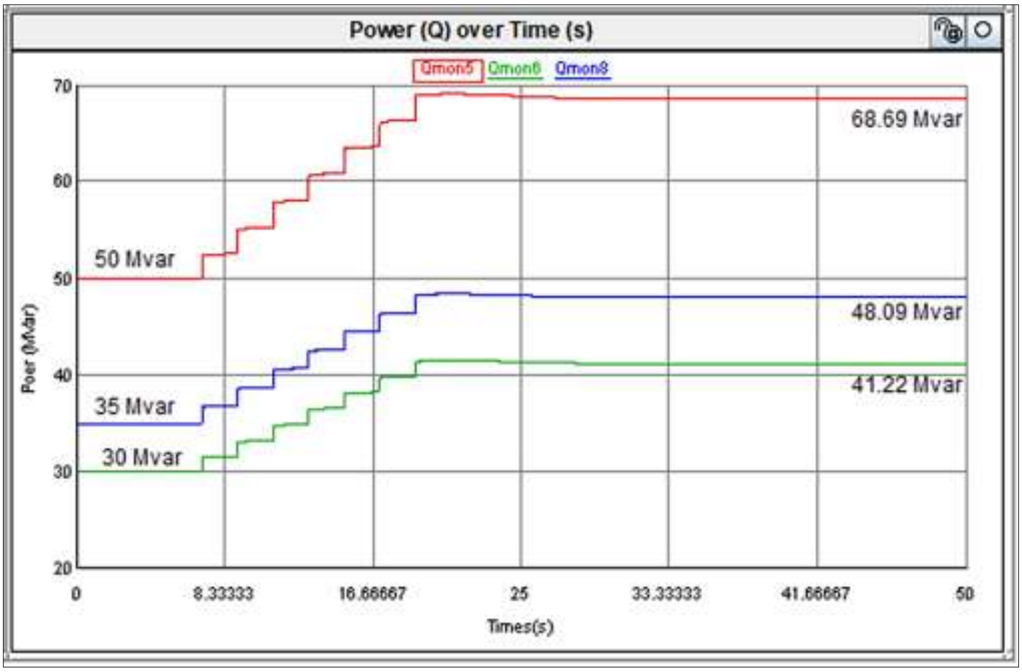


Figure 6 6: **Increase of reactive power consumption for all loads in the power system after disturbance due to a 35% load increase**.

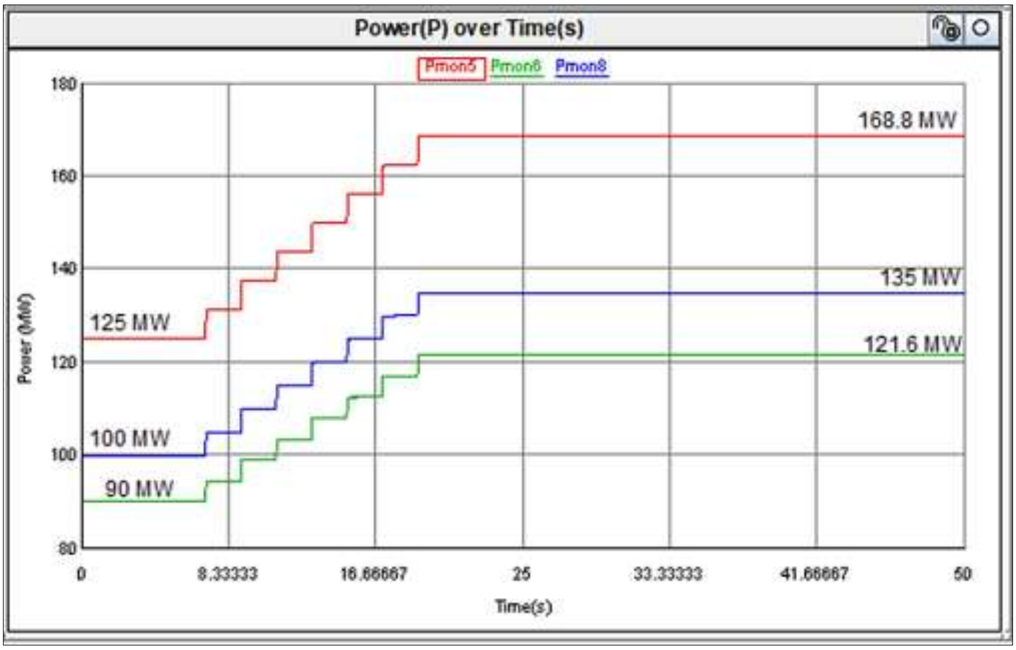


Figure 6 7: **Increase of active power consumption for all loads in the power system after disturbance due to a 35% load increase**.

Figures 6.5 and 6.7 are the graph of the load event, which determines the disturbance in the power system. The graphs describe the response of the power after the load consumption is increased by 35% with an increment of 5% from the initial value of each load. Figures 6.8 and 6.9 below are the meter representation of the variation of both active and reactive power before and after the transmission network is subject to disturbance.

Figure 6 8: **Meter reading for power before disturbance**

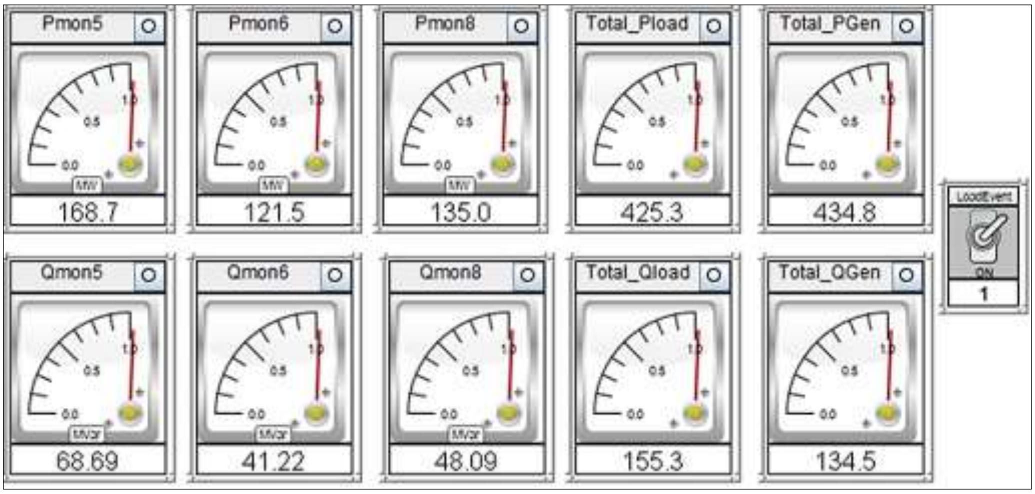


Figure 6 9: **Metering of power after disturbance**

Figures 6.8 and 6.9 represent the reading from the meter which monitors the dynamic change of power at load level when the power system is subject to a disturbance. Early on in chapter 4, figure 4.12 a control logic to monitor the dynamic change of the load was presented with the modelling of the Operator control for the load which in the RSCAD plays the role of increasing the load consumption by multiplying the given multiplier percentage. Two separate logic control in figure 6.10 and figure 6.11 are respectively used to monitor the total power generated by the power system and the total dynamic power of the loads.

