POWER QUALITY CONTROL ALGORITHMS FOR SMALL-SCALE POWER INTEGRATION SYSTEM

by

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DECLARATION

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

30 May 2024

Signed **Date**

ABSTRACT

The electrical power system is a means of supplying energy that is intended to generate, transport and supply electricity to various kinds of loads that are connected to it. The electricity providers strive to supply their customers with steady and uninterrupted sinusoidal power as they function. Traditional power plants primarily rely on fossil fuels such as coal for their energy source. Because of the influence of global warming, air pollution is becoming a major concern in traditional coal-based power generation, and measures to reduce it have been implemented. South Africa is among the many African nations that have ratified these international agreements. Incorporating renewable energy sources is the sole method to establish an environmentally friendly power generation system. Integrating various energy resources at the distribution level is possible and helps to reduce transmission power losses. However, integration of renewable energy resources requires the use of advanced non-linear technological equipment which causes some technical problems. Amongst technical problems that may be faced is high penetration of solar Photovoltaic (PV) which results in voltage swell power quality issues whilst excessive connection of non-linear load results in current harmonics.

The thesis examines the use of Custom Power Devices (CPDs) such as Dynamic Voltage Restorer (DVR), Distribution Static Compensator (DSTATCOM), and Unified Power Quality Conditioner (UPQC) for voltage and current-related power quality issues. The CPDs depend on the DC link voltage from the storage element used which is not always sufficient and the compensation of the power quality issues fail. The use of small-scale solar PV for the support of the DC-link storage element used in the CPDs is explored.

A DVR has been proposed for the mitigation of voltage-related issues to ensure that the grid supplies power with voltage variation to sensitive loads. The load is protected from such and in the case where the DC link storage is not enough solar PV will support the DVR. However, this type of compensation has proved unable to deal with harmonics caused by the non-linear load connected to the system which meant another CPD has to be proposed for current related issues. A DSTATCOM is a device that can used for compensation of current-related power quality issues but also cannot deal with voltage power quality issues. A right shunt UPQC has been proposed as a combination of the two devices connected back-to-back through the DC link side for voltage and current multiple power quality issues. Optimisation of effective compensation for the CPDs depends on the proper selection of control algorithms for the gate switching of the Voltage Source Converters (VSCs) used. A control algorithm has been implemented considering the stated dynamic behaviours of the power system to ensure that the CPDs can restore the power quality required by the consumer and the utilities as regulated by IEEE standards. The modelling and simulation were performed on MATLAB Simulink simulation software.

Keywords – Power Quality, IEEE13 Bus radial Distribution Network, Small Scale Power Integration, Smart Grids, Micro Grids, Distributed Generation, Renewable Energy Sources, Solar PV, DVR, DSTATCOM, UPQC, MATLAB Simulink

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DEDICATION

This thesis/dissertation is dedicated to my mother Nosiphelele Mlamla, my father Headman Mafu Mlamla and my beautiful daughter Indakhile Limingothando Machane.

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NOMENCLATURE

ABBREVIATIONS AND ACRONYMS

3P3W	Three phase three wire
ANN	Artificial Neural Network
APF	Active Power Filter
CPD	Custom Power Devices
DC	Direct Current
DER	Distributed Energy Resource
Dev.	Deviation
D-FACTS	Distributed Flexible Alternating Current Transmission Systems
DG	Distributed Generation
DSTATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
FL	Fuzzy Logic
HCC	Hysteresis current controller
HC-LMS	Hyperbolic Coosine Least Mean Square
HVDC	High Voltage Direct Current
IEC	International Electro-technical Committee
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IRP	Integrated Resource Plan
IRPT	Instantaneous Reactive Power Theorem
ISCT	Instantaneous Symmetrical Component Theory
kV	Kilo Volt
kW	Kilowatt (one-thousandth of a megawatt)
LMF	Least Mean Fourth
LMS	Least mean Square
LPF	Low Pass Filter
LV	Low Voltage
MATLAB	**MAT**trix **LAB**oratory
Max.	Maximum
MGs	Micro-Grids
MOSFET	Metal Oxide Field Effect Transistor
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
NAN	Neighbourhood Area Network

NERSA	National Energy Regulator of South Africa; alternatively the Regulator
N-LMS	Normalise Least Mean Square
NRS	National Regulatory Services
PBT	Power Balance Theory
PCC	Point of Common Coupling
PI	Proportional and Integral
PLL	Phase Locked Loop
PPF	Passive Power Filter
PQ	Power Quality
PU	Per Unit
PV	Photovoltaic
PWM	Pulse Width Modulation
RE	Renewable Energy
RES	Renewable Energy System
SAPF	Shunt Active Power Filter
SPV	Solar Photo-Voltaic
SRFT	Synchronous Reference Frame Theorem,
SSEG	Small Scale Embedded Generations
STATCOM	Static Synchronous Compensator
THD	Total Harmonic Distortion
UPQC	Unified Power Quality Conditioner
VL-LMS	Variable Leaky Least Mean Square
VSC	Voltage Source Converter
VSS-LMS	Variable Step Size Least Mean Square

GLOSSARY OF TERMS

Apparent Impedance:	The impedance to a fault as seen by a distance relay is determined by the applied current and voltage. It may be different from the actual impedance because of the current outfeed or current infeed at some point between the relay and the fault.
MATLAB/Simulink:	Simulink is a graphical programming environment that uses MATLAB to model, simulate, and analyse multidomain dynamical systems. Its main interface consists of a graphical block diagramming tool and a collection of block libraries that may be customized.
Microgrid:	Integrates loads and distributed energy resources connected in a distribution system, working in isolation from the power system grid and centrally controlled. It can have the option of being integrated into the power grid or operating in island mode.
Power Quality (PQ):	The grid's capacity to provide a reliable, clean power supply is defined by a pure sinusoidal wave operating in prescribed voltage and frequency ranges.
Power-Electronic Converter	A solid-state electronic device used for controlling and altering the shape or magnitude of electrical impulses, such as from AC to DC, DC to AC, or DC to DC. Due to the switching action utilised during the conversion process, devices often run at high frequency.

CHAPTER ONE
BACKGROUND AND MOTIVATION

1.1. Introduction

The electricity sector in South Africa has several problems, including inadequate network performance, a lack of generation capacity, a substantial infrastructure backlog, and an aging infrastructure (Masembe, 2015). The major problem confronting the sector is the aging infrastructure as mentioned by the Development Bank of South Africa (DBSA, 2012).

South Africa's distribution system is still built on technology from the twentieth century (DBSA, 2012). Figure 1.1 gives a typical representation of traditional power, it is a centralised system where the power is generated and transmitted over long lines at high voltage (HV), then stepped down to feed the customers and it comprises one-way communication systems.

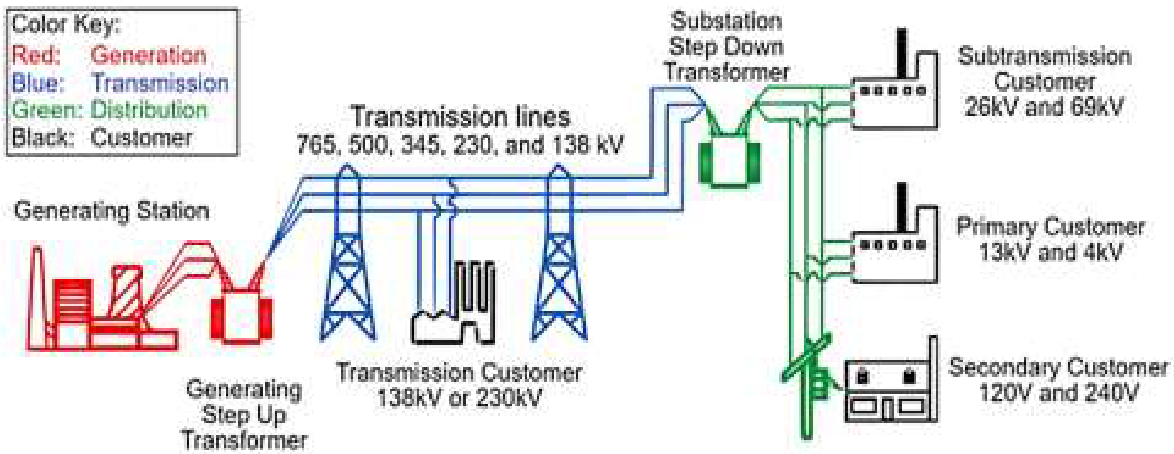


Figure 1.1: **Typical Traditional Power Grid** (DoE, 2015)

In South Africa, it is clear that technological disruptions are unavoidable in traditional electricity distribution systems (Department of Mineral Resources and Energy, 2019). A Smart Grid (SG) uses advanced innovative Information and Communications Technology (ICT) technologies to provide the necessary intelligence to effectively integrate the heterogeneous systems that must seamlessly interoperate to deliver quality, reliable, secure, affordable, efficient, and sustainable electricity, can address power system issues faced by many countries such as South Africa which suffers from the insufficient supply, aging infrastructure and high carbon emissions.

Utilities are developing and adopting SG technology to bring electricity systems into the twenty-first century through computer-based remote control and automation (Masembe, 2015). The SG makes use of Small-scale decentralised generation, distributed control, active customer side and Universal Internet Information and Communication Technologies ICT technologies.

Figure 1.2 shows the past, present and future power systems. The future power system shown is regarded as the SG which is the future concept of the power system to enable the resolution of many issues faced by the present power systems.

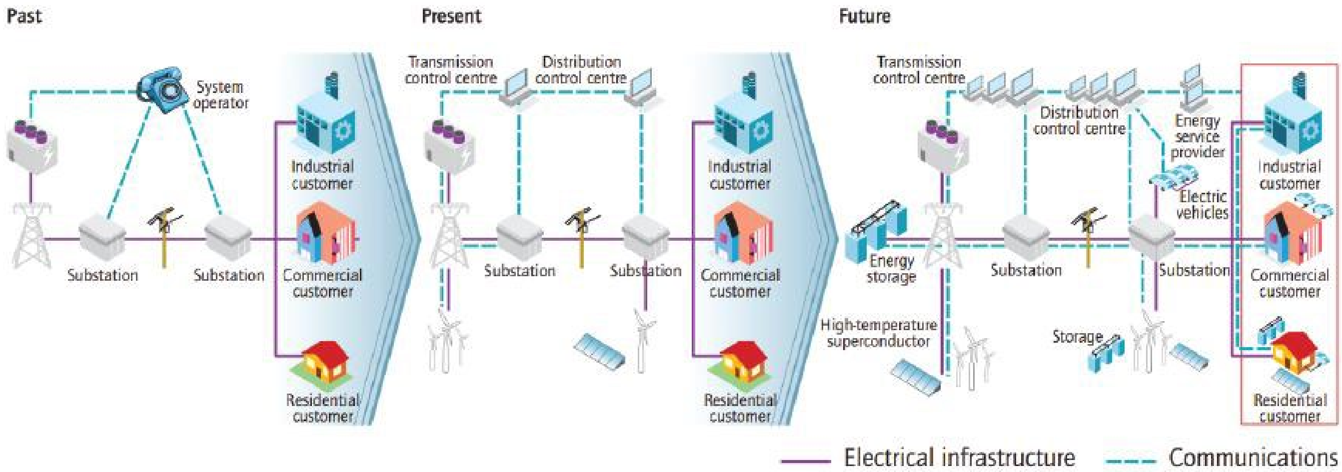


Figure 1.2: Architecture of Past, Present, and Future of Power system (DoE, 2015)

South Africa's government supports and has begun integrating Distributed Energy Resources (DER), such as Renewable Energy Generation, Embedded Generation (EG), and Distributed Generation (DG), into the country's future producing mix (Bello et al, 2013). The use of SGs also addresses the environmental issues due to the fossil fuel-based traditional power systems. In South Africa, electricity generation contributes to 50% of the total energy sector which contributes close to 80% in the country (IRP, 2019).

The present Power system illustrated in Figure 1.2 suffers from Power Quality (PQ) problems due to the growing use of power electronic devices for harmonic generation, utility, and customer disturbances (Kumar et al., 2007) (Kwan et al., 2009). For long-term growth, a dependable and strong electrical power supply network is essential. Continuous supply of the three types of load we have which are linear load, non-linear and sensitive loads may be ensured by resolving issues more quickly.

1.2. Awareness of the Research Problem

In South Africa, several electricity distributors, such as Eskom, and municipalities are allowing the integration of Small Scale Embedded Generators (SSEGs) to avoid national blackouts due to a lack of generation capacity, reduce CO_2 emissions caused by a number of traditional fossil fuel-based generation, address municipal revenue problems, mitigate electricity price increases, and provide customers with an alternative to traditional fossil fuel-based generation which will also give opportunity for them to redefine their position in the power value chain (Eskom, 2020)(SSEG, 2019).

Table 1.1 below shows South Africa's Integrated Resource Plan (IRP) where installed, committed/contracted and new additional capacity for the year 2018 to 2030 with also their different energy sources like coal, nuclear, embedded generation,.etc.

Table 1.1: **South Africa's IRP2019**

	Coal (MW)	**Nuclear** (MW)	**Hydro** (MW)	**Storage** (Pumped storage) [MW]	**PV** (MW)	**Wind** (MW)	**CSP** (MW)	**Gas / Diesel** (MW)	**Other** (CoGen, Biomass, Lanfill) [MW]	**Embedded Generation** (MW)
2018	39126	1860	2196	2912	1474	1980	300	3830	499	Unknown
2019	2155					244	300			200
2020	1433				114	300				200
2021	1433				300	818				200
2022	711				400					200
2023	500									200
2024	500									200
2025					670	200				200
2026					1000	1500		2250		200
2027					1000	1600		1200		200
2028					1000	1600		1800		200
2029					1000	1600		2850		200
2030			2500		1000	1600				200
INSTALLED (MW)	**33847**	**1860**	**4696**	**2912**	**7958**	**11442**	**600**	**11930**	**499**	**2400**
Installed Capacity Mix (%)	**44.6**	**2.5**	**6.2**	**3.8**	**10.5**	**15.1**	**0.9**	**15.7**	**0.7**	

Installed Capacity
Committed / Already Contracted Capacity
New Additional Capacity (IRP Update)

The IRP2019 is a revised plan of 2010-2030 which was promoted in March 2011 by South Africa's National Development Plan (NDP) in articulating its 2030 long-term idea for the energy sector. Since the promulgation of the IRP2010-2030, a new generation of about 18GW has been committed (IRP, 2019). In South Africa's four major metros (eKurhuleni, Johannesburg, eThekwini, and Cape Town), photovoltaic-based SSEGs have an installed capacity of 38.46 MWp, with commercial users accounting for 29.08 MWp of that total which is about 0.08% of the country's total capacity generated (Filipova and Morris, 2018).

Figure 1.3 shows an indicative bar graph for generated capacity in terms of three types of systems which are municipal, residential, and commercial from renewable energy resources. These four metros have totals of 29.08MWp, 4.51MWp and 1.36MWp from commercial, municipal and Residential respectively as shown in Figure 1.3. The commercial is leading the race.

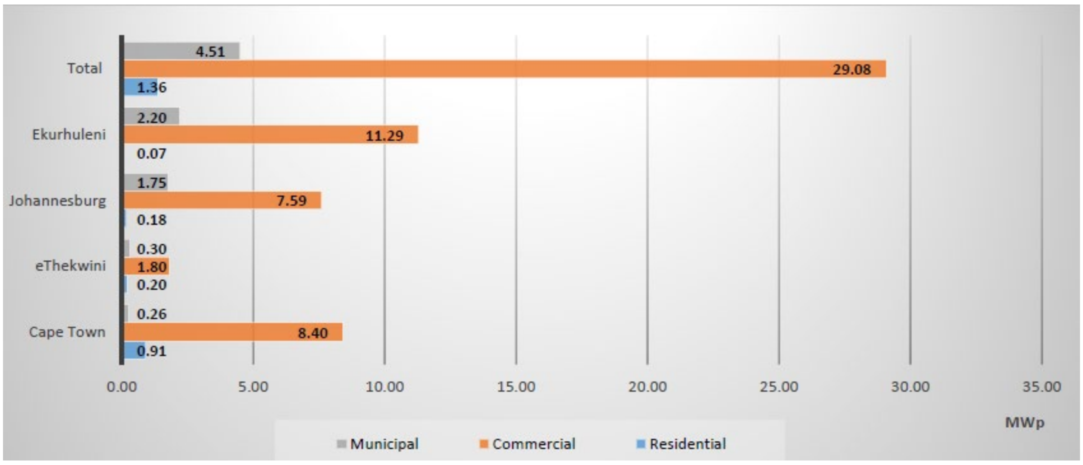


Figure 1.3: Installed SSEG's legally (Filipova and Morris, 2018)

The majority of small-scale generating methods have low capacity factors, which means that electricity is generally not generated at all hours of the day or night. Intermittent power producers must be integrated and managed using smart technologies for a balanced and safe linked power system to operate sustainably (Department of Mineral Resources and Energy, 2019).

The infrastructure that has reached the end of its life span will be decommissioned with some like Koeberg reaching a 40-year life span in 2024, however, due to the generation capacity crisis the life of the Koeberg nuclear-generating station will have extended design life and renewed license. The IRP 2019 indicates the coal-generating plants that will be decommissioned as a result of the end of life and are non-performing like Grootvlei, Komati, Hendrina, and Camden. The customers should anticipate continued power outages driven by this lack of capacity and poor quality as a result of disturbances in the network. On the other hand, the integration of SSEGs will increase sharply though they have negative implications such as PQ.

1.3. Statement of the Research Problem

The Smart Grid (SG) concept intends on extensive use of renewable energy sources (RESs) which are not reliable because of their dependency on weather conditions. As indicated in the introduction and the awareness of the problem, the power quality of the network will be compromised/disturbed, and the country is yet to be subjected to a lot of customers sharing power (Load Shedding) as the power capacity issue is yet to be resolved. These are all the issues mentioned that affect the power quality of the network. In the distribution network, there are 3 types of loads which are linear load, non-linear and sensitive loads are very sensitive to poor power quality.

Problem statement: To investigate techniques that can be used to address the voltage and harmonics which are part of power quality issues that arise as a result of the integration of small-scale power generation and technology advancement. The high penetration solar PV which is weather-dependent might cause voltage variation (Sag and swell) on the distribution network and connection of these RES which make use of advanced non-linear technological equipment that causes harmonics. The use of CPD depends on the DC link storage and if it is not enough the controller fails to compensate for the power quality disturbance.

1.4. Research Aim and Objectives

1.4.1. Research aim

The study aims to investigate and develop voltage and harmonics power quality control algorithms and mitigation methods for future Microgrids which will be RES supported on the DC link side for effective compensation of power quality and compliance with IEEE power quality standards.

1.4.2. Objectives of the research

The objectives of the research are as follows where the following needs to be developed:

- Literature review on the traditional, current, and future (Smart Grid) methods used to deal with Power Quality (PQ) issues looking at voltage, current, harmonics control and mitigation strategies for distribution networks particularly the low voltage where the SSEGs are integrated, a comparative analysis of the developments has been conducted.

- Background theory of Custom Power Devices (CPDs) which are Active Power Filter (APFs) that use Voltage Source Converters (VSCs) for mitigation of power quality issues. International and National Power Quality standards should be adhered to for good power supply.
- Modelling, simulation, and analysis of the distribution network considered with Dynamic Voltage Restorer (DVR) proposed for compensation of voltage sag and swell coming from the grid to protect sensitive loads. Solar PV is also considered for DC link voltage support in the case when the DC link storage is not enough for compensation of the PQ issues states.
- Modelling and simulation of Distribution Static Compensator (DSTATCOM) for compensation of current related power quality issues when the non-linear load is connected and should not affect the grid quality.
- Modelling and simulation of Unified Power Quality Conditioner (UPQC) proposed for compensation of multiple voltages and current power quality issues. The DC link voltage is controlled using an Instantaneous Reactive Power Theory (IRPT) based control algorithm to ensure that it is maintained at a DC voltage of 700V which would enable the controller to compensate for the Power Quality issue. Solar PV has also been proposed for DC link voltage support for effective power quality compensation.
- Investigation of the performance of the algorithm for various types of operating conditions, and comparison of the performance of the developed algorithms.
- The modelling, simulations and analysis has been done in MATLAB Simulink software environment.

1.5. Hypothesis

The proposed power quality device and control algorithms will be able to compensate for multiple power quality issues that may occur in the distribution network. This will be achieved by the integration of small-scale solar PV which will be used to support the DC link voltage when the storage element is not enough for full compensation of the power quality disturbances.

1.6. Delimitation of Research

The research project focuses on the control and mitigation of voltage and current-related power quality issues, with an emphasis on voltage sag and swell supplied by the grid to sensitive non-linear load. It also emphasizes the mitigation of harmonic currents caused by the connection of non-linear loads. The optimisation of the proposed device depends on a proper control algorithm and enough DC storage capacity which can be supported by solar PV for effective compensation. The following outlines the issues and analysis addressed in this project:

- Case study for distribution network where it analysed in steady state and when there is grid disturbance focusing on the voltage and Total Harmonics Distortion of the grid voltage and current.
- Case study when the DC link storage is less than the calculated values for all the proposed devices with an emphasis on voltage and current disturbance mitigation.
- Proposed a combination device for multiple voltage and current-related power quality issues.

1.7. Motivation for the Research Project

The importance of giving guaranteed power to the end-users and industries instead of supplying them a power with quality issues is of main concern. The SG initiative has ensured that it does not add the same issue to the consumers. Power quality should be sustained to the highest customer satisfaction, with minimum strain on power supply companies or distributed generators, to ensure dependable MG operation.

1.8. Assumptions

The following assumptions are considered in this project:

- A sensitive non-linear load has been connected at the end distribution network.
- An unstable grid supply with voltage sag and swell is considered.
- Through the Power Quality measured and monitored by the customer, the communication will also be sent to the PQ control device to rectify or mitigate the PQ issue identified.
- The rectification will make use of filtering large voltage pulses and have power when there is an under-voltage.
- The Power Quality control system will make use of two APFs with the first one connected in series to the network through an injected transformer and this type of connection is known individually as Dynamic Voltage Restorers (DVR) to deal with voltage-related PQ issues. The second APF will be connected in shunt to the load, and this connection resembles individually a DSTATCOM which is reported in many studies as being able to compensate for current related PQ issues like harmonics.

- The DC link storage element will not always be enough and a PV that generates power in DC voltages is used for the voltage support of the proposed VSC devices.
- The control of two APFs used in UPQC should be controlled individually and they optimise the effectiveness of the controllers.

1.9. Research Design and Methodology

The focus of this project is on improving the operation of devices with their control algorithms used for voltage and current power quality mitigation and compensation in a distribution network with disturbances. Integration of solar PV is also considered for support of the DC storage element of the VSCs of the APF used for compensation in the case the storage is not enough.

1.9.1. Literature review

There are many control devices with different control algorithms currently used and this study focuses a proposing a device that will be able to compensate for multiple power quality issues optimised for effectiveness using a proper control algorithm. In the case where the DC link storage of the APF is not enough, the controller must be able to use integrated power from the small-scale power for the support of the DC link voltage of the VSCs. The information about the study of the components used/proposed has been gathered through Harzing's publish and perish which assisted in getting related books, internet browsing and published journals to ensure the desired outcomes are met.

1.9.2. Method for the power system voltage stability control

The are many power quality mitigation tools like passive filters that could be used but have resonance problems, dependent on the system impedance, absorb harmonics currents from non-linear which get propagated through the system. However, the use of Active Power Filters (APFs) which do not have such drawbacks is used with an emphasis on the UPQC and its control algorithms and DC link support. The following are the major benefits of selecting the APFs for power quality compensation:

- The ability to inject or absorb appropriate magnitudes of voltage and current to compensate for the disturbance experienced in the system.
- The ability to enable integration of solar PV to meet distribution network demands whilst also being able to support the DC link side of the VSC in the case the storage element fails the controller during the compensation/restore.

- The ability of the UPQC to compensate for multiple voltage and current-related power quality issues and the use of control algorithms do their best to maintain the DC link voltage at the reference value.

1.9.3. Simulation

The modelling, simulation and analysis of the investigation and implementation have been conducted using MATLAB Simulink software. A radial distribution network has been considered with a sensitive non-linear load connected. Scopes are used to view the signals and the data is logged into the workspace for further analysis. Fast Fourier Transform (FFT) of the powergui has been used for the analysis of Total Harmonic Distortion (THD) of the voltage and current signals. Trace selection is used for analysis of the signals on the scopes. The results from MATLAB Simulink are used for validation of the calculated results. The dynamic disturbance considered in this study is a connection between a non-linear load and an unstable grid supplying power with variation to sensitive loads.

1.9.4. Data collection

The outcomes and parameters of the control scheme that was created with MATLAB Simulink are gathered to develop a new control scheme on a different simulation platform. The outcomes of the computation are contrasted with software. For the control scheme to be implemented effectively and efficiently in real-time, a proper evaluation of its behaviour must be done when comparing the designed control across various platforms.

1.10. Thesis chapters

This thesis is composed of seven chapters and an appendix. The description of what these chapters and appendixes contain is as follows:

1.10.1. Chapter 1

This chapter includes an overview of the research background, goals, awareness of the issue, research motivation, problem statement, subproblems, hypothesis, research delimitation, project assumptions, research design, research design and methodology, thesis chapter breakdown, and conclusion.

1.10.2. Chapter 2

The literature on basic power system voltage power quality, significant causes of power quality, methods and devices used in power quality control, and the impact of Small-Scale Embedded Generators (SSEGs) without and without their integration on voltage power quality are covered in this chapter. Various articles related to power system frequency stability were reviewed.

1.10.3. Chapter 3

This chapter, a detailed background theory of Custom Power Devices (CPDs) and their control algorithms which are used for optimisation. The National and international standards that are used to define power quality are defined.

1.10.4. Chapter 4

This chapter defines the modelling, simulation, and analysis of a radial distribution network with a non-linear load. A steady state and dynamic state of the distribution network considering the analysis of voltage and current signals to get their THD which defines the level of harmonics in the system that might be injected to the grid. Dynamic disturbances such as voltage sag and swell supplied by unstable grid connections are analysed with the connection of Dynamic Voltage Restorer (DVR) for compensation of the voltage variation supplied by the grid. Solar PV has been proposed for support when the DC link storage of the device is not enough. The DVR could not be compensated for the current harmonics caused by the non-linear load connected.

1.10.5. Chapter 5

In this chapter, a Distribution Static Compensator (DSTATCOM) has been proposed for compensation of the current related issues like the harmonics introduced by the connected non-linear load at the end.

1.10.6. Chapter 6

The chapter focuses on the combination of the two compensation devices for multiple power quality compensation and integration of the control algorithms of the APF devices connected back-to-back through the DC link side. It has been noted that as much as the optimisation of the UPQC device which combines the two APFs depends on the effective control algorithms but when the storage is not enough the controller will not be able to compensate for any of the power quality issues. Solar PV as part of Small-Scale Embedded Generation (SSEGs) has been proposed for support of the DC link voltage.

1.10.7. Chapter 7

This chapter reviews the important findings, the research deliverables, and the results obtained. This chapter also considers the suggestions for the future.

1.10.8. Appendix A

All the distribution network data utilised in this thesis is presented in this Appendix. The MATLAB Simulink software is the source of the data.

1.10.9. Appendix B

This Appendix gives additional information on the MATLAB Simulink control blocks for the series and shunt APFs. It also gives details of the solar PV connected for the support of the DC link voltage and the control algorithms used for the Maximum Power Point Tracking (MPPT) used in the DC-DC boost converter.

CHAPTER TWO
LITERATURE REVIEW

2.1. Introduction

Solar Photovoltaic (PV) Small Scale Embedded Generators (SSEGs) are being integrated into the power grid due to high energy demand, rising prices, environmental awareness, and the risk of power shutdowns. The low voltage distribution network lacks automation and already experiences some power quality issues at different time intervals as a result of different types of loads used. The integration of Distributed Generators (DGs) especially from the Renewable Energy Sources (RES) introduces power quality issues due to the intermittency of these RES.

This chapter presents existing literature on voltage sag/swell power quality algorithms in the Low Voltage (LV) distribution network. Section 2.2 of this chapter presents a process that has been used to gather existing literature. Section 2.3 gives a summary of Small-Scale Embedded Generators (SSEGs). Section 2.4 presents an overview of voltage power quality where the focus is on voltage sag and swell. In section 2.5 the process used when integrating the SSEGs has been indicated. Section 2.6 presents the Smart Grid (SG) concept through an application of the IEC 61850 standard which is globally adopted as a concept that will ensure the Automation, Control, and two-way communication by electricity network. An overview of this concept has been given in detail and how it is going to be applied in this case of the low voltage distribution network with voltage power quality issues. Section 2.7 presents an application of the IEC 61850 standard. Section 2.8 presents a brief theory on the Micro Grids (MGs) which is a smart grid concept where generators are in the same area of power consumption. Section 2.9 presents a review of the existing literature on voltage sag and swell power quality mitigation strategies focusing on the proposed controllers and the control algorithms conducted with comparative analysis.

2.2. Literature Search of existing voltage sag/swell control

The majority of small-scale generation technologies have low generation capacity factors, which means that power is normally not provided at all hours of the day and night. (Department of Mineral Resources and Energy, 2019) indicates that intermittent power generators must be integrated and managed by smart technology for a balanced and stable interconnected power system to be operated sustainably.

The connection of any generator to the electrical grid, regardless of its size, has a number of implications for the local utility. The implications of allowing small-scale Distributed Generations (DGs) sources create a challenge to power quality monitoring and control on the local supply (Department of Mineral Resources and Energy, 2019). This necessitates research on power monitoring and control systems, as there is a need to transition to smart technology distribution. Microgrids (MGs) are introduced as small-scale power systems that consist of local generation, local loads, and energy storage systems, enabling distributed generation (DG) to work together effectively.

A review of the voltage power quality control techniques without and with a connection of SSEGs to the low voltage distribution utility grid has been conducted. The review has been conducted to provide a clear understanding of the behaviour and technology advancement of the network, understanding potential problems and the best approaches for addressing or minimizing them enables the development of context as well as an understanding of the solutions available.

The study focuses on two areas that require a review and analysis which are voltage power quality control techniques in low voltage distribution networks **without** and **with** the integration of SSEGs. The search was conducted using Harzing's Publish and Perish tool. Figure 2.1 shows a bar graph that shows the number of papers each year for all the groups or key focus areas:

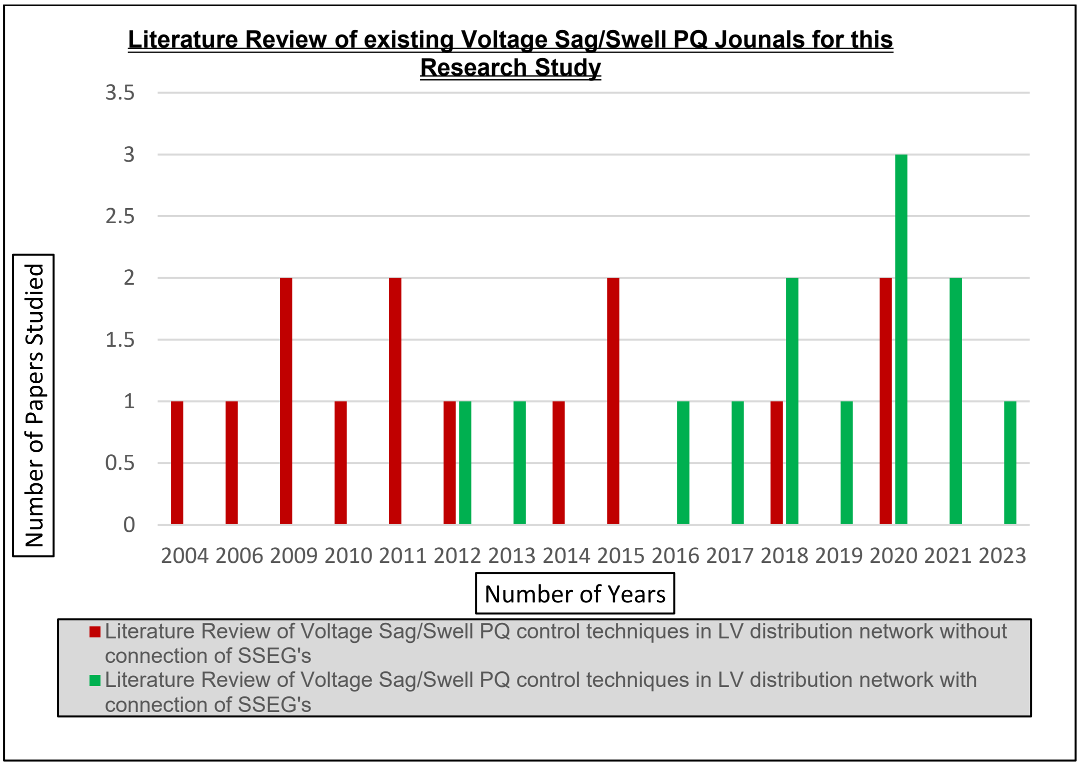


Figure 2.4: **Number of papers studied in research**

The graph indicates that there were 27 journals studied and analysed for voltage sag/swell power quality from 2004 until 2023, 14 of those papers between 2004 and 2020 are previous studies that focused on voltage sag/swell compensation control algorithms considering the use of Voltage Source Converters (VSC’s) without integrating SSEG’s in low voltage distribution network and the remaining 13 papers looked at when the SSEG’s are connected & synchronised to the utility system.

2.3. Small Scale Embedded Generation

A Small-Scale Embedded Generator (SSEG) is an Embedded Generator with a generation capacity of less than 1MVA/MW peak production energy. They are generation facilities that are found on residential, commercial, or industrial sites where electricity is also consumed (Filipova & Morris, 2018). The majority of them are solar photovoltaic (PV) systems, but there are also wind and biogas technologies included (Roberts & Manzini, 2017). The majority of the electricity generated by an SSEG is consumed on-site, but when production exceeds consumption, a small amount of power is allowed to flow in the opposite direction from the consumer to the utility grid (Eskom, 2020)(SSEG, 2019).

The energy demand and green energy motives for the integration of Solar PV SSEG increase complexity and power quality issues (Haque & Wolfs, 2016). Higher harmonic distortion in the grid network, which results in significant equipment losses, is caused by a grid's higher level of solar PV penetration(Jha & Shaik, 2023). As a result of being integrated into the utility network on the customer's side of the utility's energy meter, an SSEG produces power that is "embedded" in the local electricity distribution network (Mkhwebane & Ntuli, 2019).

2.4. Overview of Power Quality

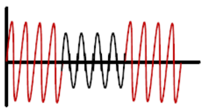
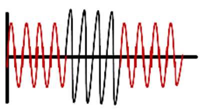
Power Quality (PQ) is any variation in current, voltage, and frequency standards that causes utility and customer equipment to malfunction or fail (Tascikaraoglu et al., 2011). The PQ to different people means different things. The most important aspect for an industrial user is power continuity. The electric utility relies on the sinusoidal component of the voltage waveform to function properly. The design and operation of the device have a lot of bearing on power continuity. Such as surge safety, fault interruption and reconnection, transmission line design, and distribution system design and operation are all factors that influence power reliability (Flory et al., 1990).

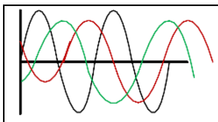
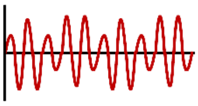
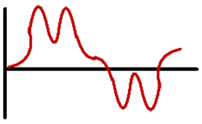
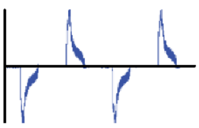
Distributed Generation (DG) has a substantial impact on the power efficiency of distribution networks. It can have a wide range of effects, including increased network reliability and voltage efficiency (Quiroga et al., 2016).

The reliable operation of electronic data processing systems necessitates the availability of high-quality electric power. On electric power lines, voltage sags, swells, surges, impulses, and other disturbances can cause equipment to fail. As a result, determining the current quality of such electric power is crucial to verify that the equipment is adequately resistant to such disruptions. The following sections cover the major power quality problems. The responsibility of the utility and the consumer in resolving relevant concerns is briefly covered.

Table 2.1 gives a summary in terms of brief indication, indicators, causes and effects of the voltage Power Quality (PQ) issues in a power system which are further discussed in the subsection below.

Table 2.1: Commonly occurring and important PQ problems in MG's (Alkahtani et al, 2020)

PQ Problem	Brief Description	Indicators	Causes	Effects
Sag 	The voltage levels decrease at the nominal frequency by 10% to 90% of the nominal RMS voltage over a period ranging from 0.5 to 1min.	• Magnitude • Duration	• Abrupt load rises • Faults • Motor starting • Energising of heavy load	• Can damage the MG's power electronics • High power loss • Damage-sensitive load equipment • Speed loss for motors • Extinguishing of lamps
Swell 	The voltage levels increase at the nominal power frequency over the period not exceeding 1 cycle and less than 1 min	• Magnitude • Duration	• Abrupt load reduction • De-energizing a heavy load	• Breakdown of components on the power supplies of the equipment • Control problems and hardware failure • Overheating
Unbalance	A variation of voltage in the three-	• Phase shift • Magnitude	• Variations in the load	• Reduce equipment's life

	phase system where the difference between phase angle and magnitude is not equal		• Large single-phase loads • Unequal load distribution	• Increase cable losses • Inject more harmonic currents • Phase faults • Poor inverter efficiency
Fluctuations 	Voltage changes up or down from its rated supply voltage	• Magnitude	• Using equipment or devices that require a higher load • Repeated ON/OFF of the electrical motors • Oscillating loads	• Changes in torque and slip in motors • Harmful to household appliances and electrical and electronic appliances of MG's • Lights flicker or glow more brightly
Harmonics 	The distortion of current or voltage sinusoidal waveform than its pure sinusoidal shape because of the harmonics	• Peak magnitude • Frequency	• Nonlinear loads • Electronic inverter • Computer drives • Variable speed motors	• Reduced performance of energy generation in MG's units • Distort the MG's output AC sine wave • Inefficiencies in equipment operations and overheating • Higher line losses ($I^2 \times R$)
Supra-harmonics 	The distortion of voltage and current waveforms with a frequency range from 2 to 150kHz	• Frequency	• Switching of power electronics • , especially inverters • Modern sources	• Inverter instability for MG units • Lost connection with smart meters • Increase power losses

				• Failures in protection devices • Damaged power supply

The focus of the study is on the voltage sag/swell power quality issues that are caused by source and loads. The integration of solar PV is reported in many studies to cause an increase in the voltage especially when considering the high penetration of solar PV which results in non-standard voltage limits and harmonics that affect the components of the utilities and consumers. Mitigation and compensation of the increased signal are important to ensure electricity standard power (Jha & Shaik, 2023).

2.5. Micro-grids

A Micro Grid (MG) is a localized grid made up of distributed generators (DGs), energy storage devices, and scattered loads that can be connected to the grid or operate on their own (Guerrero et al., 2013). They are self-contained subsystems with devoted control systems that deliver a good supply of quality electricity to resident loads like hospitals, commercial buildings, housing, and universities. Because of its local control and power quality support, the MGs model permits the modular incorporation of resident power supplies and loads into the present power grid, as well as high penetration of DGs (Bidram et al., 2014).

2.6. Literature review of existing papers for voltage power quality control

The rise of electricity demand, the aging of traditional electricity generation stations, the scarcity of fossil fuels for the traditional way of generating power, and their environmental impacts have pushed the production of electricity from renewable energy resources has increase. The emphasis is on where the electricity is also used and must be generated which is known as Microgrids, this causes power quality issues such as voltage sag/swell, voltage and current harmonics distortion, and other PQ issues. As a result, interest in ways of mitigating power quality issues has increased. A review of the existing literature in the field has been conducted by as the information gathered in section 2.2 which is according to the following two focus areas:

- A review of Voltage power quality control techniques in low voltage distribution network **without** integration of SSEGs and
- A review of Voltage power quality control techniques in low voltage distribution network **with** the integration of SSEGs

2.6.1. A review of voltage power quality control techniques in low voltage distribution network without connection of SSEGs

Table 2.4 below displays a variety of voltage power quality control and harmonics methods and technologies studied over 16 years, from 2004 to 2020. The table is divided into seven columns: the first column lists the author and the year the paper was published, the second column explains the paper's ultimate goal, the third column lists the process used, the fourth column lists the structure of the system used when conducting the study, fifth column lists the necessary hardware and software for implementation, the fifth column lists the benefits and disadvantages and the seventh column describes the author's achievements and conclusions.

Table 2.2: **A Literature review on voltage power quality control algorithms for low voltage distribution network without integration of SSEG's**

Paper	Aim of the paper/chapter	The method used for Voltage PQ mitigation	The structure of the system considered	Used hardware/ software power system model	Advantages / Drawback	Author's Conclusion & Achievements
(Marei et al., 2004)	To control Active power, manage reactive power, and mitigate harmonics and voltage unbalance.	Flexible Distribution Generation (FDG) is used in distribution levels controlled by ADAptive LINEar (ADALINE) neuron structure which is applied for parameter tracking/estimation multi-output (MO), and Fuzzy Logic Control (FLC) is used for Voltage Regulation.	Three phases three-wire system	PSCAD/EMTDC	Insensitive to parameter variations of distribution network.	With the proposed FDG the utility can get the requested loading level, in parallel improve the power factor, regulate PCC voltage, and mitigate unbalance and harmonics to enhance the network.
(Khadkikar et al., 2006)	To analyse the performance of UPQC for the sensitive load to compensate voltage sag, voltage swell, voltage, and current harmonics in the complex industrial distribution network.	Unit Vector Templates Generation (UVTG) has been used for series APF while PI controller for regulation of DC voltage is used within the UVTG for shunt APF signals. A Hysteresis Band control technique is used for PWM switching of APFs	A typical three phase three wire complex industrial distribution network	MATLAB / Simulink	The application of two inverters in UPQC to control any general load is not cost-effective which means it can only be used for sensitive customers.	The Unit Vector control algorithm UPQC used improved the system from voltage and current-related PQ issues in the feeder for the sensitive load.
(Singh & Solanki, 2009)	Performance comparison of three control algorithms for various loads of unbalanced and reactive power	DSTATCOM is controlled by either the Instantaneous Reactive Power (IRP) or Synchronous Reference Frame (SRF)Theory or ADALINE-based algorithm	Three phases three-wire system	MATLAB / Simulink	The ADALINE has compared performance results compared to IRP and SRF.	The use of the IRP, SRF, and ADALINE satisfies the behaviour of DSTATCOM. The ADALINE showed better improvement.