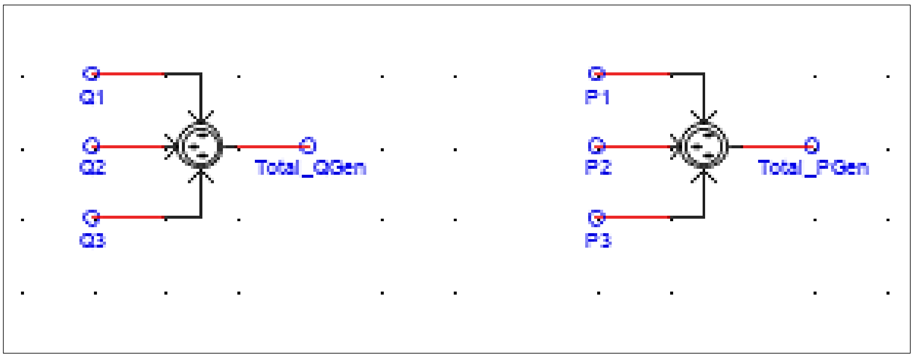


Figure 6 10: **Monitoring logic for both active and reactive power generated by the power system**

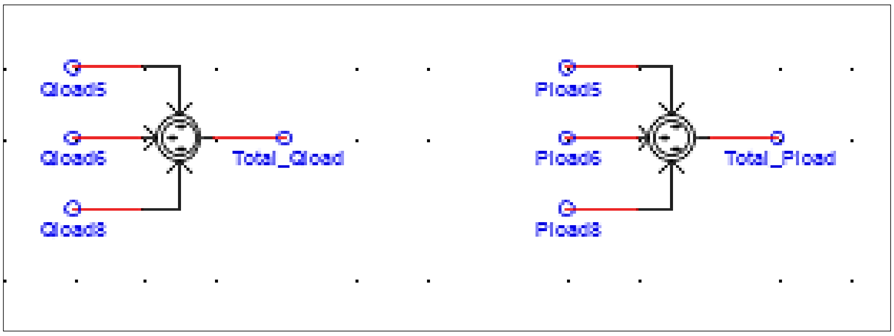


Figure 6 11: **Logic control used to monitor the dynamic change for active and reactive power at load level**

Due to the load consumption increase, the voltage magnitude at bus 5, bus 6, and bus 8 has been considerably affected. Figure 6.12 represents the system voltage after the implementation of the disturbance. Respectively ,the voltage dropped from 0.9777 p.u. to 0.9199 p.u. for bus 5,from 0.9984 p.u. to 0.9463 p.u. for bus 6 and from 0.9957 p.u. to 0.9442 p.u for bus 8. The voltage at bus 5 has considerably dropped to 0.94725392 p.u after 20 seconds of simulation while Figure 6.13 represents the constant change in voltage drop after the system is simulated indefinitely. Meaning the load consumption did not increase beyond the 35% increase.

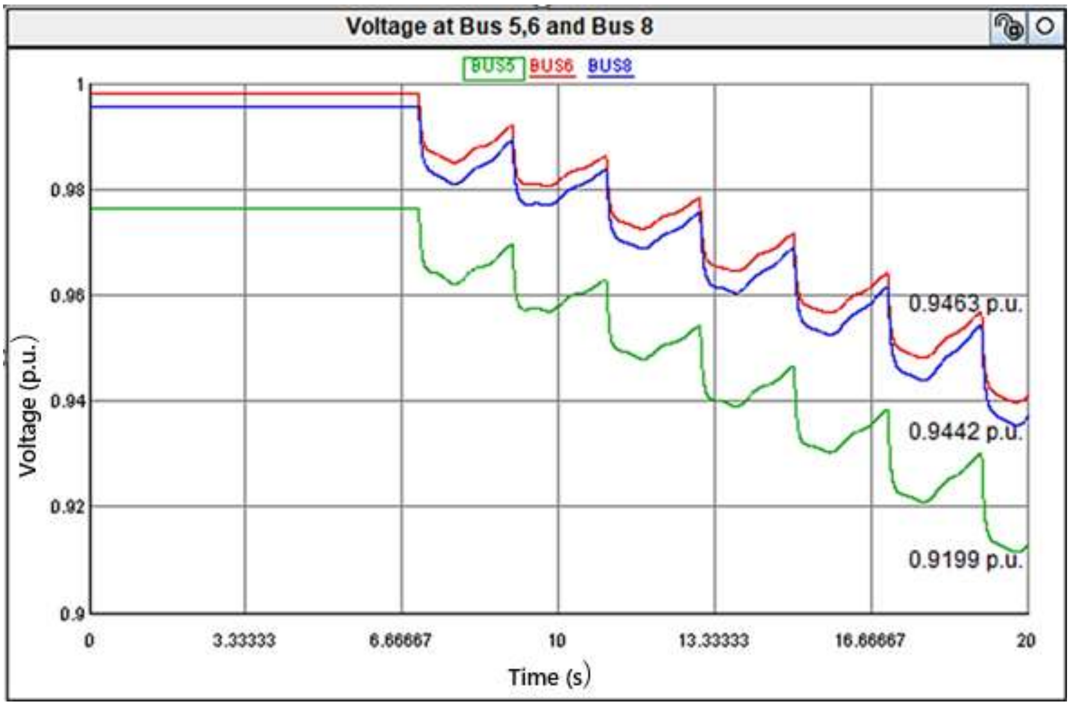


Figure 6 12: **Voltage drop at bus 5, bus 6, and bus 8 after disturbance**

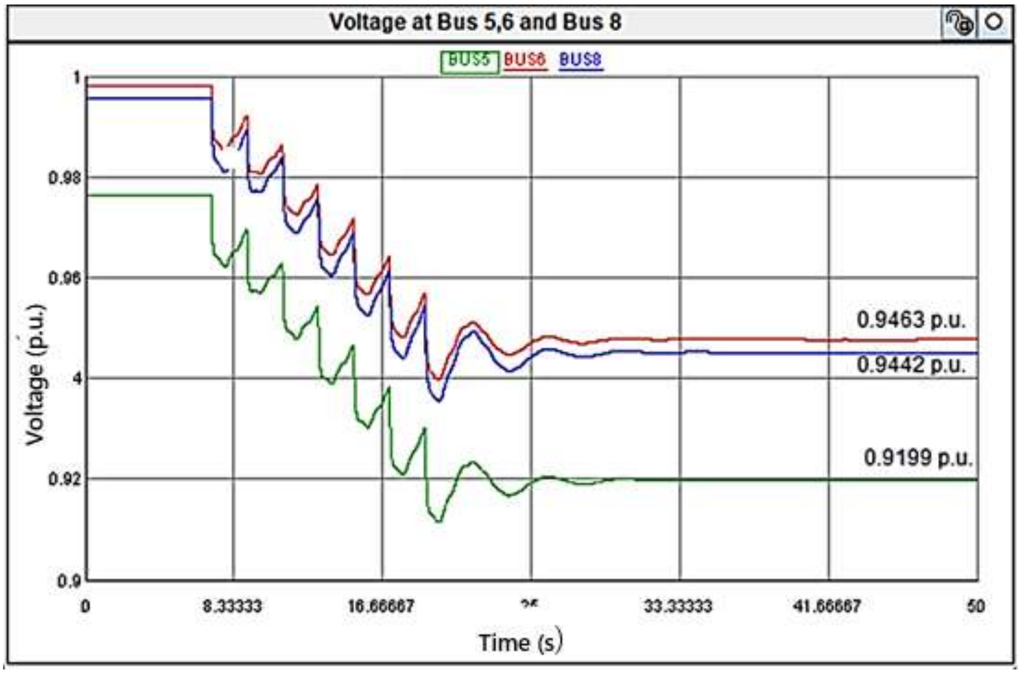


Figure 6 13: **Voltage drop at bus five when the simulation is performed undefinedly keeping the 35% increase of load demand**.

Load consumption increase caused the voltage collapse at bus5, bus 6, and bus 8. This phenomenon can be allocated to the explanation behind the application of Ohms law. Hence when the load demand increases, the voltage in the transmission network decrease, especially at the bus bar where the system loads are connected. Figure 6.14 next page presents the bus voltage of the entire transmission network. The voltage of the entire system has been affected by the disturbance, even though the drop at some bus of the system remains within the acceptable tolerance.

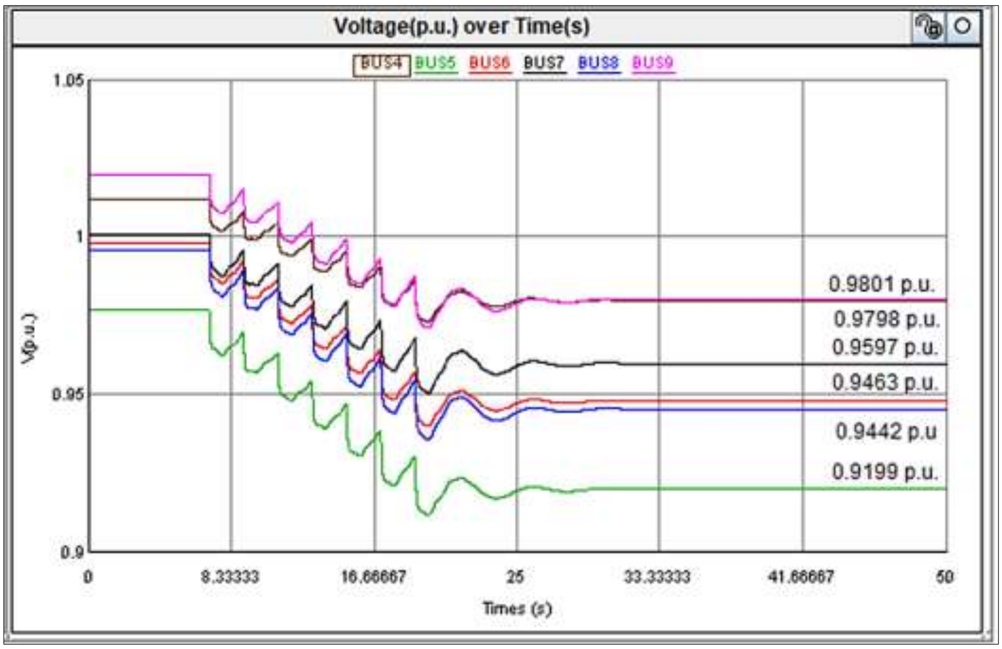


Figure 6 14: Overview of the voltage drop of the entire system after disturbance

At this point of the simulation, the controller Is expected to send a signal to the inverter to switch ON the valves, which will allow the transfer of power gradually from the PV to the power system. Figure 6.15 below shows the switching OFF state of the inverter before the disturbance while figure 6.16 is the ON state of the inverter at the same time when the voltage level of the bus bar 5 reaches the critical point of voltage instability.

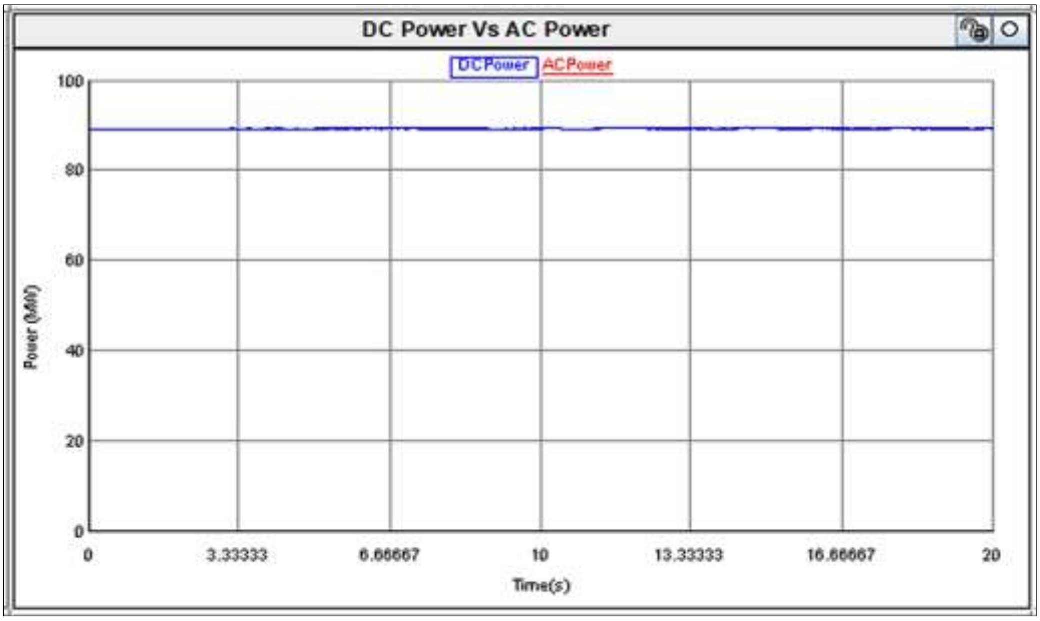


Figure 6 15: **Inverter switch OFF state before the power system is subject to disturbance**

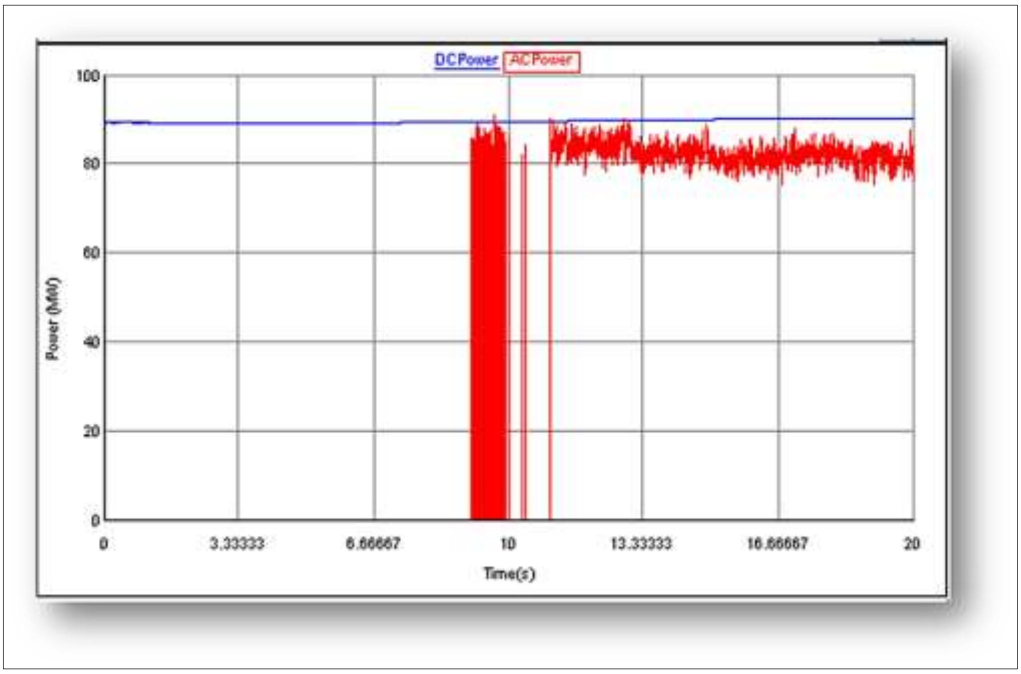


Figure 6 16: **Inverter switch ON state at 8 seconds in the simulation after voltage drop reach 0.9455 p.u.**

Figure 16 shows the start point of the inverter, which only injects power when the magnitude of the voltage at bus 5 reaches the voltage set index of 0.940 p.u. The adaptative volt/var control as the design can monitor the grid voltage at bus 5 for any variation beyond the reference voltage as a set. The importance of the voltage reference is to allow the controller to activate the inverter capability of injecting the power into the grid.

The inverter not only injects power but also responds to the dynamic change of power as it happened during the disturbance. The results from the meter in figure 6.17 below indicate the flow of power from the inverter to the grid. The flow of power from the PV to the power system is happening because of the change of state of the inverter from OFF state to ON state caused by the controller's capability to intervene in mitigation of power instability.