(Kwan et al., 2009)	Present theoretical PQ solutions for zero steady-state error robustness for uncertainties and supply frequency variations using a UPQC	Multivariable regulator theory with H-infinity loop shaping is used as a control algorithm for the UPQC APFs to mitigate harmonics, voltage sag/swell, load power factor correction, and demand changes.	Single-phase power distribution network	MATLAB/Simulink and Laboratory experiment	For a Model-based Any modelling error can have a negative impact on results, necessitating the use of a high-speed DSP and additional sensors to sample the states of the state-space model.	H-infinity loop shaping has been used in the multi-input-multi-output system to control the UPQC model-based solution.
(Omar & Rahim, 2010)	Investigate the proposed DVR controller for mitigation of voltage sag as a result of three-phase and single-phase faults as disturbances at 25%	A DVR Controller is used which uses dqo parks transformation with Phase Locked Loop (PLL) in its control algorithm	Three phases three-wire system	Matlab Simulink and prototype experiment	The results for the prototype are not presented and a comparison of the two results is not properly presented. The disturbances used are different for the tool	The study discussed the DVR control aspects for the mitigation of voltage sag. The proposed controller proved to be pivotal in fast compensating the disturbance for sensitive load
(Labeeb & Lathika, 2011)	An IGBT-based DSTATCOM with two proposed algorithms has been used for compensation of unbalanced, reactive power and harmonic current	SFR theory-based and ADALINE-based neural network algorithms are compared for control of DSTATCOM to compensate for source current harmonics because of unbalanced load	Three phases three-wire system distribution network with an unbalanced load	MATLAB Simulink	This study does a comparison of two control algorithms focusing on current harmonics, not the voltage harmonics or disturbances as they are mostly used for	It has been found that both algorithms work perfectly for the DSTATCOM controller however ADALINE based
(Conditioner et al., 2011)	The study proposes a fast PQ detection and reference signal extraction method tested on non-linear loads and a fault on the networks for the two APFs of the UPQC	A novel controller for VSC of UPQC is used for the fast generation of signals. The common DC link of the two VSC APFs is controlled using a Fuzzy Logic Controller (FLC) instead of a PI controller.	Three phases three wire weak low voltage grid	Electromagnetic Transients' dc analysis program / Power System Computer Aided Design		The proposed control system can Quickly extract voltage & current reference signals with few mathematical operands, simpler computation, reduced parameters tuned, and improved PLL is also used. The DC link is controlled using FLC

(Paul et al., 2012)	To propose a new control algorithm of DVR for voltage sag and swell PQ issue	SRFT with PI controller has been proposed to control DVR for voltage sag and swell.	415V, 50Hz low voltage distribution network with a three-phase balanced sensitive load connected	MATLAB Simulink	Provides self-DC bus support	The study proposed SRF theory with a PI control algorithm for control of DVR when there is source voltage sag and swell. The proposed algorithms can immediately detect correct single-phase-to-ground faults.
(Singh & Arya, 2014)	They implement a three-phase DSTATCOM to perform reactive power compensation, load balancing, and harmonics elimination for Zero Voltage Regulation (ZVR), Power Factor Correction (PFC) under non-linear loads	The back-propagation control algorithm has been used to control the DSTATCOM to perform PQ for ZVR and PFC mode.	Three phases three wire weak low voltage source	MATLAB/Simulink and Laboratory prototype		In this study, the non-linear loads are compensated using DSTATCOM with BPT algorithms to extract reference source current and generation of switching signals of the used IGBT which are proved in ZVR and PFC. The DC voltage has been regulated not to over/undershoot.
(Singh et al., 2015)	Presents a DSTATCOM controller which is used for reactive power compensation for PCC voltages, load balancing, and harmonics elimination	An Instantaneous Reactive Power theory (IRPT)Self Tuning Filter (STF)	Three-phase low voltage distribution network	MATLAB/Simulink simulation, DSP (Digital Signal Processor dSPACE 1104) experiment.		The proposed system proved to be satisfactory for fluctuating source voltage disturbances the overshoot/undershoot of the PI controller has been reduced
(Agarwal et al., 2018)	Propose application of an algorithm to enhance power quality due to balance & non-balanced nonlinear load, grid voltage disturbances such as distortion and imbalance	Admittance Least Mean Square (LMS)-based neural network (NN) control algorithm has been applied for a DSTATCOM to enhance power quality as per the aims	Three phases three wire weak low voltage grid	MATLAB/Simulink and Laboratory prototype	Reduced complexity, fewer computations, simple multiplication & additions. Only at Unity Power Factor (UPF) that they can compensate for PQ issues. Only laboratory prototype results are given in this study,	The proposed algorithm works at UPF to compensate for distribution network abnormalities like PQ issues resulting from grid imbalance & distorted voltages, non-linear and unbalanced load

(Rohouma et al., 2020)	The study proposed a mitigation strategy for increased local sources of reactive power and harmonic compensation in the low-voltage distribution network.	Capacitor-less DSTATCOM topology is based on Matrix Converter (MC) which is controlled using Finite Control Set Model Predictive Control (FCS-MPC) and SRF	415V, 50Hz low voltage distribution network with a three-phase balanced sensitive load connected	MATLAB/Simulink	The study does not look at the voltage disturbances though it can be seen that during the switching the voltage signal has got some noise and is being compensated by enabling the proposed control scheme. Uses inductive storage	The proposed study can mitigate source current & voltage after the PQ disturbance due to the three-phase non-linear load, non-linear & linear RL PFC correction, and voltage switching.
(Abas et al., 2020)	The study adopts the widely used Dynamic Voltage Restorer (DVR) to overcome non-standard distribution grid voltage variation to protect the sensitive load.	DVR control looking 3rd and 5th harmonic distribution grid variation modelled using three-phase programmable voltage sources	Three phases three wire 415V low voltage network with a three-phase balanced sensitive load	MATLAB/Simulink	The proposed controller uses an injecting transformer which is an additional cost and also looks at only two harmonics which are the 3rd and 5th	The proposed DVR was able to inject distorted compensation voltages to suitable levels using an injecting transformer. The THD for the harmonics was reduced to less than 4%.

2.6.2. A review of voltage power quality control techniques in low voltage distribution network with the integration of SSEGs

Table 2.3 below displays a variety of voltage sag power quality control methods and technologies studied over 11 years, from 2012 to 2023. The table is divided into seven columns: the first column lists the author and the year the paper was published, the second column explains the paper's ultimate goal, the third column lists the process used, the fourth column lists the structure of the system used when conducting the study, fifth column lists the necessary hardware and software for implementation, the fifth column lists the benefits and disadvantages and the seventh column describes the author's achievements and conclusions.

Table 2.3: **A Literature review on voltage power quality control algorithms for low voltage distribution network with integration of SSEG's**

Paper	Aim of the paper/chapter	The method used for Voltage PQ mitigation	The structure of the system considered	Used hardware/ software power system model	Advantages / Drawback	Author's Conclusion & Achievements
(Gaviano et al., 2012)	The aim is to discuss and analyse the challenges that will be faced when integrating renewable energy resources especially wind and solar Photovoltaic (PV) when considering Smart Grid	The Smart Grid through the use of IEC61850 standards ensures two-way communication, interoperability, power security, safety, and reliability in diversified infrastructure, a power quality-free system, effective control, and protection. In this study analysis of the distribution network has been the main focus since the Distributed Energy Resources (DER) are integrated into and the minimum communication on the Low Voltage systems	None	None	The Author noted that in Germany same in other countries the traditional distribution system lacks automation and the distance from generation to the consumer is about 70km. The Smart Grid enables the use of DERs to address capacity and environmental issues. The Smart Grid makes use of the IEC61850 standard which is substation automation standard but is not limited to. The energy system models are already specified like in IEC61850-7-420 but they face diverse system structures in reality and this means migration concept is required. Through the use of the IEC61850 standard power quality data can be shared amongst system devices to enable improved protection and fast operation.	The usage of distributed energy resources effectively depends on smart grid technology. The generation and consumption of energy in the future can be effectively adjusted and optimised thanks to this intelligent network. The new international standard for power utility communication, IEC 61850, was developed in response to the high level of interaction that distributed generation demands from all entities. New devices must be able to interface with old equipment since interoperability and standard compliance are crucial.

(Chidurala et al., 2013)	The aim is to integrate Solar PV while also dealing with PQ issues like voltage sag/swell, unbalance, overvoltage, and harmonics	A solar DSTATCOM controlled by Novel perception is proposed to integrate the PV whilst also mitigating PQ issues. A DC and AC voltage error signal from the desired reference is fed to a PI control and the extraction used is dq theory.	IEEE 13 bus system	PSCAD / EMTDC software	A complete control block diagram is not given but only control block diagrams for sections of the control strategies line DC link voltage. The study looks at this controller for typical applications for utilities whereas the controller looks at the main bus 632.	The study explores PQ quantities affected by high PV penetration. Solar PV DSTATCOM with control algorithms has been proposed. The study conducted three case studies on variation, symmetrical & non-symmetrical faults, and harmonics are improved.
(Mahela & Shaik, 2016)	Present the use of a DSTATCOM with battery to improve PQ disturbances and wind energy integration	Synchronous Reference Frame (SRF) theory has been used in the control algorithm of Shunt APF known as a DSTATCOM to control voltage sag & swell, feeder tripping & re-closing and load switching PQ disturbances	IEEE 13 bus system	MATLAB / Simulink	The study implements the control at the main distribution bus 632 taken as a common coupling point (PCC) which is a 4.16kV. The dq transformation used in SRF control requires a phase-locked loop (PLL) to extract the phase angle	The work investigates the use of DSTATCOM with an SRF control to mitigate grid PQ disturbances like voltage sag, swell, and PQ as a result of wind integration with others in the distribution network. The DSTATCOM proposed can be used to improve the PQ.
Dharavath et al, 2017	The study aims to mitigate PQ issues by focusing on one of its major issues which is the voltage	A battery solar PV DVR device integrated into the utility is proposed. The VSC of the DVR is controlled by the Increment conductance method.	Single-phase distribution network	MATLAB/Simulink	The DVR uses a voltage-injecting transformer which means this method is only suitable for sensitive customer	A novel integration of solar PV, battery-based DVR is discussed to meet load demand and also to maintain the DC Link voltage of the VSC
(Dash & Ray, 2018)	A control algorithm for PV integration and mitigation of voltage sag/swell, better phase detection, voltage, and current harmonics PQ issues	A PV-UPQC controlled by the notch filter novel algorithm which employs PLL to eliminate multiple zero crossing and PQ issues mentioned	Single phase, 230V, distribution network, 9.5kW PV array integrated	MATLAB simulation and DS1103 dSPACE for practical experiment prototype	Theory of SRF and unit vector has been conducted which are applied in the study but the comparison of the algorithms has not been done and also the simulation results and practical	The proposed controller can compensate for voltage sag/swell, current, and voltage harmonics when considering a highly distorted load and grid. A comparison of PLL-

					experiments are done discussed	based SRF and UVT where the proposed control strategy for the grid conditions is more efficient.
Dash & Ray, 2018	The study proposes an improvement on the PI controller of the JAYA algorithms to mitigate PQ issues whilst also integrating PV power	Novel online tuning for the auto tunes PI controller of JAYA is proposed for PV-UPQC Shunt and Series control algorithms	Three phases, three wires, 110V, 50Hz with Non-linear load.	MATLAB/Simulink simulation and DS1103 dSPACE for practical experiment prototype	The comparison is made on the PI controller modification and other optimization methods like PSO & TLBO. The comparative analysis has been conducted relative to PQ issues	JAYA optimization methods with an improved PI controller for auto-tuning are used for a PV-UPQC series and a shunt controller for PQ mitigation live voltage sag/sell. The system improved settling time, convergence time, effective dynamic response, and switching harmonics
(Paramanik et al., 2019)	To investigate power quality control strategy for Small Scale Generators in Smart Grids	Unified Power Quality Conditioner (UPQC), Inducverters, and IoT-based Smart Bi-directional controls.		Simulation and Hardware	The proposed system addresses Voltage Sag, Flicker, Swell, Neutral current, Harmonics, and Active and Reactive power.	The proposed study successfully implements Smart Grids in Small Scale integration. The system proposed produces a supply that is free from quality issues and increases the reliability of the network. The systems have Distributed Generations (DG's) from Renewable Energy Resources like Photovoltaic Array, Wind, Hydro, Bio-gas, Piezoelectric, Micro-turbine which are connected to DC grid, Battery Energy

						Storage System (BESS), Diesel Generator, and UPQC. The BESS and Diesel Generator provide faster response to improve voltage stability when there are fluctuations in the output power produced by the DG's. The utility system is observed using online flow meters and Phasor Measurement Units (PMUs). The energy consumption is metered using smart meters which also control overload.
(Kaushal & Basak, 2020)	Power quality control system for PV AC Microgrid which considers all the parameters like the condition of DER's, local load's power factor, THD, Frequency, destabilising, and voltage deviations	The power Quality control is done according to IEEE/IEC standards. Proportional-integral (PI) and fuzzy-PI controllers are used to verify the performance of the proposed Novel Artificial Neutral Network (ANN) algorithm which is proposed.	Three-phase three-wire Microgrid with	MATLAB Simulink	The proposed controller provides microgrids with fast stable, smooth, and fast responses. During the transition period, the controller has transients and sluggish response because of delay in the controller	The control system is presented which also does the monitoring of the power quality. The proposed control system works even if the DER location is changed and also international standards are considered to maintain power quality. In three-phase systems, it is proven to also be used for a large number of DERs with an also large number of customers

Shukl & Singh, 2020	Propose a new control algorithm for Active solar PV power transfer and grid/load PQ mitigation in the distribution network	DSTATCOM is controlled using a newly proposed recursive digital filter method which obtains reference current using indirect current.	Three phases three wire week low voltage distribution system, 220V, 50hz with connected non-linear loads	MATLAB/Simulink and prototype for practical experimental	None	Switching pulses of a grid-tied PV VSC is produced using a recursive digital filter for mitigation of voltage sag/swell, changing solar irradiation, non-linear load, unbalance, and distortion
(Alkahtani et al, 2020)	Evaluate and compare prior-art PQ difficulties, resolutions, and standards in MGs.	To ensure high-quality MG output power, we compare the key concerns connected to voltage sag, voltage swell, voltage, and current harmonics, scheme unbalances, and oscillations. Despite the lack of a thorough examination, superharmonic (SH) exists.	NA	N/A		An MG network is a power network that might be utilized to satisfy presumable energy demand in the smart grid and renewable energy areas. Because the performance of renewable energy sources is uncertain and weather-dependent, a substantial amount of power electronics equipment is required. For the expansion of MG, the accessibility of PQ criteria, calculations, and easing procedures is critical. In the MG framework, this research looked at the requirements, techniques, and approaches for solving MG PQ concerns such as voltage sag (LVRT), voltage swell (HVRT), voltage and current harmonic, fluctuation, and voltage imbalance. In MG and DERs, at

						least one reference standard addresses most PQ concerns; however, there is presently no corresponding standard for SH. Unified Power Quality Conditioners (UPQC) and Dynamic Voltage Restorers (DVR) are the most effective devices for alleviating PQ issues in MG, followed by Static Synchronous Compensators (STATCOM) and Static VAR Compensator (SVC) when the assessment is made in terms of cost, rating and different aspects of performance.
(Golla et al., 2021)	The study proposed an algorithm for the integration of solar photovoltaic power (PV) and PQ issues like distortion, voltage load sag/swell, and change in power produced by the PV.	Instantaneous power balance theory (IPBT) is used to extract reference signals for the UAPF filter. Positive and negative sequence components and phase angles are extracted using Modified Reduced Order Generalised Integrator (MRGOGI) based on Frequency Locked Loop (FLL)	Three phases three wire 230V, 50Hz is considered for Simulation while 110V, 50Hz is used for hardware experiment.	MATLAB and Hardware prototype experiment where results are captured using DSO-100 MHz2Gsa/s and power quality analyzer (PQA-CA8336).	The comparison between the experiment and the simulated results is not compared due to the difference in the two networks used. The signals reported on the hardware practical experience are noisy signals.	Source and load PQ issues are mitigated integration of clean energy generated from PV-UAPF controlled by the IPBT control algorithm. Sinusoidal current and voltage are produced by the shunt and series active filter of the UAPF when the PV power is injected into the utility. Steady-state and Dynamic performance analyses for the PV-UAPF are conducted for different disturbances

(Rastogi et al., 2021)	The study aims to maintain the power factor at unity, supply active power to the grid, and feed active and reactive power demanded by a three-phase unbalanced load.	DSTATCOM of a two-Level Reduced-Switch (2L3PRS) VSC with solar PV connected and controlled by Modified SRF DC Link voltage and voltage balancing for all conditions.	3P3W low voltage distribution network	MATLAB / Simulink and validated on Real Time Digital Simulator (RTDS)	The system is only used for three-phase three-wire systems, which means it does not compensate for currents flowing on the neutral.	
(Jha & Shaik, 2023)	Conduct a review of DFACT devices with control algorithms used to mitigate PQ issues when there is high penetration of solar PV in a weak distribution system	Conventional, AI-based, and adaptive control algorithms are studied for integration and PQ control	N/A	N/A	Due to initialization mistakes and noise in the mean square, the performance of adaptive LMS degrades and it is inaccurate. LMF impairs performance in a steady state.	The DSTATCOM has been considered the best when applied with Adaptive control

2.7. Comparative analysis of the developments in the existing literature

The comparative analysis has been conducted for the two focus areas of the study looking at voltage sag/swell PQ issues considering mitigation techniques before and after the integration of solar PV renewable SSEGs.

2.7.1. Voltage power quality control algorithms for low voltage distribution network without integration of SSEG's

(Marei et al., 2004) controlled active power managed reactive power, and mitigated harmonics and voltage unbalance. A Flexible Distribution Generation (FDG) was used in the distribution level controlled by the ADAptive LINEar (ADALINE) neuron structure which is applied for parameter tracking/estimation multi-output (MO), and Fuzzy Logic Control (FLC) is used for Voltage Regulation. With the proposed FDG the utility can get the requested loading level, in parallel improve the power factor, regulate PCC voltage, and mitigate unbalance and harmonics to enhance the network.

(Khadkikar et al., 2006) conducted a performance analysis of a Unified Power Quality Conditioner (UPQC) on a typical complex industrial distribution network. Unit Vector Generation (UVG) control algorithm was used for the two Active Power Filters (APFs) connected in parallel and series to the sensitive plant load with 5 loads namely two AC motors, two non-linear loads modelled as diode bridge rectifiers, and resistive load. A DC link voltage regulation for current harmonics mitigation in the shunt APF is achieved by using a PI controller from the error signal of the sensed DC voltage compared with the reference DC voltage.

(Singh & Solanki, 2009) conducted a performance comparison of three control algorithms for various loads of unbalanced and reactive power. A DSTATCOM controlled by either the Instantaneous Reactive Power (IRP) or Synchronous Reference Frame (SRF)Theory or ADALINE-based algorithm has been proposed for a three-phase three-wire system on MATLAB / Simulink simulation. The ADALINE has compared performance results compared to IRP and SRF. The use of the IRP, SRF, and ADALINE satisfies the behaviour of DSTATCOM. The ADALINE showed better improvement.

(Kwan et al., 2009) presents a theoretical solution for the improvement of PQ issues such as power factor control, voltage sag/well, load demand changes, and harmonics in low-voltage distribution networks. The PQ issues are improved by using UPQC which is controlled by the multivariable regulator with H-infinity loop shaping. The proposed controller employs Kalman's filter to extract harmonics on the UPQC which were controlled using a model based on Feed Forward (FF) and Feed Backward (FB) control as a multi-input multi-output (MIMO). The proposed controller managed to improve voltage from a Total Harmonic Distortion (THD) of 10% to 2.9% and the current THD from 26.4% to 3.5% which are acceptable.

(Omar & Rahim, 2010) investigated the proposed DVR controller with PLL-based dp0 Park Transformation's control algorithm for voltage sag introduced between 20-25% by introducing a three-balanced and single-phase fault. The proposed control scheme proved to be perfect for sensitive loads when simulated on Matlab Simulink and prototype experiments.

(Labeeb & Lathika, 2011) proposed two control algorithms for control of an IGBT-based DSTATCOM for compensation unbalanced, reactive power and harmonic current SFR theory-based and ADALINE-based neural network algorithms are compared for control of DSTATCOM to compensate for sources current harmonics as a result of unbalanced load Three phases three-wire system distribution network with unbalanced load MATLAB Simulink. This study does a comparison of two control algorithms focusing on current harmonics, not the voltage harmonics or disturbances they are mostly used for. It was found that both algorithms work perfectly for the DSTATCOM controller however ADALINE based

(Conditioner et al., 2011) proposes a fast PQ detection and reference signal extraction method tested on non-linear loads and a fault on the networks for the two APFs of the UPQC A novel controller for VSC of UPQC is used for fast generation of signals. The common DC link of the two VSC APFs is controlled using a Fuzzy Logic Controller (FLC) instead of a PI controller. Three phases three wire weak low voltage grid Electromagnetic Transients dc analysis program / Power System Computer Aided Design The proposed control systems can Quickly extract voltage & current reference signals with few mathematical operands, simpler computation, reduced parameters tuned, and improved PLL is also used. The DC link is controlled using FLC

(Paul et al., 2012) proposed an SRF theory with a PI controller as a control algorithm for the DVR controller which in this case is used to compensate source side voltage sag and swell PQ issues. The system is tested in a simple three-phase three-wire 415V, 50Hz low voltage distribution network with three phases of critical balanced load. The new proposed algorithm addresses the shortfall of the traditional algorithms such as a single phase to the ground which could not be detected.