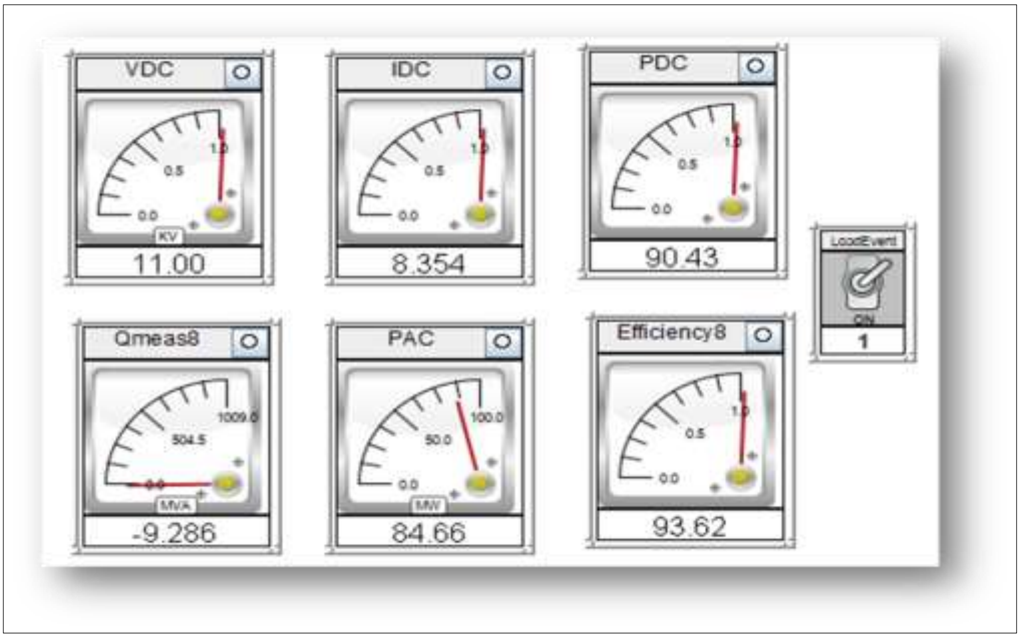


Figure 6 17: The results prove that the power flow from the PV is passing through the inverter to the power system

The role of the inverter as described by the controller, which considers the gradual drop of voltage is represented in figure 6.18 .figure 6.19, and figure 6.20 where the power supply from the microgrid assists the transmission network to recover the voltage. From respectively dropping to 0.9199 p.u for bus 5, 0.9463 p.u. for bus 6, and 0.9442 p.u. for bus 8, the effectiveness of the controller allowed the voltage to recover to 0.950 p.u. for bus 5,0.9563 p.u. for bus 6 and 0.9545 for bus 8. The recovery is not the same as the initial voltage magnitude before disturbance, but the recovery is within the acceptable limit for voltage stability. The inverter in this regard is acting by considering the dynamic state of the power system. Dynamic voltage stability considers the time of the simulation, which gives a frame sequence of events leading to voltage instability in the power system.

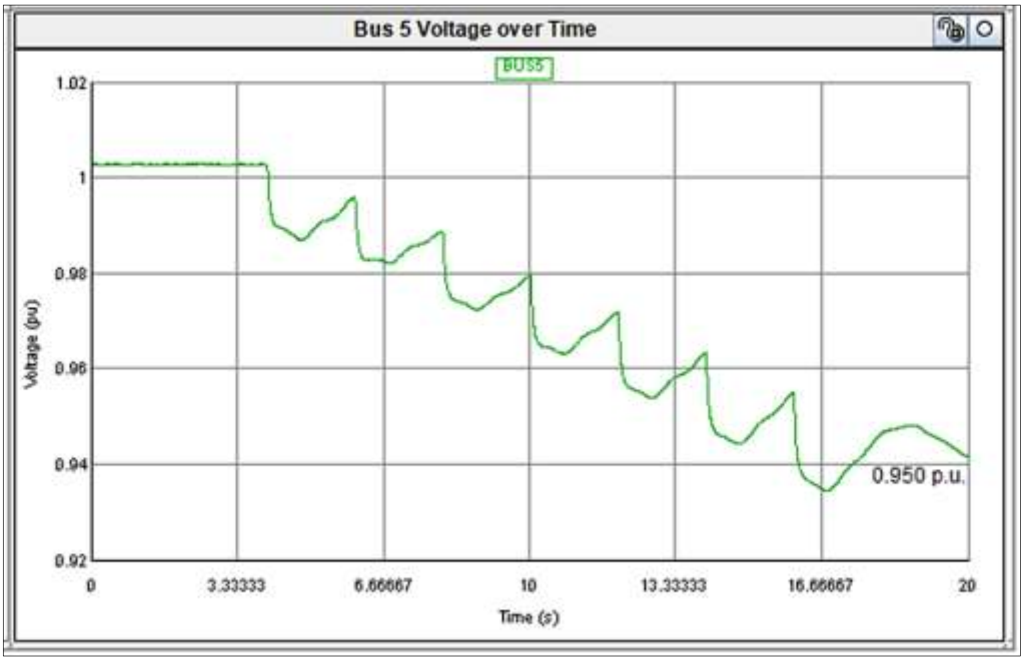


Figure 6 18: **Voltage recovering at bus 5 when PV action is simulated for 20 second**

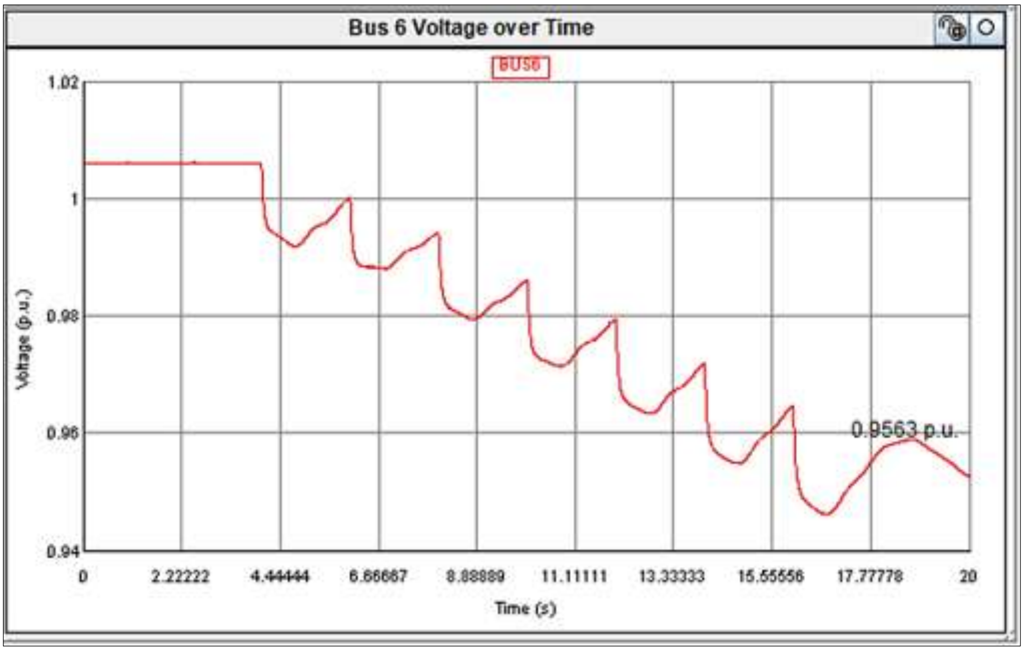


Figure 6 19: **Voltage recovering at bus 6 when PV action is simulated for 20 second**

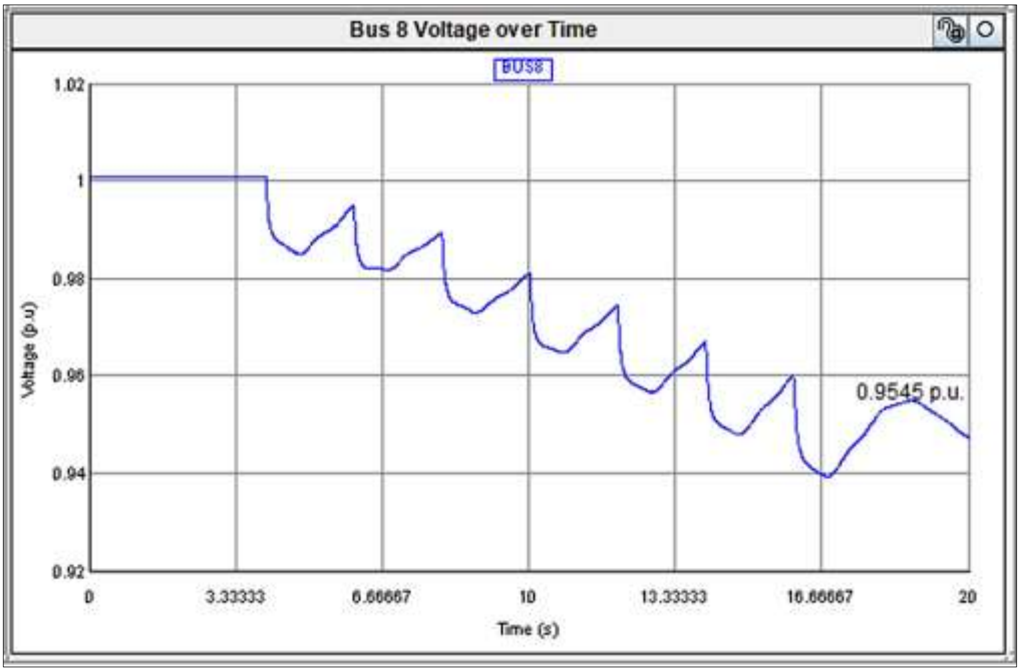


Figure 6 20: **Voltage recovering at bus 8 when PV action is simulated for 20 second**