(Singh & Arya, 2014) in the study, PQ issues caused by the non-linear load are compensated using the DSTATCOM which is controlled using the Back-Propagation control algorithms for Power Factor Correction (PFC) and Zero Voltage Regulation (ZVR)

(Singh et al., 2015) presented a DSTATCOM controller which is used for reactive power compensation for PCC voltages, load balancing, and harmonics elimination. An Instantaneous Reactive Power Theory (IRPT) with Self Tuning Filter (STF) Three phase low voltage distribution network MATLAB/Simulink simulation, DSP (Digital Signal Processor dSPACE 1104) experiment. The proposed system proved to be satisfactory for fluctuating source voltage disturbances the overshoot/undershoot of the PI controller has been reduced.

(Agarwal et al., 2018) Propose application of an algorithm to enhance power quality due to balance & non-balanced nonlinear load, grid voltage disturbances such as distortion and imbalance Admittance Least Mean Square (LMS)-based neural network (NN) control algorithm has been applied for a DSTATCOM to enhance power quality as per the aims The proposed algorithm works at UPF to compensate for distribution network abnormal like PQ issues resulting from grid imbalance & distorted voltages, non-linear and unbalanced load

(Abas et al., 2020) propose the widely used Dynamic Voltage Restorer (DVR) to overcome non-standard distribution grid voltage variation to protect the sensitive load. DVR control looking 3rd and 5th harmonic distribution grid variation modelled using three-phase programmable voltage sources Three phases three wire 415V low voltage network with a three-phase balanced sensitive load The proposed DVR was able to inject distorted compensation voltages to suitable levels using injecting transformer. The THD for the harmonics was reduced to less than 4%.

(Rohouma et al., 2020) proposed a Capacitor-less DSTATCOM based on a Matrix Converter (MC) which is controlled using normal SRF and Finite Control Set Model Predictive Control (FCS-MPC) to mitigate source current & voltage harmonics and PFC. The electrolytic capacitor that is normally used on the DC side for storage is replaced by an inductor. The study only analyses the source’s current harmonics and voltage harmonics using the FFT of the Simulink. Only the source's current profile is studied. The PQ disturbance considered in the use cases of the study is three-phase linear and non-linear loads.

2.7.2. Voltage power quality control algorithms for low voltage distribution network with integration of SSEG's

(Mahela & Shaik, 2016) investigated the use of Distributed Static Compensator (DSTATCOM) with Synchronous Reference Frame (SRF) theory control to mitigate distribution grid disturbances like voltage swell, sag, feeder tripping and reclosing, and load switching when integrated with wind considering its operation disturbance like wind generator outages, wind speed variations and synchronisation into the grid. The study has been carried out in a modified radial IEEE 13 bus system where the DSTATCOM has been installed in bus bar 632 which is the main supply bus bar. The study has been modelled on MATLAB/Simulink and verified/validated on Real Digital Simulator (RTDS) where the results from the two tools are close.

(Dash & Ray, 2018) proposed a control algorithm for PV integration and mitigation of voltage sag/swell, better phase detection, voltage, and current harmonics PQ issues. A PV-UPQC controlled by the notch filter novel algorithm employs PLL to eliminate multiple zero crossing and PQ issues mentioned. Single phase, 230V, distribution network, 9.5kW PV array integrated. MATLAB simulation and DS1103 dSPACE for practical experiment prototype. Theory of SRF and unit vector has been conducted which are applied in the study but the comparison of the algorithms has not been done and also the simulation results and practical experiments are done discussedThe proposed controller can compensate voltage sag/swell, current, and voltage harmonics when considering a highly distorted load and grid. A comparison of PLL-based SRF and UVT where the proposed control strategy for the grid conditions is more efficient.

(Golla et al., 2021) proposed an algorithm for the integration of solar photovoltaic power (PV) and PQ issues like distortion, voltage load sag/swell, and change in power produced by the PV. Instantaneous power balance theory (IPBT) is used to extract reference signals for the UAPF filter. Positive and negative sequence components and phase angles are extracted using Modified Reduced Order Generalised Integrator (MRGOGI) based on Frequency Locked Loop (FLL) Three phases three wire 230V, 50Hz is considered for Simulation while 110V, 50Hz is used for hardware experiment. MATLAB and Hardware prototype experiment where results are captured using DSO-100 MHz2Gsa/s and power quality analyzer

(PQA-CA8336). The comparison between the experiment and the simulated results is not compared due to the difference in the two networks used. The signals reported on the hardware practical experience are noisy signals. Source and load PQ issues are mitigated integration of clean energy generated from PV-UAPF controlled by the IPBT control algorithm. Sinusoidal current and voltage are produced by the shunt and series active filter of the UAPF when the PV power is injected into the utility. Steady-state and Dynamic performance analyses for the PV-UAPF are conducted for different disturbances

(Rastogi et al., 2021) investigated the use of a solar PV grid integrated DSTATCOM. The DSTATCOM is made of a two-Level Reduced-Switch (2L3PRS) which is controlled using Modified SRF which is used to maintain DC-link voltage, the voltage across capacitors in all different loading conditions, power factor at unity, supply active power to the grid, feed active and reactive power demanded by a three single phase unbalanced inductive linear loads in a three-phase three-wire low voltage distribution network modelled on MATLAB Simulink and validated on RTDS.

(Jha & Shaik, 2023) conducted a comprehensive review of DFACT devices controlled by different control algorithms categorised under conventional, adaptive, and AI-based algorithms for enhanced integration of solar PV in a weak distribution system to deal with various power quality challenges.

(Poshtkouhi et al., 2015) have conducted a study for a novel Intelligent Distribution Panel (IDP) which will be used for quality control, monitoring, and consumption in distribution networks taking into account different loads and grid conditions. The IDP can also be used to enhance grid stability, be cost-effective, and during islanding must alert the workers (Poshtkouhi et al., 2015). When there is an integration of PVs and EVs, demand-side management (DSM) is proposed to manage the quality of the distribution network. Because high PV integration increases voltage magnitude, this system improves voltage quality by re-scheduling the power consumption of EVs in line with PV generation. This system helps reschedule the upgrade needs (Al Essa, 2020). (Cipcigan et al., 2007) investigated the impact of high penetration of Small-Scale Wind Turbines (SSWTs). Distributed energy resources affect the voltage profile of the distribution network. A large SSEG amount of penetration introduces voltage rise on the steady-state system. The violation of limits in terms of voltage subjects the network to voltage stress which the equipment will not be able to handle (Cipcigan et al.,

2007) Active local controller is issued to address the problems within the zone which will allow control to minimise reverse power from the load and energy storage (Cipcigan et al., 2007).

The voltage profile is affected by the integration of the DERs mentioned above. It is highlighted that as the large number of DGs are integrated, the greater the voltage rise on the network. After these have been studied control mechanisms are presented like IDP and DSM.

The improvement of the control algorithms to make sure that the high penetration of SSEGs like solar PV into the different low voltage distribution systems does not violate voltage-related PQ issues like sag/swell. Different components like PLL, PI controller, Reference AC extraction, and voltage regulation methods of the algorithms will be changed/varied whilst also just specifying the Point of Connection (POC) filter and type of MPPT device used.

2.8. Discussion

The literature study has been conducted on ways of mitigating voltage sag and swell in a Low Voltage distribution network which is the most common power quality issue and with many researchers globally looking into the level of penetration of solar Photovoltaic (PV) systems. Solar PV is the most common Renewable Energy Source (RES) which are Distributed Energy Resources (DER) that are intermittent due to weather dependency on the low voltage distribution network which lacks automation. The researches in this field of study focus on Custom Power Devices (CPD')/Distribution Flexible Alternating Curren Transmission Systems (DFACTS) which are made of Voltage Source Converters (VSC) Active Power (APF) to for compensate power quality issues due to Source PQ issue or Load disturbances. There are three most common defects proposed in the studies the Unified Power Quality Conditioner (UPQC), Static Voltage Regulator (SVR), and Distribution Static Compensator (DSTATCOM). The optimisation of the DFACTS devices is done through the control algorithm where the gate switching signals are controlled by the algorithm to ensure a compensating signal is produced to mitigate the PQ issue.

Many researchers focus on the UPQC and DVR which are mostly used for the mitigation of sensitive/crucial loads and compensating the disturbances caused by the sources to ensure that the components within the area are not affected by the grid PQ issues. This application is mostly considered by the end-use customer.

The use of AC to DC converters like non-linear loads, unbalanced loads, motor and capacitor switching, power power factor, harmonics, and faults, are the contributors to the grid disturbances which leaves the utility having to mitigate these power quality issues. A DSTATCOM is a VSC-based shunt APF that is used to mitigate current-related PQ issues and can also be controlled to mitigate most of the LV PQ disturbances like voltage sag and swell. It is used to mitigate source voltage and current to ensure the grid code is maintained. The control algorithms mostly considered are the Adaptive for integration of SSEG while the traditional algorithms like Synchronous Reference Frame theory are still adequate to mitigate the PQ issues even when the SSEGs are integrated.
Finding system parameters for the complex UPQC is difficult and makes it difficult to find the optimum solution for power quality mitigation.

2.9. Conclusions

This chapter provided a brief overview of Small Scale Embedded Generations (SSEGs), voltage-related power quality issues focusing on the voltage sag/swell, integration of small-scale power on low voltage distribution networks, Smart Grid concept for the low voltage distribution network which lacks automation as reported by many studies with a focus on the IEC 61850 standard which is widely being adopted and Microgrids which is where the SSEG's like Solar Photovoltaic (PV) in rooftop are integrated where there are also different types of loads. A literature review on previous work in the Power Quality (PQ) field by various researchers has been conducted and presented on the Distribution of Flexible Alternating Current Transmission Systems (DFACTS) also known as Custom Power Devices (CPDs) with Voltage Source Converters (VSCs) controlled by different Power Quality (PQ) algorithms to mitigate voltage sag/swell and other issues that can be used with and without integration of the renewable SSEG's.

This thesis focuses on developing improved control algorithms of VSC gate pulses for not only the integration of SSEGs but also the mitigation of voltage sag/swell power quality experienced on the low voltage distribution network from the source and different types of loads. This will also assist the consumers and utility in protecting the equipment that gets damaged, mal-operated, and reduced life span as a result of the power quality issues on the distribution networks.

Theoretical considerations for voltage sag/swell, VSC, and control algorithms after the integration of solar PV SSEG are discussed in Chapter 3.

CHAPTER THREE
THE BACKGROUND THEORY OF CUSTOM POWER DEVICES

3.1. Introduction

Power Quality (PQ) is a major concern for the end user customers and the utility, it has gained much interest due to the use of power electronics, microprocessor-based devices, controllers in industrial processes, non-linear loads, and the expansion of computer networks (Ibrahim & Morcos, 2003). The quality of the power delivered is further impacted by the grid integration of renewable distributed generation (DG) technologies including wind, fuel cells, and solar photovoltaics (Ray et al., 2013). The integration of renewable energy sources into the existing grid is motivated by rising demand, scarcity of fossil fuels, hiking prices, and global environmental impact. Solar PV systems have gained much momentum in Low Voltage (LV) distribution networks as part of Small Scale Embedded Generations (SSEG) and cater for the area where power is also consumed by residential, commercial and industrial consumers and eliminates distribution and transmission costs (Filipova & Morris, 2018).

The high level of solar PV system integration into the existing Low Voltage (LV) network is causing several Power Quality (PQ) problems. Variable output power and limited predictability cause intermittent generation, which can result in power imbalance on the utility grid, as the main issues with this kind of resource. Poor PQ may result from the fluctuation of PV power and the nonlinear loads already present in the grid (Jha & Shaik, 2023)

This chapter provides a theoretical background on Distribution Flexible AC Transmission Systems (DFACTS) also known as Custom Power Devices (CPDs) which are widely used for compensation of power quality issues. Furthermore, gives a brief theory of when the solar PV model is integrated and the theory of control algorithms. Section 3.2 provides background theory of DFACTS and components like ripple filter, interfacing filter, Voltage Source Converter (VSC), and solar PV model that need to be specified for designs and during the analysis. Section 3.3 gives the power quality and solar PV international and national standards to be considered for voltage power quality limits. Section 3.4 gives optimisation strategies that can be used in a DSTATCOM device to mitigate voltage sag/swell power quality.

3.2. Custom Power Devices (CPD's)

The distribution grid uses Custom Power Devices (CPDs), also known as Distributed Flexible AC Transmission Systems (DFACTS) devices, to regulate line impedance, phase angle, voltage & current harmonics, voltage magnitude unbalanced load, and non-linear loading to preserve the distribution network's power quality. It is advised to use this DFACTS concept, which offers a potentially cost-effective way to power quality devices in a utility grid connected to RES (Muttaqi et al,.2015)(Georgilakis and Hatziargyriou, 2015). In addition, they offer numerous benefits because of their tiny size, low cost, and ease of implementation when compared to traditional FACTS.

The most common PQ issues in an LV distribution system are voltage dips, swell, and unbalance. Several studies have been analysed in Chapter 2 where the active power filters (APF) connections are leading in the field of voltage sag/swell power quality mitigation. Different control algorithms are used to optimise the connected type of the APF which are preferred over the traditional ways that utilise passive filters only. Figure 3.1 illustrates the classification connection combination of APF which are DFACT's. The APF can be connected in series, shunt, two APFs connected in shunt, and another in series or both connected in series.

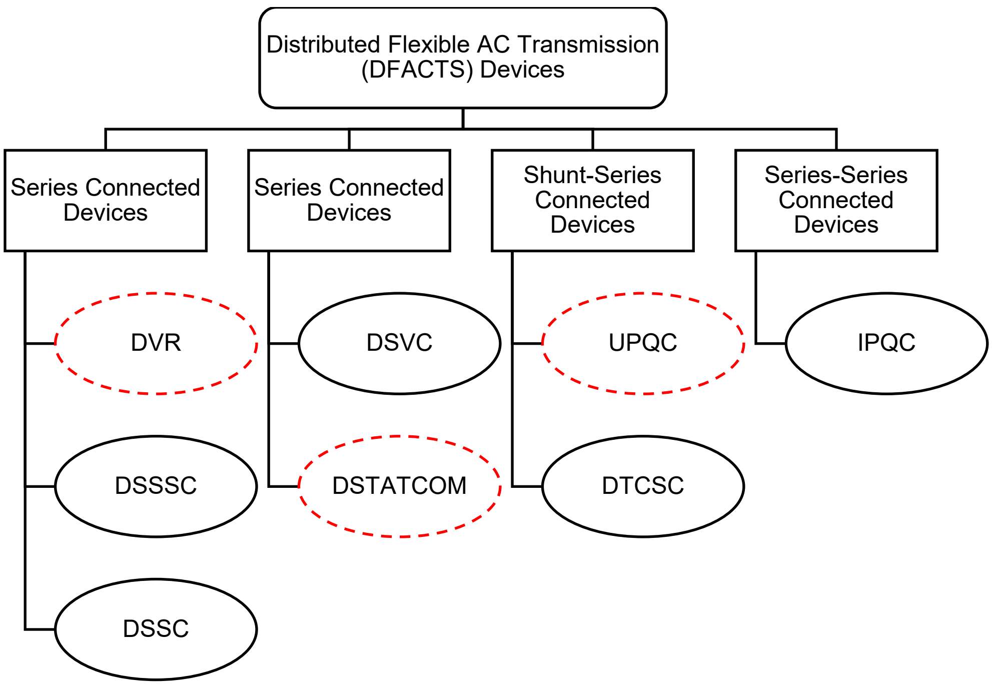


Figure 3.1: DFACTS devices classification (Chawda et al., 2020)

The shunt-connected device DSTATCOM has been reported in many studies as superior to other DFACTS devices as it can compensate for voltage variations, current harmonics, reactive power compensation and load balancing. This device is suitable for most of the PQ issues that occur in an LV distribution network and will be utilised in this study.

3.2.1. Dynamic Voltage Restorer (DVR)

A DVR is a type of series-connected DFACTS device. It can function as a series active filter to isolate the source from harmonics produced by the loads and is linked in series with other CPDs to protect sensitive loads from supply-side disturbances (apart from outages). It is composed of a low pass filter, a coupling transformer, and a voltage source PWM converter that is outfitted with a DC capacitor and coupled in series with the utility supply voltage. This device restores the load side voltage to the required amplitude and waveform even when the source voltage is imbalanced or distorted by injecting a set of adjustable AC voltages in series and synchronism with the distribution feeder voltages.

3.2.2. Distribution Static Compensator (DSTATCOM)

A DSTATCOM also known as Shunt Active Power Filter (SAPF) is a shunt-connected VSC static device that is used to rectify current harmonics, power factor, filtering, and regulate the voltage at distribution bus and balance loads (Lee et al., 2013). It is made up of a shunt-connected voltage source converter (VSC) that mounts Insulated Gate Bipolar Transistors (IGBTs) switches with anti-parallel diodes since they have high switching frequency which improves speed and runs on PWM (Sannino et al., 2003). The DSTATCOM is also used to maintain desired Point of Common Coupling (PCC) voltages by injecting currents into the system where it operates in Zero Voltage Regulation (ZVR) mode.

Figure 3.2 presents a schematic diagram of a DSTATCOM system where the non-linear load is connected which is fed from the utility and single-stage PV array. The PV array is connected on the DC side of the DSTATCOM where it supplies the load and feeds the excess power to the grid for storage. The parallel connection to the utility is done through a Point of Intersection (PIC) filter also known as an interfacing filter is used to feed compensating current and eliminate harmonics to improve the power quality.

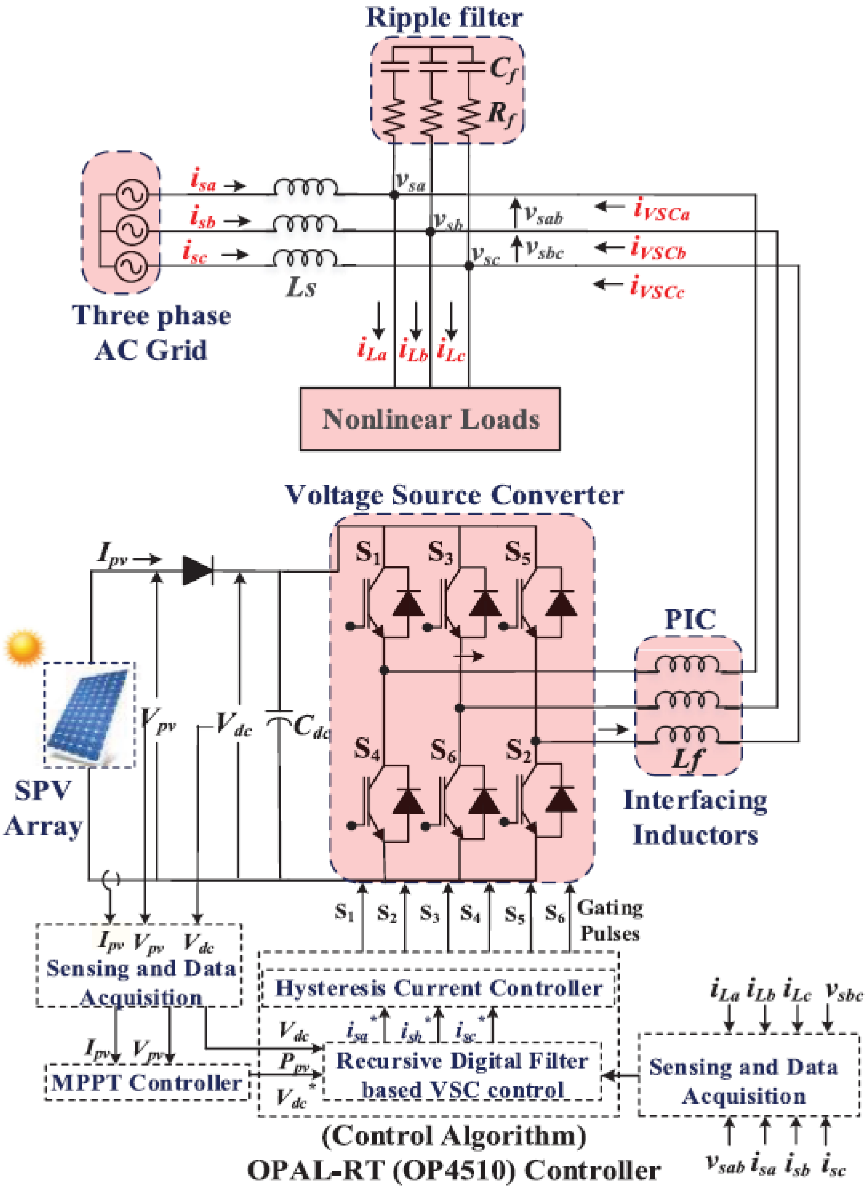


Figure 3.2: **Typical DSTATCOM schematic diagram** (Shukl & Singh, 2020)

The other important component of the DSTATCOM is having the ripple filter to remove switching ripples in the system. The DSTATCOM is used to integrate solar PV on the DC side of the VSC. The solar energy is converted from DC to AC using the VSC supplying the grid with additional active energy. It can also supply reactive power to the utility in compensating for power quality issues like voltage sag/swell variations.

3.2.3. Unified Power Quality Compensator (UPQC)

Series and shunt active filters are connected back-to-back in a UPQC. These two filters are usually coupled at the DC side and share a DC capacitor. Voltage sags/swells, flicker, voltage imbalance, and harmonics are all compensated for by the series components on the supply side (Hossain et al., 2018).

A UPQC provides voltage to keep load voltages at the desired level. Poor power factor, load harmonic currents, and load imbalance are all mitigated by the shunt component. It injects currents into the system to bring the source currents in phase with the source voltages (Blondel & Monney, 2010). Figure 3.3 illustrates a combination of a series and shunt compensator, which is suggested as a single solution for mitigating numerous voltage and current PQ issues (Kazmierkowski, 2015)

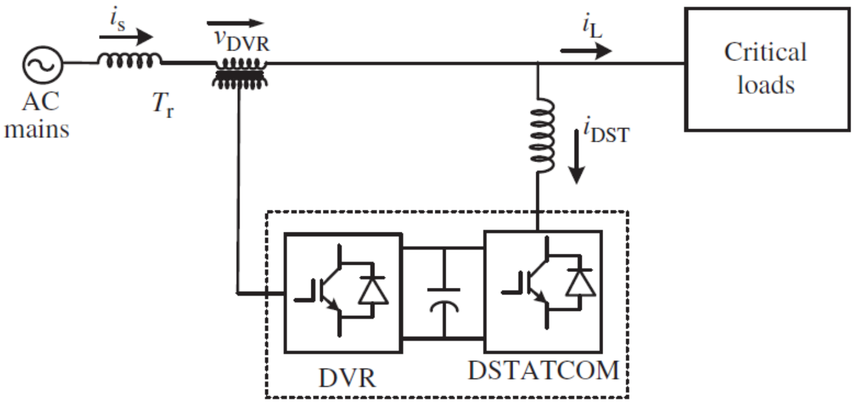


Figure 3.3: A VSC-based unified power quality compensator (Kazmierkowski, 2015)

A common DC link capacitor at the DC bus, respectively, connects the two voltage source converters (VSCs) that make up a UPQC's power circuit back-to-back. The UPQC's shunt device, also referred to as a DSTATCOM (distribution compensator), is connected in parallel to the consumer load or AC mains, depending on the configuration, as a right or left shunt UPQC. It offers reactive power compensation, load balancing, neutral current compensation, and harmonic elimination (if necessary).

The DVR, which is the UPQC's series device, maintains the consumer load end voltages immune to supply voltage quality issues like depression, imbalance, sag/swell, surges, spikes, notches, fluctuations, and so on. To return the load voltage to its reference value, the DVR injects a compensating voltage between the supply and the consumer load.

3.3. Custom Power Devices (CPDs) components

The CPDs indicate the topology connection of Active Power Filters (APF), they have components that are used to complete them. The CPDs have a VSC, DC link storage element, interfacing filters, Ripple Filters, PWM control of the VSC, and solar PV that can be connected to support the DC voltage and also supply power into the system.

3.3.1. Voltage Source Converter (VSC)

A voltage-source converter (VSC) is a type of power electronic device that can generate sinusoidal voltages with any necessary magnitude, frequency, and phase angle. A partial voltage replacement or an injection of the "missing voltage" are both accomplished with the VSC. The difference between the nominal and real voltage is known as the "missing voltage". They are commonly used in adjustable speed drives but are also used to mitigate voltage sag and other PQ issues like harmonics and flicker. In most cases, the converter is based on a form of energy storage that provides a DC voltage to the inverter. The two-level or multilevel three-phase converters, which distribute a DC capacitor among all phases, are a commonly used technique. This capacitor has a comparatively low energy storage demand since its primary function is to absorb harmonic ripple, especially when it operates in balanced circumstances (Kumar & Nagaraju, 2007).

If necessary, this capacitor's size must be raised to maintain the voltage under imbalanced situations. The inverter's solid-state electronics, such as the MOSFET, GTO, and IGBT, are then switched to provide the required output voltage. IGBT, a three-terminal programmable switch utilized in VSC, combines the high voltage capability of the GTO with the quick switching times of the MOSFET. The VSC is typically used to mitigate additional power quality concerns, such as flicker and harmonics, in addition to voltage dips.

A multipurpose topology that may be utilized for up to three quite different purposes is provided by the VSC linked in shunt with the AC system:

- Reactive power compensation and voltage control
- Power factor correction
- Line harmonic elimination

3.3.2. DC link storage

A capacitor is the most used DC link storage element which is connected on the DC side of the VSC and is called a DC link capacitor. The capability of VSC to regulate voltage during transients determines how this capacitor is designed (Kumar & Mishra, 2013). The DC Link capacitor can be calculated as follows:

$$C_{dc} = \frac{6VaIt}{{V_{dc}}^2 - {V_{dc1}}^2} \quad (3.1)$$

Where:

C_{dc} – DC Link capacitor.

V – AC Phase voltage (V)

V_{dc} – DC Link bus voltage (V), $V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m}$, V_{LL} – Supply RMS Line to Line voltage (V),

m – Modulation index = 1

V_{dc1} – Minimum voltage level of DC bus (V),

I – AC Line current (A)

t – Time to restore DC Link bus voltage

3.3.3. Interfacing Filters

The interfacing/PIC filters are used after the DC to AC conversion by VSC to smoothen and attenuate out all the noise that is found in the AC power produced by the inverter. There are three commonly used filter configurations which are L, LC and LCL filters. In comparison to a normal L filter, an LCL filter uses a substantially smaller inductor value while yet having outstanding switching harmonics removal capabilities. A lesser inductance will result in a smaller voltage drop across it, further reducing the size of the DC bus voltage and, as a result, the VSI rating.

3.3.4. Ripple Filter

The ripple filter is a high-pass first-order filter with a series resistor (R_f) and capacitor (C_f) adjusted to half the switching frequency. It is a shunt connected to the power system which helps to remove noise from the voltage at the PCC (Singh et al., 2008). It is further needed to get rid of the higher-order harmonics that the source's low pass filter didn't completely remove. The ripple filter's time constant (T) should meet the following requirement because it is very modest in comparison to T (Singh et al., 2009).

$$\mathrm{R_f C_f} \ll \frac{\mathrm{T}}{10} \tag{3.2}$$

3.3.5. PWM current control

PWM current control of a voltage source converter can be produced using the commonly used hysteresis current control technique that produces an output current that closely matches a reference current waveform using hysteresis comparators and non-linear control loops. This technique ramps the current through an inductor up and down so that it follows a reference by controlling the switches in an inverter asynchronously. The current delivered into the grid must follow a reference value when a VSI is regulated with a hysteresis controller. The hysteresis controller has a straightforward design, is resilient by nature, and is not affected by changes in load parameters. Additionally, it offers a good transient reaction. It is necessary to develop a controller with an adaptive band to acquire a fixed switching frequency (Lavanya & Senthil Kumar, 2018).

To improve the load voltage and identify switching signals for inverter gates, hysteresis voltage control is applied. An error signal between an injection voltage (V_{inj}) and a DVR reference voltage (V_{ref}), which generates the necessary control signals, is the foundation of the hysteresis voltage control. A Hysteresis Band (HB) exists both above and below the reference voltage. The voltage is compelled to drop or rise when the difference between the reference and inverter voltage approaches the upper/lower limit. Figure 3.4 below depicts a block diagram of the Hysteresis Controller.

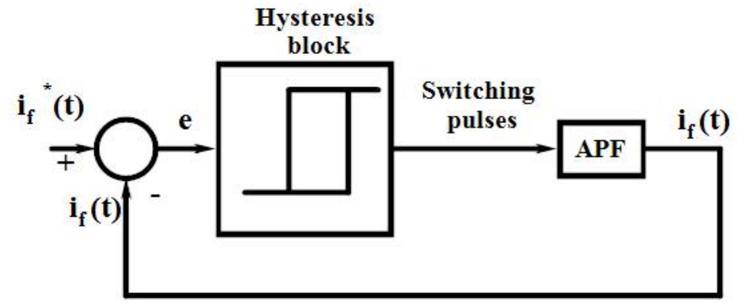


Figure 3.4: Hysteresis Controller block diagram (Lavanya & Senthil Kumar, 2018)

3.3.6. Solar PV Model

Direct conversion of solar energy to electricity has been feasible since the 1930s through the Photovoltaic Systems (PVs) also popularly known as solar panels (Al Essa, 2020). A photovoltaic (PV) system consists of one or more solar panels, an inverter, and other electrical and mechanical components that use sunlight to create power. Small rooftop or portable PV systems to enormous utility-scale power facilities are all possible. The system can be connected to the electrical utility grid or as a stand-alone.

Electrical current is generated because of the photovoltaic effect that occurs when sunlight, which is made up of packets of energy called photons, falls upon a solar panel/module made up of many PV cells which are the fundamental building blocks of PV systems that can generate 1 or 2 watts of power. The PV cells are constructed of semiconductors, which are materials that carry electricity only fairly well. Silicon (Si), cadmium sulphide (CdS), cuprous sulphide (Cu2S), and gallium arsenide (GaAs) are the most widely utilised materials. They can be assessed based on solar irradiation while considering manufacturing parameters such as the efficiency of solar cells (Al Essa, 2020). When lighted, these cells are grouped into modules that produce a specified voltage and current. The PV modules can be connected in parallel or series as PV arrays to produce larger voltages and currents (Kalogirou, 2009). Figure 3.3 shows an equivalent circuit of a single solar cell.

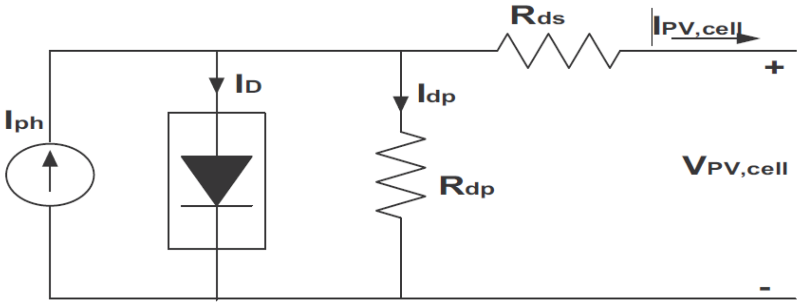


Figure 3.5: Solar PV cell model (Rastogi et al., 2021)

The model has a current source $\mathrm{I_{ph}}$, one diode, and a series of resistance $\mathrm{R_{ds}}$, which represents the resistance within each cell, as illustrated in Figure 3.4. The diode also contains an internal shunt resistance$\mathrm{R_{dp}}$. The difference between the photocurrent $\mathrm{I_{ph}}$ and the normal diode current, $\mathrm{I_D}$, The solar PV cell model can be mathematically analysed using equation 3.1:

$$\mathrm{I_{pv,cell}} = \mathrm{I_{ph}} - \mathrm{I_D} - \mathrm{I_{dp}} \tag{3.3}$$

Where:

$\mathrm{I_{pv,cell}}$ – Solar PV cell current (A).

$\mathrm{I_{ph}}$ – Photocurrent (A)

$\mathrm{I_D}$ – Diode current (A)

$\mathrm{I_{dp}}$ – It is the current (A) that flows through the resistance $\mathrm{R_{dp}}$

$$\mathrm{I_{pv,cell}} = \mathrm{I_{ph}} - \mathrm{I_0}\left\{\mathrm{e}^{q_e\left(\frac{\mathrm{V_{pv,cell}}+\mathrm{I_{pv,cell}}\mathrm{R_{ds}}}{a\mathrm{V_t}}\right)} - 1\right\} - \frac{V_{\mathrm{pv}} + \mathrm{I_{pv,cell}}\mathrm{R_{ds}}}{\mathrm{R_{dp}}} \tag{3.4}$$

Where:

$\mathrm{I_0}$ – Reverse saturation current (A).

q_e – Charge of electron (1.602 × 1019 J/V)

$\mathrm{V_{pv,cell}}$ – Voltage across the diode (V)

$\mathrm{V_t}$ – Thermal voltage (V)

$\mathrm{R_{ds}}$ – Leads wire and semiconductor resistance (Ω)

$\mathrm{R_{dp}}$ – Parallel leakage resistance (Ω)

$$\mathrm{I_{ph}} = \mathrm{I_{ph,n}} + \frac{\mathrm{K_i}(\mathrm{T} - \mathrm{T_n})\mathrm{G}}{\mathrm{G_n}} \tag{3.5}$$

Where:

$\mathrm{I_{ph,n}}$ – Rated photocurrent (A).

K_i – Coefficient of short-circuiting current/temperature

T – Junction Temperature (A)

T_n –

G – Solar irradiation (W/m^2)

G_n – Parallel leakage resistance (Ω)

$$I_{ph,n} = I_{sc,n} \frac{\left(R_{dp} - R_{ds}\right)}{R_{dp}} \tag{3.6}$$

Where:

$I_{sc,n}$ – Rated short-circuiting current (A).

$$I_0 = \frac{I_{sc,n} + K_i dT}{e^{\left[\frac{V_{oc,n} + K_v dT}{a\,V_t}\right]} - 1} \tag{3.7}$$

Where:

$V_{oc,n}$ – Rated open-circuiting voltage (V).
K_v – Coefficient of open-circuiting voltage/temperature.
dT – The variation between the ideal and actual junction temperatures.

Equations 3.1 – 3.5 covered analysis of a solar PV cell. In order to increase current and voltage, solar-PV modules are connected in parallel and series in the basic modelling of solar-PV cells. A practical array is a configuration of several PV cells that are connected. The solar PV array current is calculated using equation 3.6.

$$I_{pv} = N_{pp} I_{ph} - N_{pp} I_0 \left[e^{q_e\left(V_{pv,cell} + I_{pv,cell} R_{ds}\left(\frac{N_{ss}}{N_{pp}}\right)\right)/N_{ss} a\,V_t} - 1 \right] - \frac{\left(V_{pv,cell} + R_{ds}\left(\frac{N_{ss}}{N_{pp}}\right) I_{pv,cell}\right)}{R_{dp}\left(\frac{N_{ss}}{N_{pp}}\right)} \tag{3.8}$$

Where N_{ss} & N_{pp} are series and parallel cells of the PV module.

3.4. Power Quality standards

Power Quality standards are designed to maintain the power quality in solar PV systems that are connected to the grid, and monitoring the power quality aids in finding the many PQ problems that may be present in the system. The subsections that follow discuss these PQ requirements, measures, and problems.

3.4.1. International Standards of Power Quality

International organisations are continuously working together to standardise the PQ at the grid level including the International Electrotechnical Commission (IEC), the European Committee for Electrotechnical Standardization (CENELEC), and the Institute of Electrical and Electronics Engineers (IEEE). These organisations offer a variety of PQ-related international standards that assist in regulating PQ both with and without RE penetration. Harmonics in the power system network are easier to explain according to IEEE Standard 519-1992. According to the IEEE-P1547 standard, voltage variations must be less than 5% and DC content must account for no more than ±0.5% of the PCC's overall output current (Chawda et al., 2020).

IEEE Standard 519-2014 updates the harmonic voltage and current restrictions for various voltage levels. The statistical evaluation of quick and short-time harmonic measurements was added to this new standard, which placed a large emphasis on harmonic measurements. According to IEEE Standard 519-2014, the voltage distortion level reduces as the voltage level rises and the maximum current harmonics are determined by the system's short circuit strength. Table 4.1 lists the pertinent IEEE standards for PQ and RE penetration into the power grid.

Table 3.1: Important power quality international standards(Chawda et al., 2020)

Standard	Guidelines
929-2000	Guidelines for compatible operation on grid-tied-SPV
1159	Guidelines for monitoring of electrical PQ
519-1992	Guidelines on voltage, current harmonics level
P1547	Guidelines for grid-tied RES with the power system
519-2014	Guidelines on updated voltage, current harmonics levels, and short-time harmonics measurements
61000-4-7	Guidelines on harmonics and inter-harmonics measurements and instrumentation
61000-4-15	Guidelines for testing and measurement methods – flicker meter functional and design specifications
61000-4-30	Guidelines for PQ Measurement Methods
P1409	Guideline for PQ improvement in utility network using custom power technologies

3.4.2. National Standards of Power Quality

In South Africa, electricity utilities are standardised according to the National Regulation Standard (NRS) and South African National Standards (SANS). The low voltage distribution network is regulated by NR048. In the case of power integrated on the low voltage distribution network also known as Small Scale Embedded Generations (SSEG') are regulated by NRS 097 standards presented in Tables 3.2 and 3.3.

Table 3.2: **Voltage requirements for grid-connected SSEGs**

Voltage requirements	
Normal voltage operating range	• 85% ≤ V ≤ 110%
Maximum Direct Current (DC) voltage	• 1000V; this is the voltage on the DC side of an inverter, for instance when no load is taken and maximum source energy is available (e.g. peak solar radiation for PV panels)
Maximum voltage change.	• Generation rejection (i.e. Thank you. tripping of SSEG while generating at full capacity should result in a voltage change of less than 3% at POC. This is in accordance with VDE-AR-N 4105.
Voltage unbalance.	• Maximum unbalanced generation of 4.6kVA for single and dual phase embedded generation. Units larger than 4.6kVA should be split evenly between available phases. • Voltage unbalance contribution should be kept at 0.2% for the three-phase generation connected to a network with an impedance equal to that of the reference.

Table 3.3: **Harmonic Distortion requirements for grid-connected SSEGs**

Harmonics and waveform distortion requirements	
Harmonic distortion.	• Total harmonic distortion should be limited to 5%. • Harmonic and inharmonic current distortion should conform to the relevant emission limits outlined in IRC 61726.
Communication notches.	• Relative depth of communication, not just due to a line connected in better, should be limited to 5% of nominal voltage at the POC For any operational modes.

3.4.3. Solar PV capacity standards

Table 3.4: **Standards for PV capacity**

Standard	Publication	Nature	Capacity
IEEE std.929	IEEE	Only PV	<10kW
IEC 61727	IEC	Only PV	<10kW

Table 3.5: **PV plant response for abnormal grid voltage**

Standard	Voltage	Clearing Time
IEEE1547	V < 45% 45% < V < 60% 60% < V < 88% 110% < V < 120% 120%	0.16s 1s 2s 1s 0.16s
IEEE929	V < 50% 50% < V < 88% 110%< V < 120% 120%	6 cycles 120 cycles 120 cycles 6 cycles
IEEE1547	V < 50% 50% < V < 85% 110% < V < 135% 135%	0.1s 2s 2s 0.05s

Table 3.6: **IEEE 1547 and IEC61727 harmonics levels**

Old Harmonics	Percentage of fundamental
3 ≤ h ≤ 9	< 4.0%
11 ≤ h ≤ 15	< 2.0%
3 ≤ h ≤ 21	< 1.5%
23 ≤ h ≤ 33	< 0.6%
33 ≤ h	< 0.3%
Even	25% of odd harmonics
THD	< 5%

The DSTATCOM/SAPF is connected in parallel to the load as illustrated in Figure 3.2. The AC side of the VSC of DSTATCOM is connected in shunt to the distribution network and normally across the PCC or consumer load, while the DC side is connected to the DC bus with storage element and possible connection of solar PV. The voltages and current are sensed which are used to implement the necessary control algorithm to generate the gating signal of the VSC of the DSTATCOM/SAPF. PWM current control is normally used to control the VSC of DSTATCOM to inject required currents.

The PQ standards mentioned in Table 3.1-3.6 show the power quality standards for voltage that need to be met by the control algorithms in readjusting the PQ issue.

3.5. Power Quality control algorithms

Several control algorithms for DFACTS can be used with current and voltage reference signals derived accordingly. In the existing literature, there are time-domain and frequency-domain control algorithms. The frequency-domain algorithms have been reported to be slow, sluggish, analog to digital signal processors required and heavy computation burden making them unsuitable for real-time control. The study focuses on the time domain control algorithms presented in Figure 3.5.

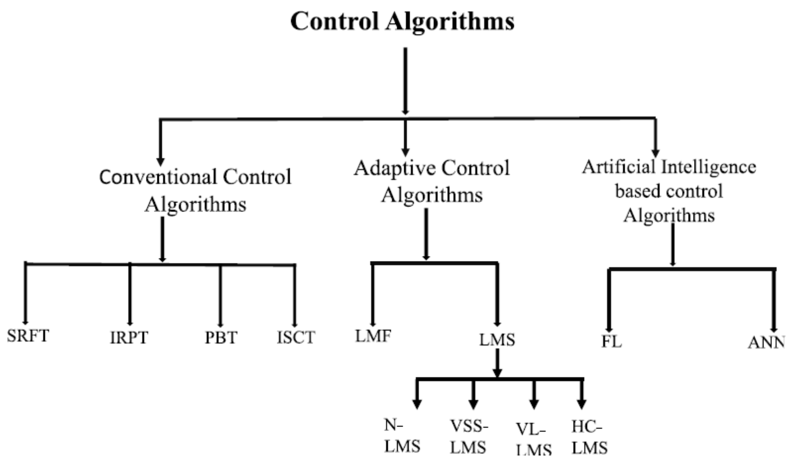


Figure 3.6: Classification of control algorithms (Jha & Shaik, 2023)

Due to the easy implementation of the conventional control algorithms, they have been considered in this study and further explained the phases of constructing the algorithms. The SRF theory-based control algorithm has been further considered for this study since it has been used in many studies to deal with voltage-related PQ issues with Shukl & Singh, 2020 indicating that the trending Adaptive algorithms for RES have steady-state performance degradation due to input signal power noise and initialisation error.