The PV action on the power system is positive in restoring the voltage magnitude to an acceptable level. The penetration of the PV in the power system can strengthen its impact on the entire system. The bus bar voltage profile as seen in figure 6.21 shows how the PV integration in the power system affects most of the bus bars by increasing their voltage magnitude.

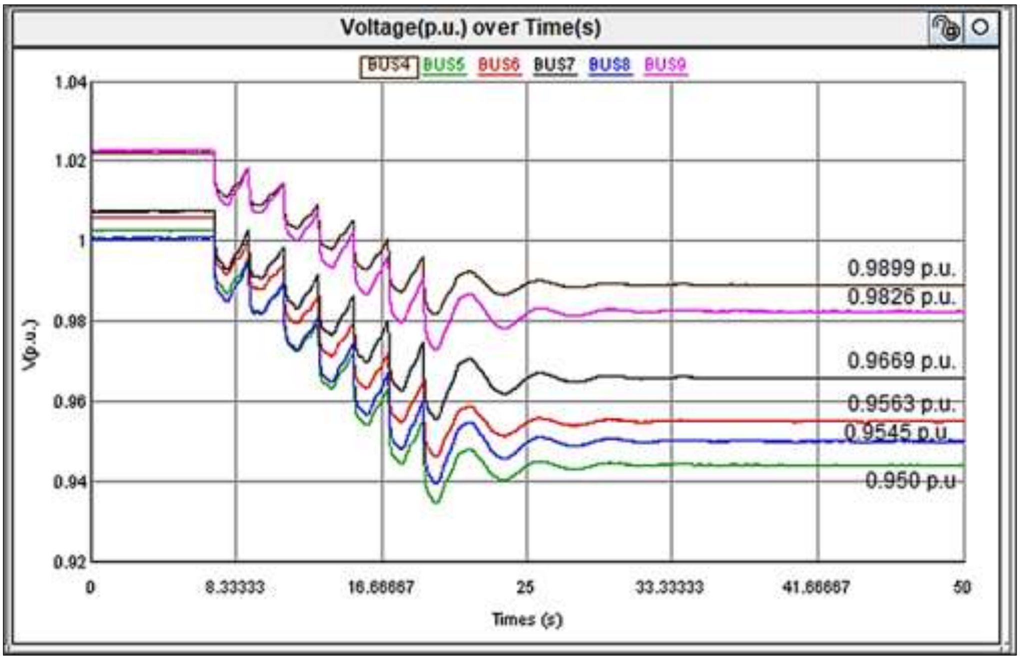


Figure 6 21: **Voltage recovery of all buses due to PV penetration when the system is simulated indefinitely,**

The case study results recorded from the real-time simulation are shown in Table 6.1. The results before and after the application of the control algorithm are drew

Table 6 1: **Summarise results of the impact of the algorithm on the simulation of power system with microgrid considering the disturbance**

Case study				Objectives			Type of disturbance			Control method	
Microgrid with the developed controller				The algorithm was developed to help the transmission network in recovering the voltage after voltage instability caused by the disturbance of increase of load consumption			Load demand increases by 20% in increments of 5% every 2 seconds of the simulation			Adaptive Volt/Var algorithm	
Monitored values of the transmission network											
Bus 5, Bus 6, and bus 8 voltage magnitude (p.u.)				**Active power interchange at bus bar (MW)**		**Reactive power interchange at bus bar (Mvar)**		**Total load demand (MW)**		**Total power generated (MW)**	
Bus	Base case	Under disturbance	PV integrated	before	after	before	after	before	after	before	after
5	0.9777 p.u.	0.9199 p.u.	0.950 p.u.	125	168.8	50	68.69	315.15	425.4	320	434.8
6	0.9984 p.u.	0.9463 p.u.	0.9563 p.u.	90	121.6	30	41.22				
8	0.9957 p.u.	0.9442 p.u.	0.9545 p.u	100	135	35	48.09				

6.4 Discussion of results

Table 6.1 is a description of all results recorded for the case study of a power system with integrated PV considering the disturbance. The result presents the contribution of the algorithm “adaptive volt/var control” in the smart grid for the voltage stability study. The results show that the implementation of the controller in RTDS supports the algorithm because the voltage versus power relation has been well supervised in supporting the transmission network to keep its voltage between the permissible magnitude for the safe operation of the grid. The contribution of the adaptive volt/var control scheme has improved the voltage stability of the grid after disturbance from dropping from 0.9199 p.u to 0.950 p.u. for bus 5, 0.9463 p.u. to 0.9563 for bus 6, and 0.9442 p.u. to 0.9545 for bus 8.

The response of the controller is good enough as it proves that even though the system is simulated indefinitely, the voltage magnitude remains stable and constant for the duration of the simulation. This is a good behaviour of the controller by keeping the inverter response active and sensitive to any change in voltage from the grid side.
The controller keeps the inverter response dependent on the instability of voltage caused by the disturbance. The gradual and dynamic response of the inverter also corresponds to the dynamic impact of the disturbance in the power system. The adaptative Volt/var control algorithm scheme is ideal for voltage control in a smart grid.
The integration of the PV into the power system shows that there is a relation between the profile of the 9-bus system voltage and the maximum level of penetration of the photovoltaic system. The observation made is that by interconnecting the PV to the power system, the profile of the power system tends to increase before even the inverter delivers the power to the electrical network. This can be justified by the concept of the PV as load, which forces the generators of the power system to supply more power from their reserve. These observations did not disturb the case study on the effectiveness of the proposed but helped to illustrate the voltage sensitivity of the PV neighbourhood to PV penetration level into the power system.

6.5 Conclusion

The stability of the power system is a major concern in modern society especially when microgrid PV is involved as part of the grid. The high penetration of the PV power in the transmission network brings some major concern about the safe operation of the grid unless some adequate control strategies are put in place to ensure that such integration does not negatively affect the grid but rather supports its normal operation. The control of PV power has been interrogated in the chapter. The proposed algorithm of adaptive volt/var control in a smart grid has been put to test on an IEEE 9 bus system model in a Real-Time Digital Simulator. The results obtained show that the control implemented in RTDS has managed to control the voltage versus power curve when a power system is subject to disturbance. The complete Volt/Var control task is concerned with keeping the system voltage profile within a preferred range and minimizing system losses by monitoring the reactive power flow between the microgrid PV and the Transmission network. The inverter function in accordance with the function of the adaptive volt/var algorithm is expected to respond gradually to the signal command received from the controller. The chapter demonstrates the feasibility of the adaptive volt/var control algorithm in a power system with a microgrid considering the disturbance. The description of the controller topology builds and simulated in Real-Time Digital Simulation was presented. Later in section two of the chapter, the simulation results of the modified IEEE 9 bus system with integrated PV microgrid are presented and discussed.

In summary, the chapter questioned the applicability of the adaptive volt/var control scheme in a power system with high penetration PV power considering the disturbance. The algorithm for voltage stability in a power system with a microgrid has been presented and confirmed as a possible solution to restore voltage stability after disturbance in a power system with a microgrid.

CHAPTER SEVEN
CONCLUSION AND RECOMMENDATION

7.1 Introduction

Power quality in the power system cannot be comprised as many things such as countries' economies, and customers day to day operations depend on it. Unfortunately for one reason or another, the quality of power can be comprised. Power utilities across the globe have come up with various ways to restore the quality of the power in the power system once the stability of the voltage is compromised. One of the many ways is to integrate microgrids in power systems for power reliability in a condition where there is a shortage of power or depletion of the primary source of energy or again where the need for clean energy is a major concern.

This thesis focuses on the development of a control scheme algorithm for the integration of renewable energy in the power system in the event of voltage instability due to disturbance. The IEEE 9 bus system has been modified for experimentation to achieve the aim and objective of this thesis. The base case of the IEEE 9 bus was investigated through a load flow analysis in DIgSILENT and RTDS. The reason for the load flow analysis considering the increase of load consumption as a disturbance was to demonstrate that the generator of the transmission system was unable to provide enough power to assist the power system in recovering its safe operational state. The intelligent control scheme "adaptive volt/var was developed as a mechanism to monitor the operation of the power system, to communicate with the inverter, and to constantly keep monitoring the grid during the entire simulation time.

The test benchmark control scheme was investigated in Real-Time Digital Simulation for better performance which can relate to actual-world scenarios. Therefore, this chapter gives a brief detail of the work performed to achieve the aim and objective of the thesis. Section 7.1 is the introduction; section 7.2 focuses on the deliverables of the study. section 7.3 presents the feasibility of the study as performed in an academic and industrial environment, and section 7.4 focuses on future work and recommendations, which can be undertaken to improve the work done in this thesis. section 7.5 of the chapter is dedicated to publications related to the researcher

7.2 Thesis delivery

This section outlines the summary of the work performed in achieving the aim and objectives of the thesis.

7.2.1 Literature review

A detailed literature review was reached in this study to investigate and present the progress made in voltage stability control in power systems with a microgrid. Various phenomena of power system instability, as well as their mitigation factor, were explored. The integration of the photovoltaic system in the power system and the impact of their integration was addressed. The use of electrical engineering books and IEEE journals related to voltage stability and microgrid integration in Power systems were used to assemble the literature review, which will direct the study's aim and objectives.

7.2.2 Theoretical aspect

The use of digital libraries, textbooks, and journals was used to develop the theoretical aspect of PV technology in the power system. PV power topology and generation technology were presented for a better understanding of PV as a distributed generation plant with appropriate control schemes.

7.2.3 System analysis of IEEE 9 bus system

The Load flow analysis was performed in the DIgSILENT simulation environment, and the real-time simulation RTDS was used to validate the results obtained in DIgSILENT. The contingency analysis in DIgSILENT was done to identify the factor that influences the stability of the power system. The contingency analysis led to uncovering bus 5 of the power system as the weakest bus in the system. Furthermore, a load event based on load consumption increase by 35% with an increment of 5% every two seconds was carried out in both cases as a preferred disturbance to understand how an increase in load demand affects the voltage stability of the power system. The results of the load event are crucial in the implementation of the PV system control algorithm in the power system.

7.2.4 Integration of solar photovoltaic system into a grid

The introduction of the microgrid to counteract the necessary quantity of power following a load consumption increase contingency was investigated. The solar power with a non-ideal controller is integrated into the IEEE 9 bus system and the impact was recorded. The non-ideal control loop was tested, and it was discovered not appropriate to restore the voltage stability. The non-ideal control creates more instability in the grid by increasing the voltage at the PPC beyond the acceptable voltage level for a steady-state electrical grid. The PV microgrid with a non-ideal controller has proven to be unable to restore the voltage of the grid at a safe magnitude as per the grid code.

7.2.5 The developed controller for integration of microgrid into the grid to mitigate voltage stability

The results obtained show that the adaptive volt/var control schemes implemented in RTDS have managed to regulate the voltage versus power curve when a power system is subject to disturbance. The proposed algorithm is built in RTDS/RSCAD and managed to support the power system in restoring the voltage stability after a disturbance caused by the increase of load demand pushes the voltage into instability. the applicability of the adaptive volt/var control scheme in a power system with high penetration PV power considering the disturbance was questioned and the algorithm for voltage stability in a power system with a microgrid has been presented and confirmed as a possible solution to restore the voltage stability after disturbance in power system with a microgrid. The algorithm reacted well to the dynamic simulation of the IEEE 9 bus system.

7.3 Academic and industrial application

This research has developed a real-time test bench where academics can refer to expand knowledge in voltage stability control schemes in power systems with a microgrid. This will also assist many students to understand the control systems of a photovoltaic system and the implementation of such a control system in a power system where microgrids are integrated. The developed control scheme built-in RTDS is suitable to replace old fashion control switches such as capacitors or STATCOM and other devices used in voltage stability control. By keeping the PV system constantly tied to the grid, The algorithm built-in RTDS uncovers the importance of Programmable Logic Controllers (PLC) in the power system, especially where the microgrid is installed far from the accessible site. The industry will also find in this thesis a suitable contribution to the effort of dealing with voltage stability and power shortage. Thus, to avoid the implementation of load-shedding.

7.4 Future Work

The thesis investigates a possible way for the safe operation of integrating solar PV power to the IEEE 9 bus transmission network with voltage instability as disturbance, in the future, the study could be extended its investigation to:

- Impacts of high penetration PV on harmonic content, fault currents, and grid protection apparatus.
- The capability of the inverter and the controller to regulate the output power when the solar PV power production is subject to dynamic climatic conditions.
- Impacts of penetration of hybrid renewable energy on the IEEE 9 bus system.
-

7.5 Publication

SD. Lumina, M.E.S Mnguni, Y Mfoumboulou 2022. Photovoltaic controller design based on Adaptive Volt/Var algorithm to stand the impact of load increase in grid tied microgrid system, Under review for publication in International Journal of Electrical and Electronic Engineering and Telecommunication (IJEETC).

SD. Lumina, M.E.S Mnguni, 2022. Photovoltaic energy integration issues: an investigation under voltage disturbance, Under review for publication in the International Journal of Electrical and Computer Engineering (IJECE).

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APPENDICES

APPENDIX A
IEEE 9 BUS SYSTEM DATA

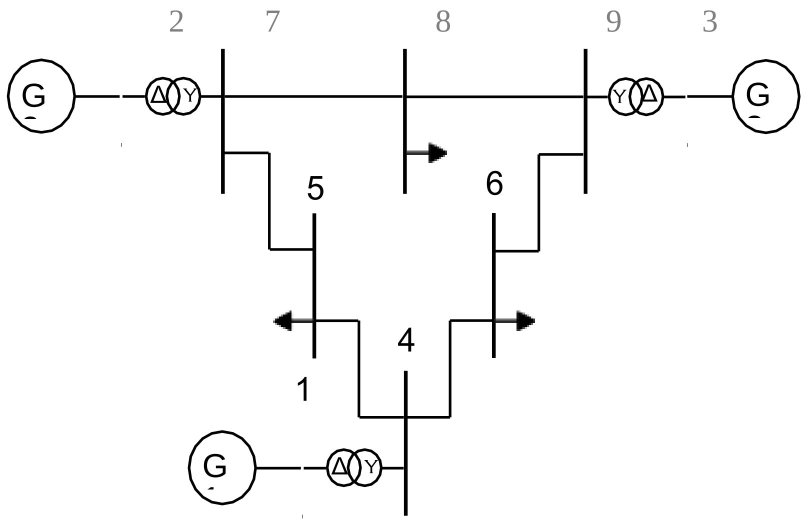

Figure A 1: IEEE 9 bus system

A.1 RSCAD/RTDS SYSTEM DATA

Table A 1: **RSCAD Power Flow Data expressed in 100 MVA**

BUS	Type	V (pu)	PG (MW)	QG (MVAr)	PL (MW)	QL (MVAr)
1	SLACK	1.040 ∠0.0°	71.6	27.0	-	-
2	P-V	1.025 ∠9.3°	163.0	6.7	-	-
3	P-V	1.025 ∠4.7°	85.0	-10.9	-	-
4	P-Q	1.026 ∠-2.2°	-	-	-	-
5	P-Q	0.996 ∠-4.0°	-	-	125.0	50.0
6	P-Q	1.013 ∠-3.7°	-	-	90.0	30.0
7	P-Q	1.026 ∠3.7°	-	-	-	-
8	P-Q	1.016 ∠0.7°	-	-	100.0	35.0
9	P-Q	1.032 ∠2.0°	-	-	-	-