3.5.1. Conventional Control Algorithms

Traditional control techniques estimate the reference gate signals needed to drive the DFACTS devices by transforming voltage and current signals from 3-phase to 2-phase and from 2-phase to 3-phase using a phase-locked loop circuit (Singh & Solanki, 2009). The paragraph below explains the design method used to create a traditional control algorithm.

3.5.1.1. Design of conventional control algorithm

The subsections below give a breakdown of the many phases required in constructing conventional/traditional control algorithms. Based on the research publications, standard notation and terminology are employed.

a. **Estimation of in-phase and quadrature unit templates:**

Equation 3.8 can be used to determine the terminal AC voltage (V_t) of a three-phase system:

$$V_t = \sqrt{\frac{2}{3}({V_{sa}}^2 + {V_{sb}}^2 + {V_{sc}}^2)} \quad (3.9)$$

Where V_{sa}, V_{sb}, V_{sc} are grid voltages.

U_{pa}, U_{pb}, and U_{pc} are three-phase in-phase (active) unit vector templates which can be written as:

$$U_{pa} = \frac{V_{sa}}{V_t}, U_{pb} = \frac{V_{sb}}{V_t}, U_{pc} = \frac{V_{sc}}{V_t}, \quad (3.10)$$

U_{qa}, U_{qb}, and U_{qc} are three-phase quadrature (reactive) unit vector templates which can be written as:

$$\left\{\begin{array}{c} U_{qa} = -\frac{U_{pb}}{\sqrt{3}} + \frac{U_{pc}}{\sqrt{3}} \\ U_{qb} = \frac{\sqrt{3}U_{pa}}{2} + \frac{(U_{pb} - U_{pc})}{2\sqrt{3}} \\ U_{qc} = -\frac{\sqrt{3}U_{pa}}{2} + \frac{(U_{pb} - U_{pc})}{2\sqrt{3}} \end{array}\right\} \quad (3.11)$$

b. Estimation of Loss components:

Active and reactive loss components are produced using a PI voltage regulator. The reactive loss component ($i_{qr}(n)$), which is obtained from the PI voltage regulator, and is used to maintain the terminal voltage at the PCC.

$$i_{qr}(n) = i_{qr}(n-1) + k_{pq}(v_{te}(n) - v_{te}(n-1)) + k_{iq}v_{te}(n) \quad (3.12)$$

Where:

$i_{qr}(n-1)$ and $v_{te}(n-1)$ – preceding values of the reactive loss component and voltage error

$v_{te}(n)$ –The current value of the voltage error,

$$v_{te}(n) = v_{tn}(n) - v_t(n) \quad (3.13)$$

Where v_{tn} is the reference value for the terminal voltage and indicates the peak amplitude of the phase voltage v_t

By computing the active loss component $i_{dr}(n)$, the PI voltage regulator keeps the DC bus voltage constant.

$$i_{dr}(n) = i_{dr}(n-1) + k_{pq}(v_{de}(n) - v_{de}(n-1) + k_{id}v_{de}(n) \qquad (3.14)$$

Where the preceding values of the active loss component and dc voltage error are $i_{dr}(n-1)$ and $v_{de}(n-1)$. However, this dc voltage error's current value is:

$$v_{de}(n) = v^*_{dc}(n) - v_{dc}(n) \qquad (3.15)$$

$v^*_{dc}$is the reference DC bus voltage calculated by:

$$v^*_{dc} = \frac{2\sqrt{2}v_{LL}}{\sqrt{3}m} \qquad (3.16)$$

Where:

v_{LL}- Line to Line voltage at PCC

m – Modulation index

v_{dc} – Actual DC Link voltage

c. Extraction of the fundamental component of load currents:

The control algorithms use the 3-phase to 2-phase and 2-phase to 3-phase conversion methodologies to determine how the active and reactive components of the load current are calculated.

d. Generation of three-phase reference signals:

Voltage unit templates are used to correct the extracted in-phase and quadrature load currents obtained using the PLL circuit to determine the active and reactive components of the grid current signals. By converting these elements from 2-phase to 3-phase, reference grid signals are produced. Depending on the type of algorithm, the specifics of the reference current generation signals may change.

e. Generation of gating signals:

The Pulse Width Modulation (PWM)-based controller receives the generated 3-phase reference signals (i^*_{abc}) and actual grid signals (i_{abc}) to provide gating signals for DFACTS devices. In a three phase four wire utility system the gating signals for the fourth leg switches of DFACTS devices are calculated by comparing the sensing neutral signal (i_{sn}) and reference neutral signal (i^*_{sn}).

$$\begin{Bmatrix} i^*_{sn} = 0 \\ i_{sn} = -(i_{sa} + i_{sb} + i_{sc}) \end{Bmatrix} \quad (3.17)$$

The generalised approach has been applied in many Synchronous Reference Frame Theory (SRFT) based algorithms. It has been applied by many studies to deal with voltage sag/swell in a power system and has had so many advantages compared to other conventional control algorithms like dealing with most Low Voltage distribution PQ issues other than just the attributes focused on in this study which is voltage sag/swell.

3.6. Discussion

The Low Voltage (LV) distribution network experiences power quality issues because of the different types of loads connected to the network and the high penetration of solar PV which mostly causes the voltage to sag and swell on the network. The traditional ways like the use of passive filters such as capacitor banks, On Load Tap Changer (OLTC), and more in dealing with the power quality are not adequate because of difficulties in attenuating. The use of active power filters (APF) emerged with different connections and algorithms. In this study, a shunt connection of APF which is known as a DSTATCOM also known as the SAPF concept has been studied in dealing with voltage control to deal with power quality issues. The DSTATCOM is used to compensate for voltage sag and swell power quality issues. Through the AC side of VSC, it injects the necessary current required to compensate for the power quality issues that occurred. They are also used when integrating solar PV power generated into the existing grid to assist in the power demand. The solar PV is connected on the DC side of the VSC across the DC storage. The optimisation of the DTSTACOM controller depends on the type of algorithm that is used also and, in this study, the SRFT-based control algorithm which is a conventional control algorithm is considered.

3.7. Conclusion

The concept of DSTATCOM has been presented in this chapter initially looking at important components of the DSTATCOM such as Ripple Filter, Interfacing Filter/PIC circuit, VSC, Solar PV model, and PWM current control technique. The power quality control algorithms supply the PWM current control block with reference current which is used to obtain the control pulses of the VSC to define the necessary switching operations for compensation. Hysteresis current control is a popular technique among the various current control methods because of its straightforward topology, quick response, precision, and unconditioned stability. Important power quality international and South African standards to define the voltage and harmonic limits when integrating solar or any other SSEG. The stages of designing a conventional control algorithm have been presented with a focus on the synchronous reference theory. A DVR has been analysed for compensation of voltage variation on MATLAB Simulink. The network considered is a radial distribution line with a sensitive non-linear load connected and the end of the line.

CHAPTER FOUR
SIMULATION OF DVR FOR COMPENSATION OF POWER QUALITY ISSUES IN IEEE 13 BUS DISTRIBUTION NETWORK

4.1. Introduction

Voltage, alongside frequency, stands as one of the primary indicators of power quality. Most power quality metrics are established with voltage considerations, and adherence to IEEE 1159 and IEEE 519 standards is necessary to uphold them. This chapter examines the power quality analysis in a distribution network through MATLAB Simulink modelling and simulation. This analysis encompasses steady-state conditions and dynamic disturbances like voltage sag and swells in radial distribution networks with sensitive non-linear loads. The primary emphasis lies in analysing voltage variations, specifically voltage sags, and swells, resulting from disturbances originating from both the load side and the source side. A Dynamic Voltage Restorer (DVR) has been analysed in compensation for the power quality issues identified because of the disturbances introduced.

This chapter's organisation is as follows. Section 4.2 is about the system configuration which provides the systems considered for this study and its parameters are covered in detail. Section 4.3 is on simulation results when considering a steady state with and without connection of a three-phase balanced load. Section 4.4 focuses on the simulation and results of dynamic disturbances applied to the radial distribution network.

4.2. IEEE 13 Bus System Configuration with PV - DVR

An IEEE 13 Bus distribution network has been utilised for the study as represented in the one-line diagram of the distribution network in Figure 4.1. Its original system is a 4.16kV and 0.48kV, 60Hz, 5MVA radial distribution with a voltage regulator of three single-phase units connected in star (wye). The power in this network is distributed through overhead lines and underground cables with different phasing to unbalanced spots and distributed load with some capacitor banks.

In the proposed study a non-linear load has been connected in Bus 634 which is the LV side of the inline transformer connected between bus 633 and 634 which steps down the voltage from 4.16kV to 0.48kV. The consideration of Small Scale Embedded Generators (SSEG) which comprise mostly Renewable Energy Sources (RES) are mostly connected on the LV side and hence a Dynamic Voltage Restorer (DVR) with solar Photovoltaic (PV) is connected at bus 634.

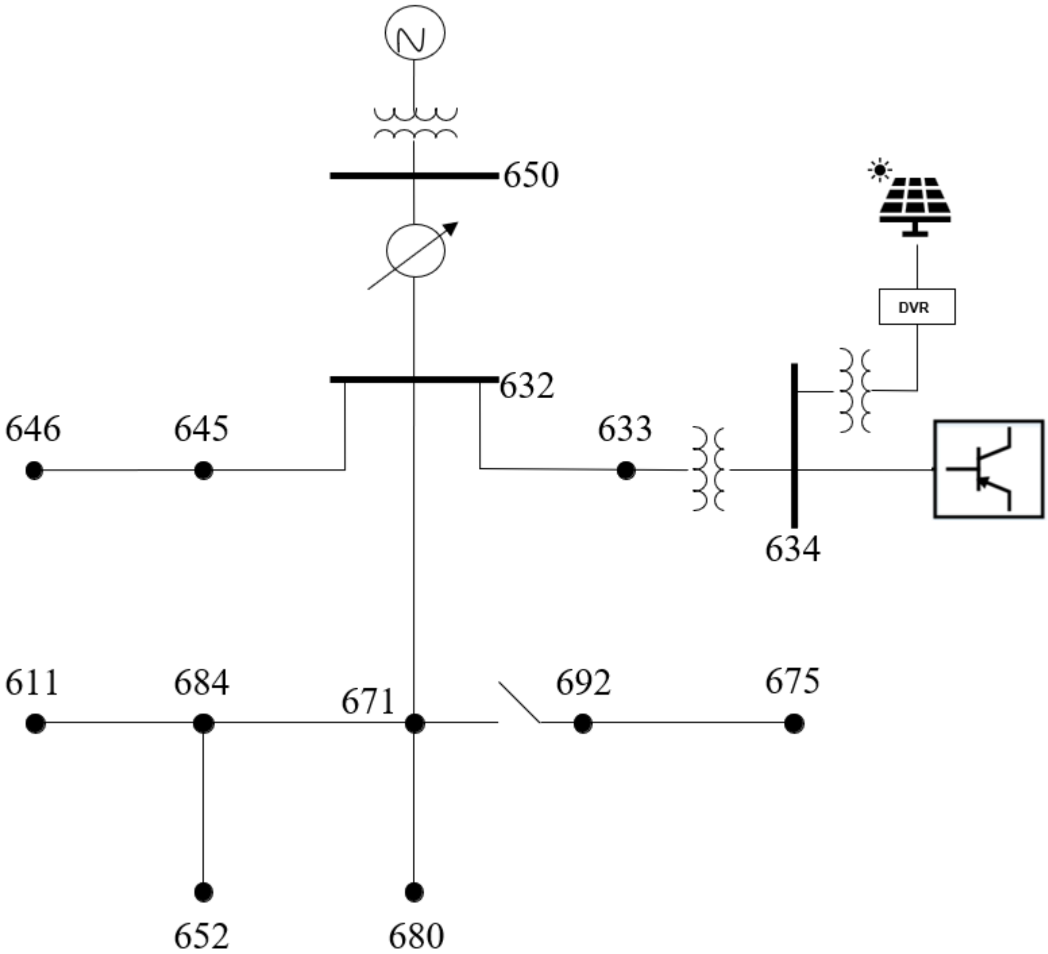


Figure 4.1: **Modified IEEE 13 bus distribution network with Solar PV – DVR**
(Kersting, 2001)

The network parameters of the system presented in Figure 4.1 are given in Annexure A.2.2 and the system has been modelled on MATLAB Simulink. The distribution network employs a programmable voltage source which is used to indicate the grid connection for the non-linear load connected. The non-linear load has been represented with a series three-phase series RL branch and diode bridge rectification circuit with an RL load connected on the DC side of the rectification circuit. The programmable voltage source has been used because it allows the introduction of dynamic disturbances to be modelled like voltage sag, swell, and harmonics.

4.3. Network Steady-state analysis

The distribution network presented in section 4.2 has undergone analysis through the MATLAB Simulink simulation. Based on the theoretical studies connection of non-linear load causes harmonics in the system. A steady state analysis of the distribution network with the non-linear load connected has been conducted by analysing the Total Harmonic Distortion (THD) of the distribution network to inform the state of distortion of the voltage and current signals using calculations and MATLAB Simulink.

According to IEEE 519, the THD for the grid's current and voltage should be kept below or equal to 5%. The THD for the current and voltage are monitored in this case study and solutions should be provided if the system current or voltage does not comply with the IEEE519 standards to return the system to its steady state, where the current and voltage are within acceptable THD. The THD can be calculated using the following equation:

$$\boldsymbol{THD} = \frac{\sqrt{\sum_{h=2}^{h_{max}} {I_h}^2}}{I_1} \qquad (4.1)$$

Where:

I_h - RMS current of nth harmonic

n=1 at the fundamental frequency

The signals viewed on the scope are logged into the workspace for further analysis using the powergui's Fast Fourier Transform (FFT) analysis. Figure 4.2 illustrates the process that has been taken to load the information of the voltage and current signal in the workspace for further analysis.

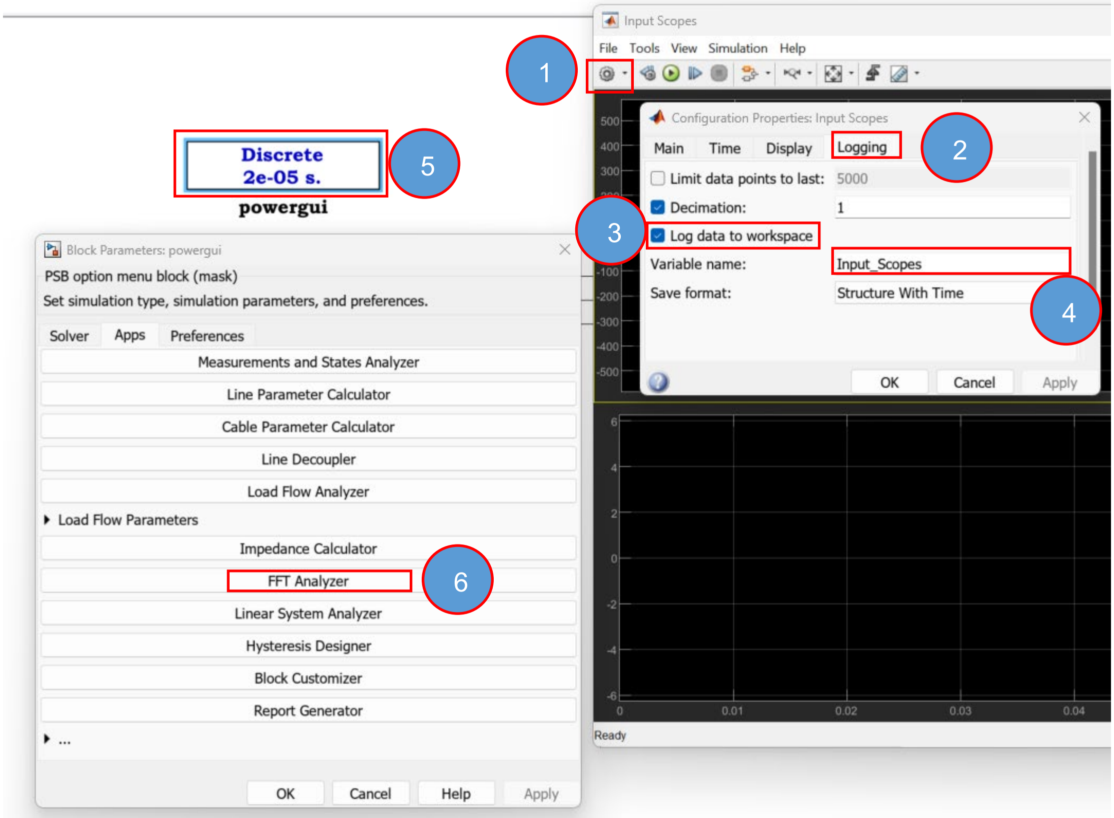


Figure 4.2: Logging signals data into workspace

The numbered steps taken have been indicated in Figure 4.2 and they are followed to get the FFT Analyser which is used to indicate the percentage distortion of the voltage and current signals. Figure 4.3 presents an FFT analysis for the source voltage signal as measured from bus 634. The crucial settings that should always be corrected are highlighted in the Figure.

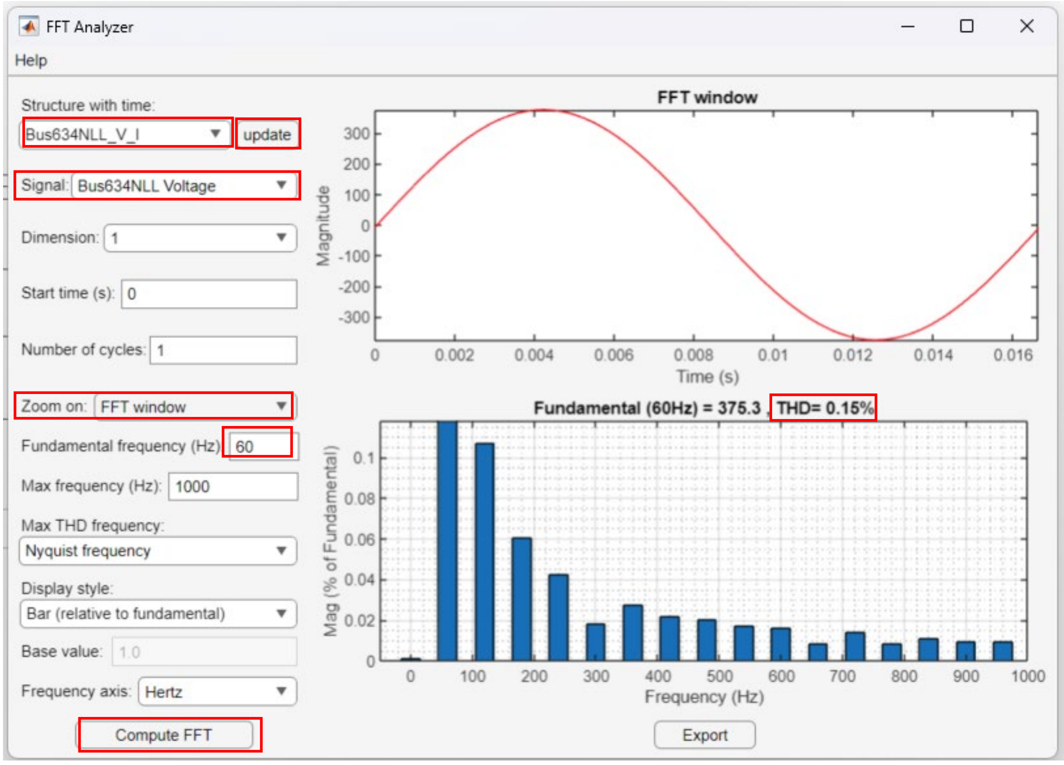


Figure 4.3: **Source (Bus634) voltage FFT analysis results**

The computed THD of the source voltage signal is 0.15%, which means that the non-linear load connected to the distribution network does not disturb the voltage of the grid. Figure 4.4 illustrates the computed THD results of the source current measured from bus 634 of the distribution network. The current signal is connected as a second signal of the scope, and it needs to be selected on the signals for correct analysis. The THD of the source current signal is 20.53%.

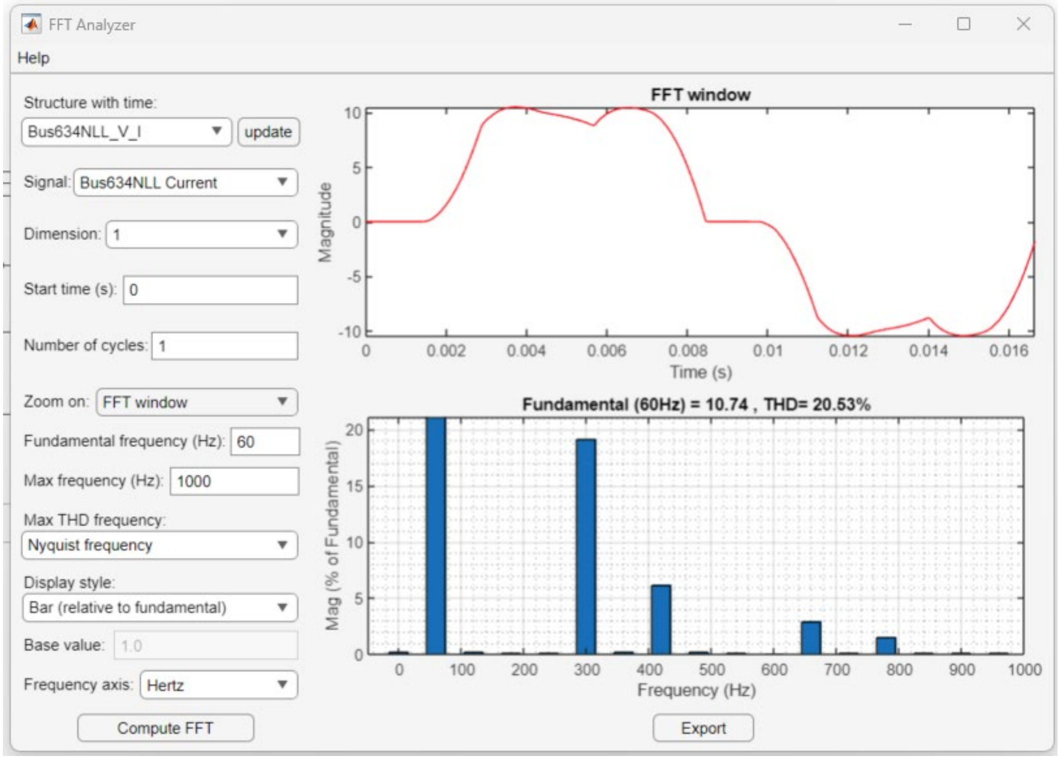


Figure 4.4: **Source (Bus634) current FFT analysis**

The inclusion of the non-linear load in a distribution system causes unacceptable current harmonics which may cause a lot of issues like failure, and damage to components. The results of the computed THD for the source current signal are highly distorted with a THD of 20.53% which is way higher than the 5% regulated by IEEE 519. The harmonics need to be compensated so that they do not affect the grid code and to maintain the harmonics with a THD of less than 5% as regulated by IEEE 519.