Table A 2: IEEE 9 bus Line data in RSCAD

From BUS	To BUS	R (pu)	X (pu)	B (pu)
4	5	0.0100	0.0850	0.1760
4	6	0.0170	0.0920	0.1580
5	7	0.0320	0.1610	0.3060
6	9	0.0390	0.1700	0.3580
7	8	0.0085	0.0720	0.1490
8	9	0.0119	0.1008	0.2090

Table A 3: Transformer Data

From BUS	To BUS	R (pu)	X (pu)	Tap Ratio[1]
1	4	0.0	0.0576	1.0
2	7	0.0	0.0625	1.0
3	9	0.0	0.0586	1.0

Table A 4: Generator Data-1 (100 MVA Base)

GEN	BUS	Xa (pu)	Xd (pu)	Xd' (pu)	Xd" (pu)	Xq (pu)	Xq' (pu)	Xq" (pu)
1	5	0.01460	0.1460	0.0608	0.06	0.1000	0.0969	0.06
2	7	0.08958	0.8958	0.1198	0.11	0.8645	0.1969	0.11
3	9	0.13125	1.3125	0.1813	0.18	1.2578	0.2500	0.18

Table A 5: Generator Data-2 (100 MVA Base)

GEN	BUS	Ra (pu)[2]	Tdo' (s)	Tdo" (s)	Tqo' (s)	Tqo" (s)	H (s)	D(pu/pu)
1	5	0.000125	8.96	0.01	0.310	0.01	23.64	0.0
2	7	0.000125	6.00	0.01	0.535	0.01	6.40	0.0
3	9	0.000125	5.89	0.01	0.600	0.01	3.01	0.0

Table A 6: Exciter Data-1 (IEEE Type DC1A)

GEN	KA	TA	VRmin	Vrmax	KE	TE	KF	TF
1	20.0	0.2	-5.0	5.0	1.0	0.314	0.063	0.35
2	20.0	0.2	-5.0	5.0	1.0	0.314	0.063	0.35
3	20.0	0.2	-5.0	5.0	1.0	0.314	0.063	0.35

Table A 7: Exciter Data-2 (IEEE Type DC1A*)*

GEN	EX1	S(EX1)	EX2	S(EX2)
2	3.3	0.6602	4.5	4.2662
3	3.3	0.6602	4.5	4.2662
4	3.3	0.6602	4.5	4.2662

Table A 8: Governor Data (TGOV1)

GEN	R	T1	Vmax	Vmin	T2	T3	Dt
1	0.05	0.05	5.00	-5.00	2.1	7.0	0.0
2	0.05	0.05	5.00	-5.00	2.1	7.0	0.0
3	0.05	0.05	5.00	-5.00	2.1	7.0	0.0

A.2 DIgSILENT SYSTEM DATA

Table A 9: Power consumption per load in DIgSILENT

Load	Bus	P [MW]	Q [Mvar]
Load A	Bus 5	125	50
Load B	Bus 6	90	30
Load C	Bus 8	100	35

Table A 10: DIgSILENT Generator Data (x based on 100 MVA)

Quantity	G1	G2	G3
Nominal apparent power [MVA]	247.5	192.0	128.0
Nominal voltage [kV]	16.5	18.0	13.8
Nominal power factor	1.00	0.85	0.85
Type	hydro	steam	steam
Nominal speed [rpm]	180	3600	3600
x_d[p.u.]	0.1460	0.8958	1.3125
x'_d[p.u.]	0.0608	0.1198	0.1813
x_q[p.u.]	0.0969	0.8645	1.2578
x'_q[p.u.]	0.0969	0.1969	0.2500
x_l(leakage) [p.u.]	0.0336	0.0521	0.0742
τ'_{d0}[s]	8.960	6.000	5.890
τ'_{q0}[s]	0.000	0.535	0.600
Stored energy at the nominal speed [MW·s]	2364	640	301

Table A 11: **Generator Data in the Power Factory model (x based on rated power)**

Quantity	G1	G2	G3
Nominal apparent power [MVA]	247.5	192.0	128.0
Nominal voltage [kV]	16.5	18.0	13.8
Nominal power factor	1.00	0.85	0.85
Plant Category Rotor Type	Hydro salient pole	Coil round rotor	Coil round rotor
x_d[p.u.]	0.3614	1.7199	1.6800
x'_d[p.u.]	0.1505	0.2300	0.2321
x_q[p.u.]	0.2328	1.6598	1.6100
x'_q[p.u.]	-	0.3780	0.3200
x_l(leakage) [p.u.]	0.0832	0.1000	0.0950
τ'_{d0}[s]	8.960	6.000	5.890
τ'_{q0}[	-	0.535	0.600
Inertia Constant H (Rated to Pgn) [s]	9.5515	3.9216	2.7665

Table A 12: **Generator dispatch and voltage setpoints**

Generator	Bus	P [MW]	u [p.u.]
G1	Bus 1	N/A	1.040
G2	Bus 2	163.0	1.025
G3	Bus 3	85	1.025

Table A 13: Data of lines based on 100 MVA

From	To	r [p.u.]	x [p.u.]	b/2 [p.u.]
Bus 4	Bus 5	0.0100	0.0850	0.0880
Bus 4	Bus 6	0.0170	0.0920	0.0790
Bus 5	Bus 7	0.0320	0.1610	0.1530
Bus 6	Bus 9	0.0390	0.1700	0.1790
Bus 7	Bus 8	0.0085	0.0720	0.0745
Bus 8	Bus 9	0.0119	0.1008	0.1045

Table A 14: Data of lines in the Power Factory model

Line	From	To	R [Ω]	X [Ω]	B [μS]
Line 4-5	Bus 4	Bus 5	5.2900	44.9650	332.70
Line 4-6	Bus 4	Bus 6	8.9930	48.6680	298.69
Line 5-7	Bus 5	Bus 7	16.9288	85.1690	578.45
Line 6-9	Bus 6	Bus 9	20.6311	89.9300	676.75
Line 7-8	Bus 7	Bus 8	4.4965	38.0880	281.66
Line 8-9	Bus 8	Bus 9	6.2951	53.3232	395.08

Table A 15: Data of transformers based on 100 MVA

Transformer	From	To	Ur HV [kV]	Ur LV [kV]	x1 [p.u.]
T1	Bus 1	Bus 4	230	16.5	0.0576
T2	Bus 2	Bus 7	230	18.0	0.0625
T3	Bus 3	Bus 9	230	13.8	0.0586

Table A 16: **Data of transformers in the Power Factory model**

Transformer	From	To	Rated Power [MVA]	Ur HV [kV]	Ur LV [kV]	x1 [p.u.]
T1	Bus 1	Bus 4	250	230	16.5	0.1440
T2	Bus 2	Bus 7	200	230	18.0	0.1250
T3	Bus 3	Bus 9	150	230	13.8	0.0879

APPENDIX B
PHOTOVOLTAIC CONTROL DESIGN IN RTDS

B.1 Power and voltage measurement logic
B.1 P/Q Measurement at VSC terminal

The measurement logic unit of output active and reactive power summation developed on RSCAD in MW and MVars.