In the power industry, passive filters have long been employed to reduce distortion brought on by harmonic current (Moran et al., 1995). However, they have several disadvantages, including a resonance issue, a performance dependence on the system impedance, and the ability to absorb the harmonic current of a nonlinear load, which may cause more harmonic propagation in the power system (Haddad, 1998). To overcome the challenges faced with the passive filters Active Power Filters (APF) have been used recently for compensation for power quality issues. The APFs are used for dynamic compensation when the magnitude and phase angles vary. They absorb or inject reactive power to compensate for the power quality problem faced which can be voltage Sag and swell, harmonics, etc. The APFs, like passive filters, can be connected in series or parallel, depending on the kind of source that is causing harmonics in the power system. Active filters reduce the impact of harmonic current by generating equal amplitudes of opposing phases using active power conditions. This cancels out the harmonics generated in the nonlinear components and substitutes the nonlinear load's current wave.

The study focuses on the power quality analysis and compensation of voltage sag and swell variation that occur on the source. A Dynamic Voltage Restorer (DVR) is one of the Distributed Flexible Alternating Current Transmission Systems (D-FACTS) also known as Custom Power Devices (CPDs) which is connected in series with the line via an injection transformer, Voltage Source Converter (VSC), and a common DC link capacitor. It is employed to maintain appropriate voltage for sensitive loads under dynamic fluctuations. In this chapter, the DVR is employed to compensate for voltage sag and swell introduced at the source.

4.4. Implementing Dynamic Voltage Restorer (DVR) for Effective Compensation of Voltage Sag and Swell

The utility grid might have its disturbance which can be incorrect switching, Auto-reclose of a breaker on the MV network, and machine starting. All these disturbances can cause voltage variation in the distribution network. In this case study a programmable voltage source has been used to simulate the voltage variations resulting from disturbances occurring on the grid system.

Figure 4.5 details the internal voltages of the programmable voltage source which are programmed to introduce the variations in the system as follows [1 0.5 1 1.5 1] p.u at time [0 0.5 0.7 1.5 1.7] s. The source voltage is reduced by 50% at time 0.5s until time 0.7s where the source voltage is restored to 100%, this indicates a 50% voltage sag that has been introduced for 0.2 seconds. According to IEEE 1159 any Route Mean Square (RMS) voltage variation level of 10% – 90% occurring in less than one minute is a voltage sag. At times 1.5s to 1.7s a voltage swell has been introduced by increasing the voltage magnitude by 50%, this is also classified by the IEEE 1159. At 1.7s the magnitude has been restored to 100% as shown in.

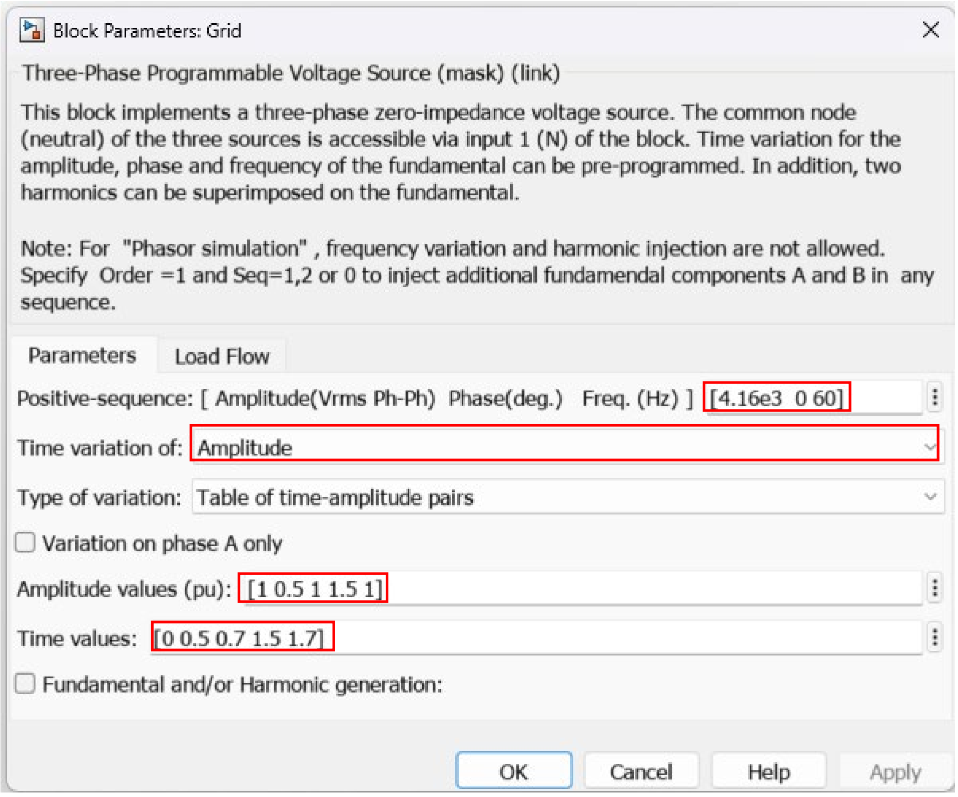


Figure 4.5: **Programmable Voltage Sources (Bus 632) Parameters**

Figure 4.5 above indicates important parameters to be updated which are highlighted starting from the system grid parameters to the harmonics generation depending on the parameters considered and introduced from the source.

In this chapter, a DVR has been used to compensate for dynamic voltage variations introduced on the source from IEEE13 bus 634 which simulates when the system is unstable contributing to PQ issues. The DVR is employed to protect sensitive loads connected against utility-supplied voltage variations like sag and swell. The DVR regulates the voltage variation injected by the grid by injecting an opposite voltage through the injection transformer. Figure 4.6 illustrates a basic block diagram of a DVR that has an injecting transformer, Passive Interfacing Circuit (PIC) filter, VSC, control, and DC storage. Based on the theory typical signals expected are also indicated.

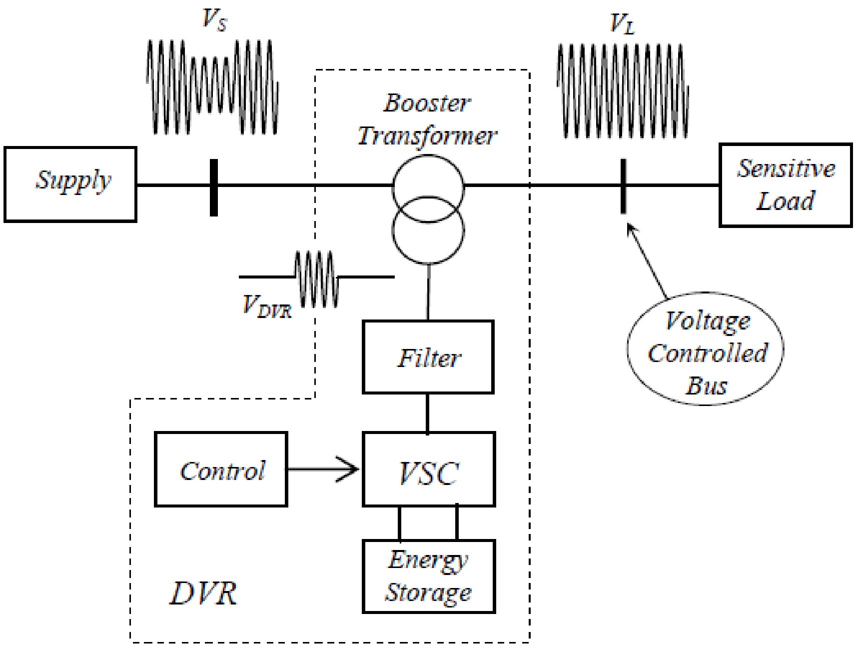


Figure 4.6: Basic Block Diagram of a Dynamic Voltage Restorer (Ramesh et al., 2018)

The simulation of the DVR involves various elements based on the depicted basic block diagram. These include a programmable voltage source, injection transformer, filter circuit, connected non-linear load, Voltage Source Converter (VSC), DC capacitor for energy storage, and a power vectorial theory control algorithm, as presented in Figure 4.7.

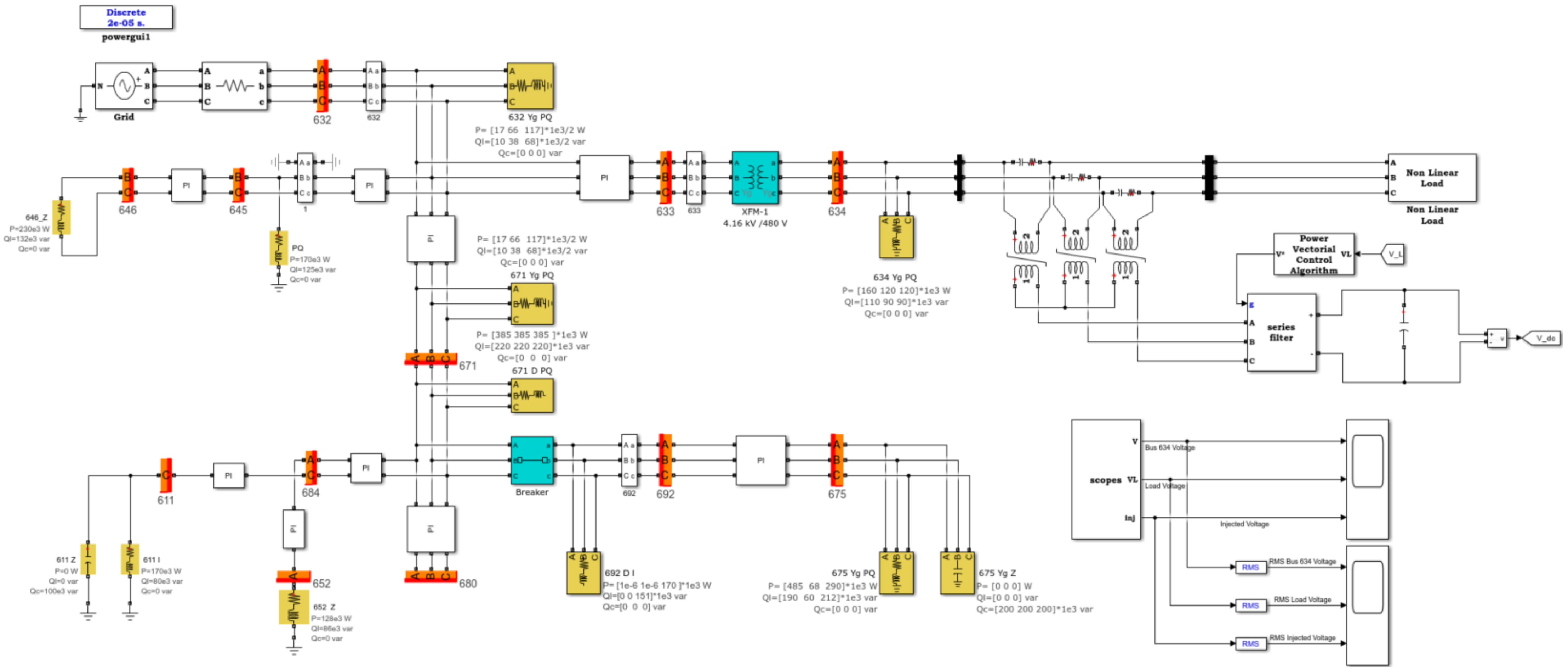


Figure 4.7: Simulink Diagram of an IEEE13 Bus with Dynamic Voltage Restorer

To run the simulation a powergui is used with a discrete simulation type and sampling time of 0.2μs and the simulation is allowed to run for 2.5seconds. Scopes are used to show the voltage of the grid, load, and injected voltage. The system parameters are further detailed in Annexure B. Figure 4.8 illustrates the system voltages. Figure 4.8 (a) shows the source voltage with the dynamic variation introduced in Figure 4.5, this voltage is measured from bus 1 of the system. Figure 4.8 (b) illustrates voltages injected by the DVR through the injection transformer to restore the quality disturbed for the sensitive load that is connected at the end. A maximum phase AC voltage expected at Bus 634 of the system can be calculated using the following equation:

$$V_{ph\_max} = \sqrt{\frac{2}{3}} V_{rms} \tag{4.2}$$

Where:

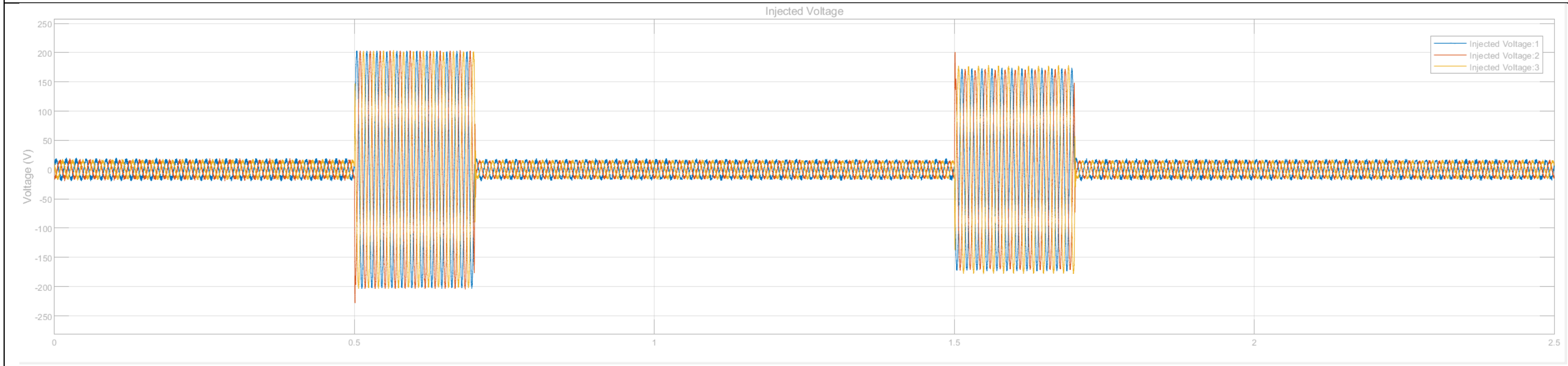
V_{ph_max} – Phase maximum voltage

V_{rms} – Three-phase Route Mean Square (RMS) rated voltage

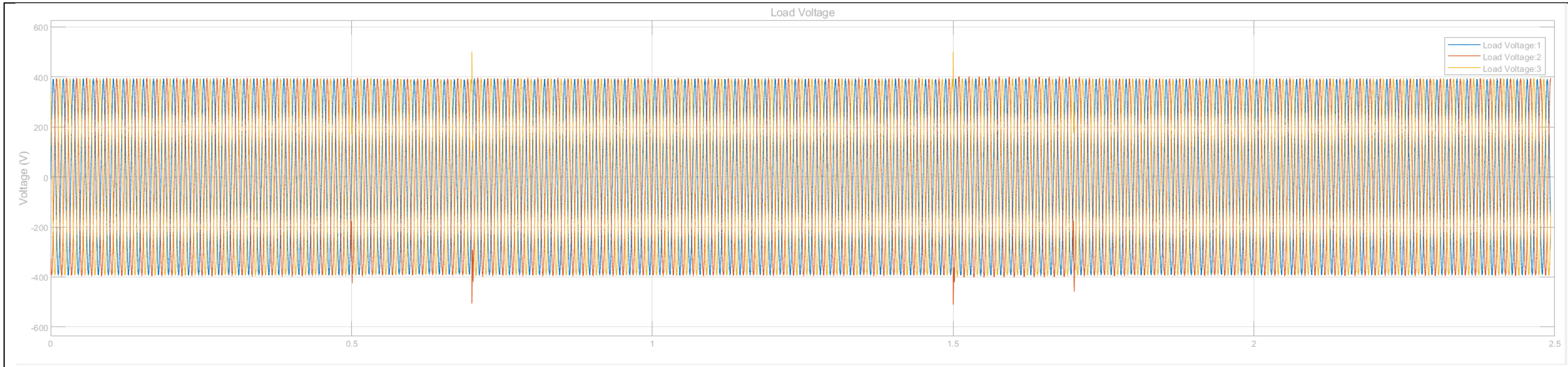
The calculated voltage is 391.92V. A trace selection for cursor measurements has been conducted where the signal maximum voltage is measured to be 375.5V. The voltage sag variation of 187.8V (At 50% of Supply Bus 632) has been compensated at bus 634 by injecting a positive signal of 201.1V which is added to the already distorted voltage to retain the 100% voltage magnitude that is supposed to be supplied by the system before the variation. Voltage swells of 563.6V (At 150% of Supply Bus 632) are compensated at Bus 634 by injecting a voltage signal with magnitude -170.9V (in the opposite direction) to reduce the magnitude of the swell voltage which retains the load voltage to the nominal safe magnitude for the load. Figure 4.8 (c) indicates the load voltage after the variation has been compensated by the DVR.


Bus 634 Voltage
Voltage Sag
Voltage Swell
Bus 634 Voltage:1
Bus 634 Voltage:2
Bus 634 Voltage:3
Voltage (V)
600
400
200
0
-200
-400
-600
0
0.5
1
1.5
2
2.5

(a)


Injected Voltage
Injected Voltage:1
Injected Voltage:2
Injected Voltage:3
Voltage (V)
250
200
150
100
50
0
-50
-100
-150
-200
-250
0
0.5
1
1.5
2
2.5

(b)

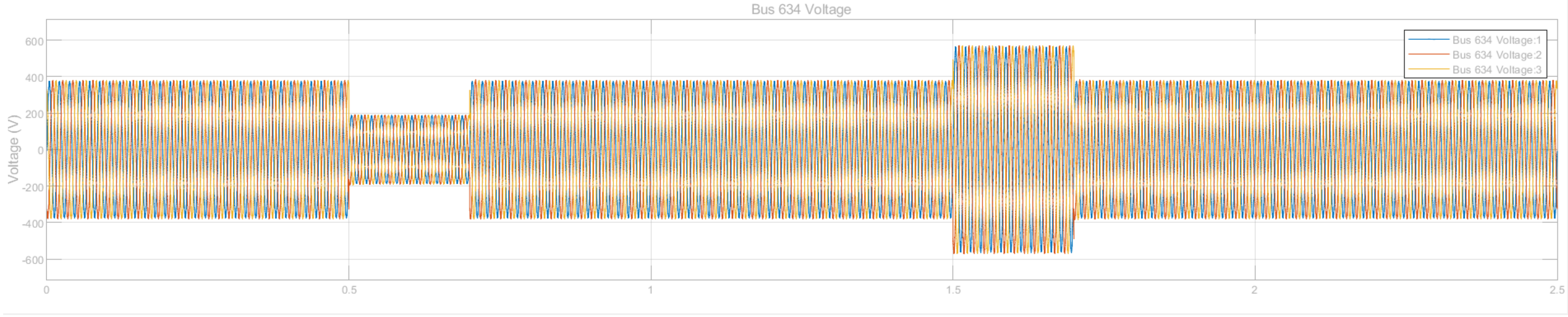


(c)

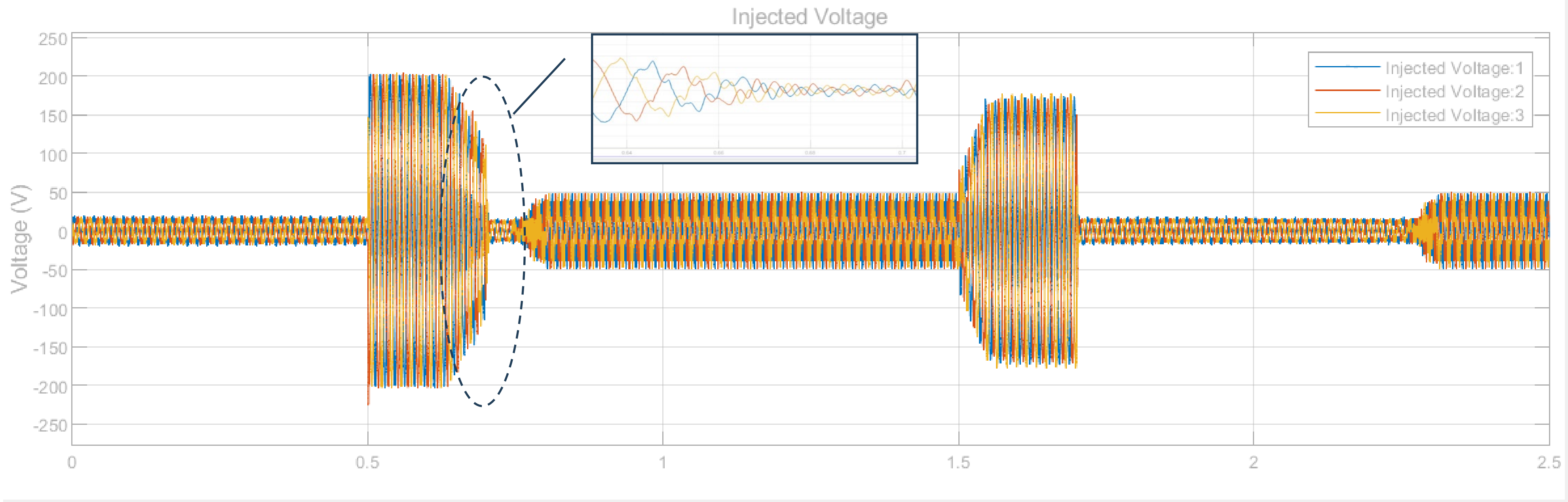
Figure 4.8: **DVR used for voltage variation (a) Shows the Grid voltages where the voltage variation has been introduced, (b) illustrates the voltage injected by the DVR to restore the voltage supplied to the sensitive load connected at the end of the distribution line and (c) Shows the load voltage after the voltage injected by DVR to compensate for the voltage variations introduced by the Grid.**

In the Figures above the injection of the voltage by the DVR considers a case where the DC link storage/supply of the VSC is enough to restore the variation. However, this is not always the case as at times the DC link capacitor might have a small storage capacity which implies the DVR does not have enough power stored on the DC Link storage element and would not be able to restore the voltage throughout the duration of the variation. In the analysis conducted with results shown in Figure 4.8, the DC link capacitor value is 6000μF which is enough to store energy for compensation.