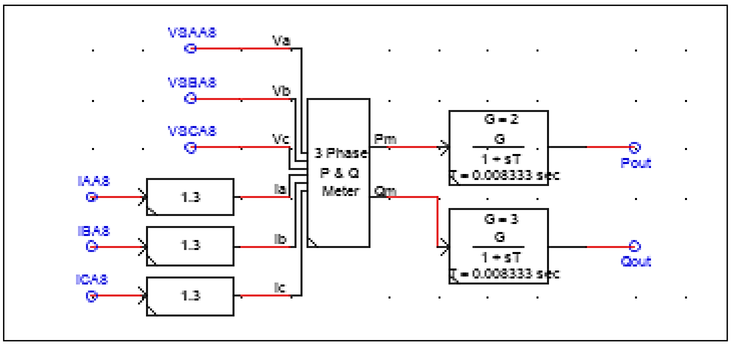

Figure B 1: Power measurement at VSC

B.2 Limit to PV open circuit voltage

The logic is used to limit the output voltage of the PV at 11KV

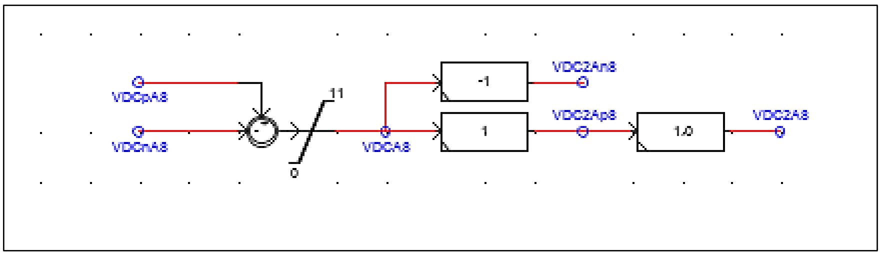

Figure B 2: Logic to control the limit of PV voltage

B.3 DC source power

The efficiency of the PV is measured through a DC source power logic

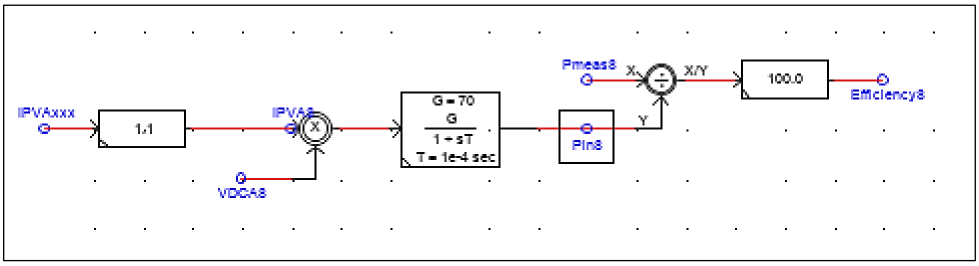

Figure B 3: PV efficiency measurement logic

B.2 Dq frame

B.2.2 ABC to dq VSC terminal voltage and current

The output voltage and current of the VSC terminal are transformed into dq voltage and dq current through a dq frame logic

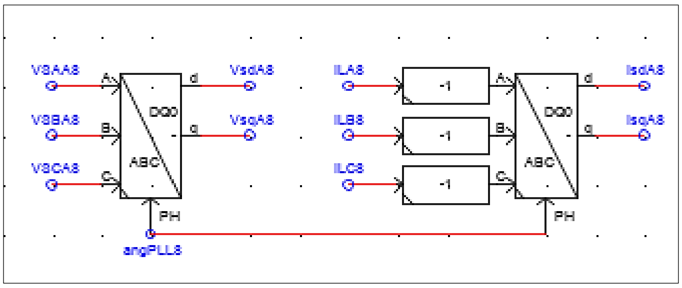

Figure B 4: ABC to dq frame terminal logic

B.2.3 inner loop dq current control

The logic is used to monitor the direct and quadrature grid currents, Id and Iq, respectively. The logic lets both active and reactive powers be monitored.

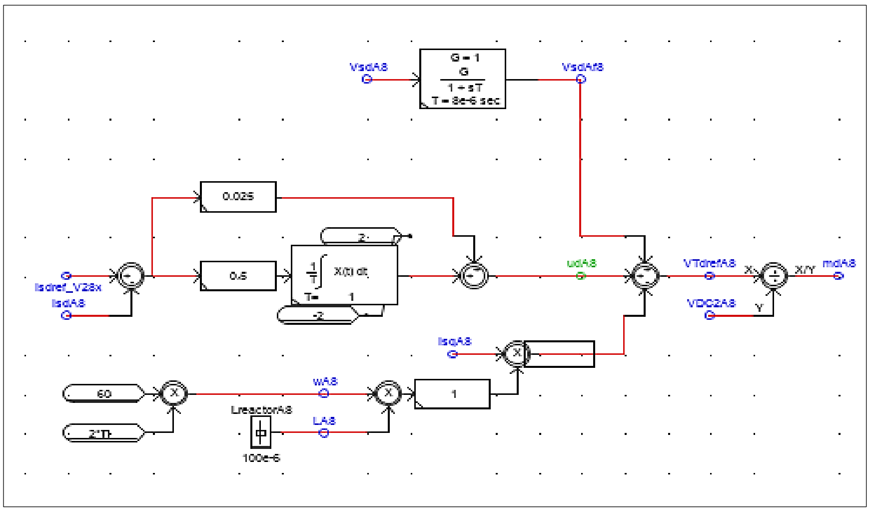

Figure B 5: Inner loop dq current control

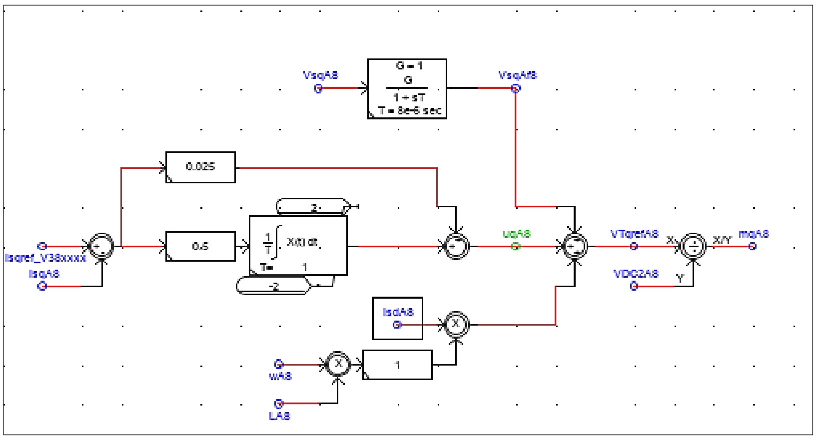

Figure B 6: Inner loop dq current control

B.3 MPPT outer loop

The maximum power tracking capability need to transfer power from the PV to the grid is done process with the help of the MPPT outer loop logic.

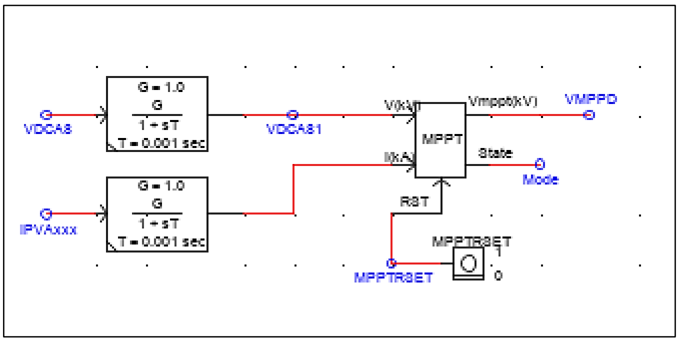

Figure B 7: MPPT outer loop control

B.4 Reference MI wave generator for DC/AC converter

The signal from the inner loop dq current control is processed across the wave generator together with the angle from the dq frame to generate a signal used by the VSC to generate the millimeter wave

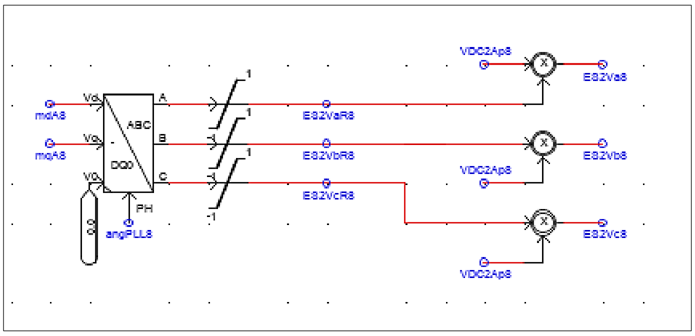

Figure B 8: A reference wave generator