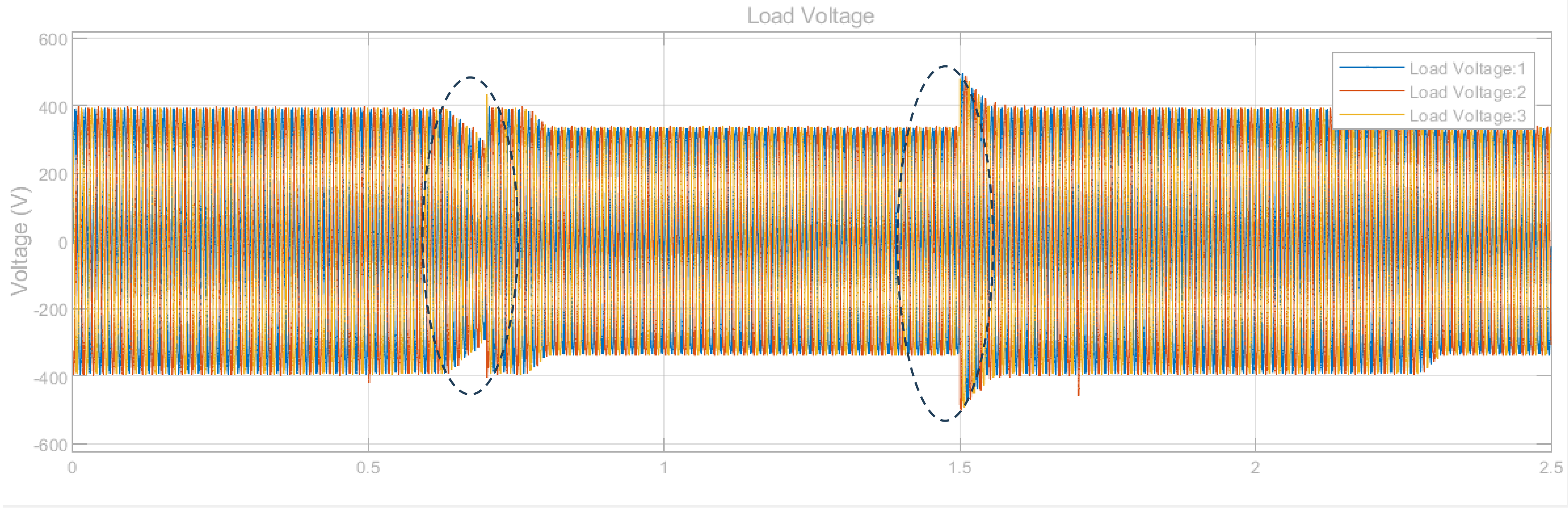
An analysis has been conducted when the DC link capacitor is reduced to less than 6000μF**.** Figure 4.9 shows voltage signals when the DC link capacitor size has been reduced. Figure 4.9 (a) shows the same variation considered in Figure 4.8 (a). Figure 4.9 (b) illustrates the voltage injected by the DVR to compensate for the voltage sag injected by the Grid between 0.5 to 0.7 seconds. It has been noted that in this case, the DVR is not able to compensate for the voltage sag for the duration as a result it collapses its compensation from 0.625s to 0.7 seconds. Figure 4.9 (c) shows the load voltage signal which is not compensated by the DVR for the whole duration of the variation.


Bus 634 Voltage
Voltage (V)
Bus 634 Voltage:1
Bus 634 Voltage:2
Bus 634 Voltage:3

(a)


Injected Voltage
Voltage (V)
Injected Voltage:1
Injected Voltage:2
Injected Voltage:3

(b)



(c)

Figure 4.9: **DVR with insufficient DC link storage for compensation (a) Shows the Grid voltages where the voltage variation has been introduced, (b) illustrates the insufficient voltage injected for the voltage sag duration by the DVR to restore the voltage supplied to the sensitive load connected at the end of the distribution line and (c) Shows the load voltage after the insufficient voltage injected by DVR to compensate for the voltage variations introduced by the Grid.**

Figure 4.10 illustrates a DC link voltage signal when the DC link storage element has been reduced. The charges stored in the capacitor collapse to a point where the DVR is not able to fully compensate for the voltage variations. The DC Link voltage of the DVR's VSC collapses and at 0.6985s with a DC voltage of 172.424V, the injection voltage supplied by the DVR starts collapsing which results in the voltage injected by the grid not being compensated for the full 0.10372s duration.

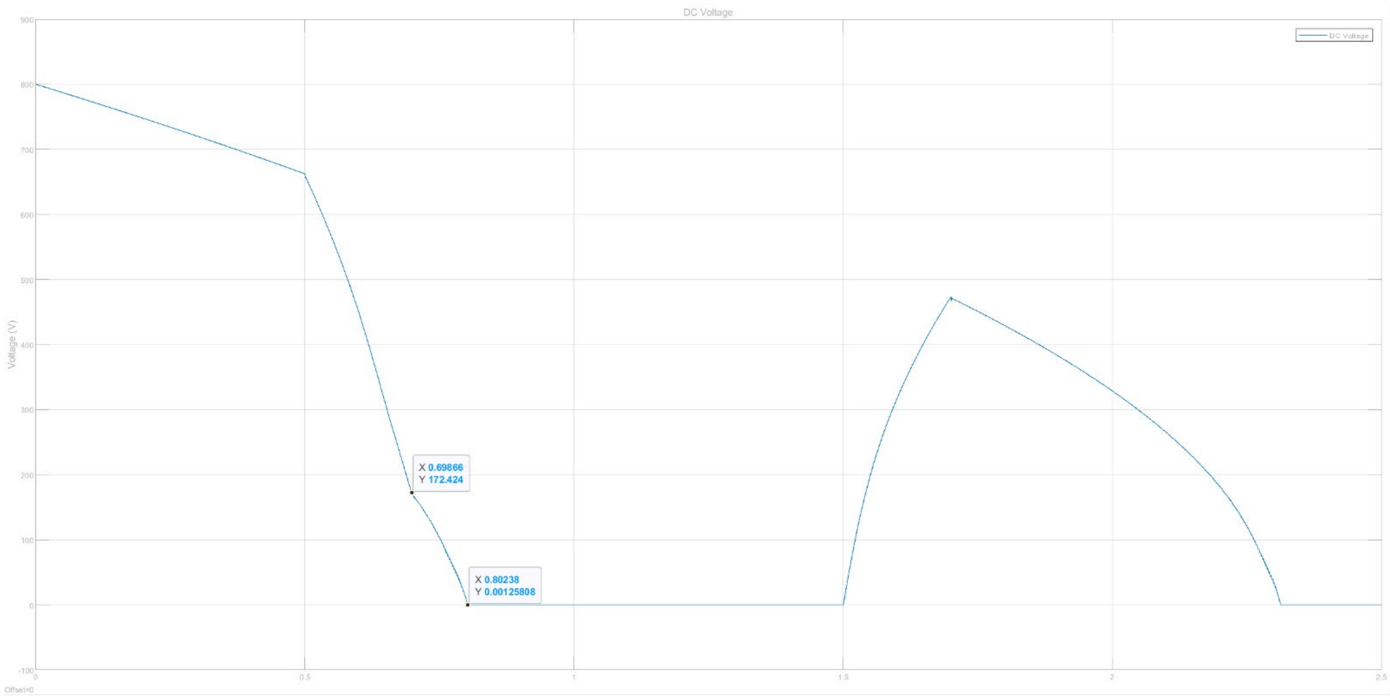


Figure 4.10: **DVR voltage signal when the DC link capacitor is reduced.**

In the Figure above the period where the DVR fails to restore the voltage is highlighted in the DC voltage signal. The DC voltage goes to zero volts.

Solar Photovoltaic (PV) system can be utilised to stabilize the DC link voltage which will assist the DVR to continue compensating and restoring by injecting necessary voltage into the distribution system for the full duration of the variations.

4.5. Integration of Solar PV to improve DVR compensation

The use of Small-Scale Embedded Generation (SSEG) is becoming prevalent worldwide. The SSEG power is generated and consumed by the customer. This also allows customers to redefine their role in the electricity value chain. The SSEGs fall under Renewable Power Producing (RPP) generators in Category A, which are generators producing not more than 1MVA power with a voltage range of -15% to +10% around nominal voltage at the Point of Connection (POC). In this study, solar PV SSEG generators are considered as they're most used on the low-voltage distribution network. In this subsection, an integration of Solor PV SSEG on the DC Link side of the VSC for the DSTATCOM connection has been analysed for improving DVR compensation under varying DC storage. The focus of the study is only on the support that can be provided by the solar PV systems for power quality in the case of varying DC storage and the DVR not being able to compensate for the power quality for the full duration.

Figure 4.11 shows a DVR with solar PV integrated on the DC side of the VSC across the DC Link capacitor storage.

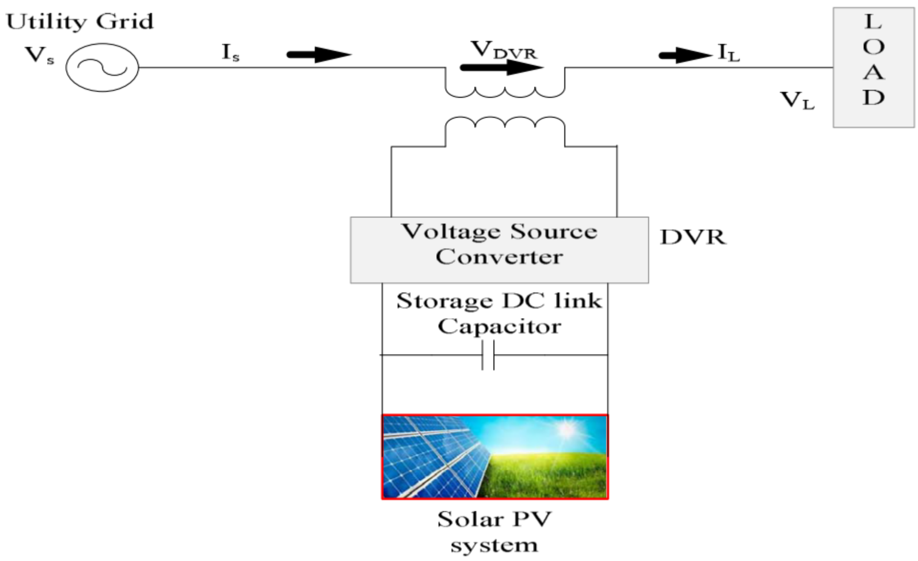


Figure 4.11: Basic Block Diagram of a Dynamic Voltage Restorer with solar PV integration (Dharavath et al., 2017)

The modelling of SSEG Solar PV requires the expected DC voltage, the power system's nominal voltage, and the intended outpower. Most of the time, the remaining parameters are calculated during the modelling process. The software offered by PV system engineers makes it simple to ascertain the characteristics needed for solar power plant design. Figure 4.12 is a MATLAB Simulink diagram with solar PV connected on the DC side. The integration of solar PV requires a Maximum Power Point Tracking (MPPT) and DC-DC boost converter.

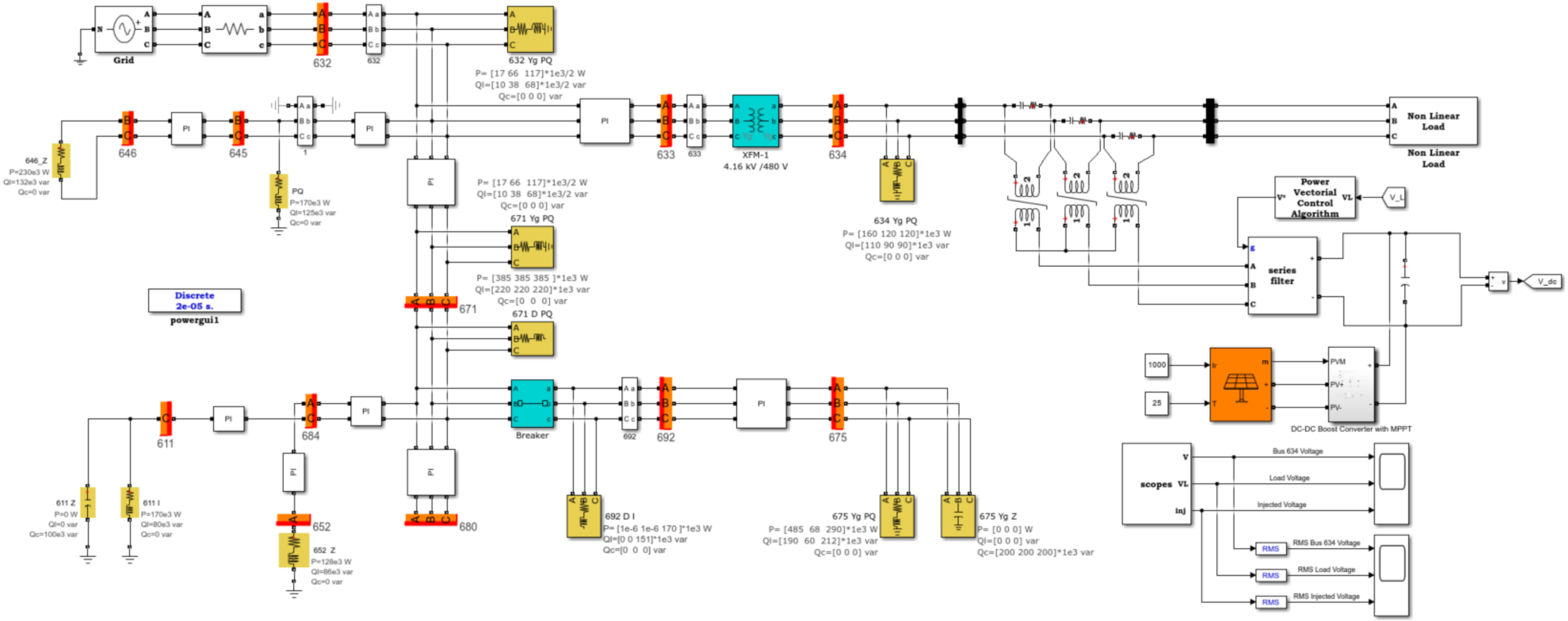
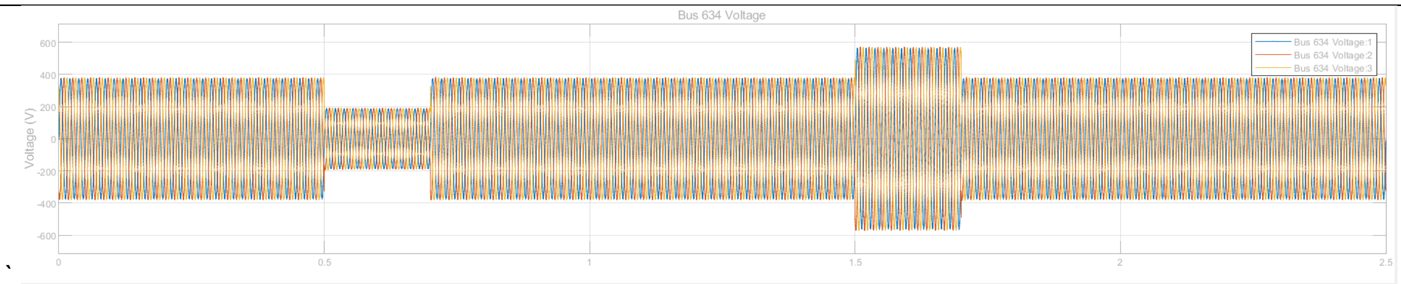


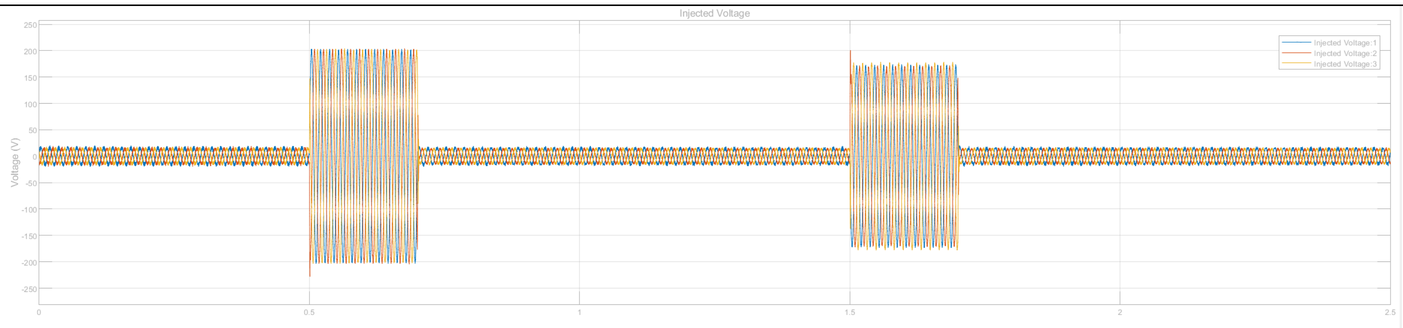
Figure 4.12: Simulink Diagram of a Dynamic Voltage Restorer with solar PV

MATLAB Simulink software has already built a model for PV where module data in terms of the type of a module or user-defined, Maximum power, cells per module, open circuit voltage, short circuit current, and array data in terms of parallel strings and series-connected modules per string is defined. The selected solar PV module at Trina Solar TSM-250PA05A.08 The other data are predefined for this module like maximum power being 250.1W. To have the power produced by the PV not more than 1MW for SSEG, 47 parallel strings and 10 series-connected modules per string are selected.

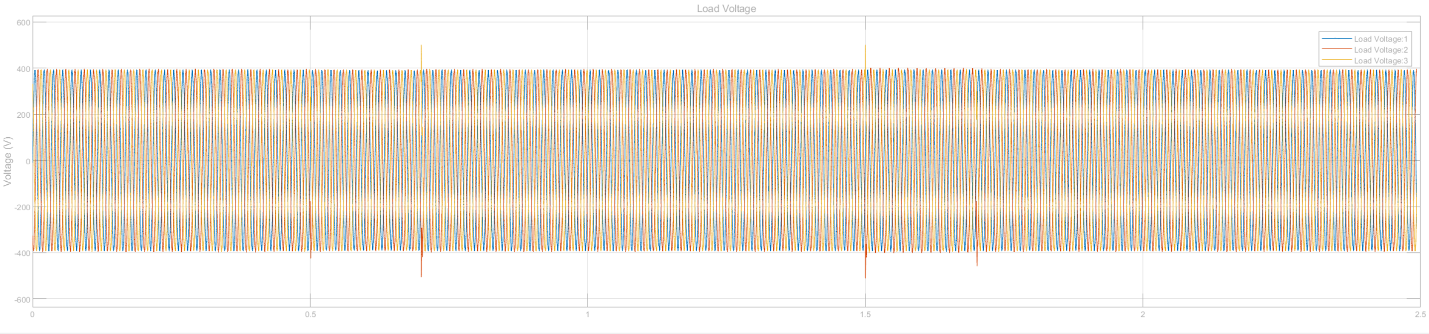
The estimated DC output power is 118kW (110kW actual) and the irradiance of 1000 $W/m2$ at 25℃. The control of the Solar PV is considered by having a DC-DC boost converter with Maximum Power Point Tracking (MMPT) which is used for stabilizing and optimising the power produced by the solar PV. This information is further detailed in Annexure A.4.1.



(a)



(b)

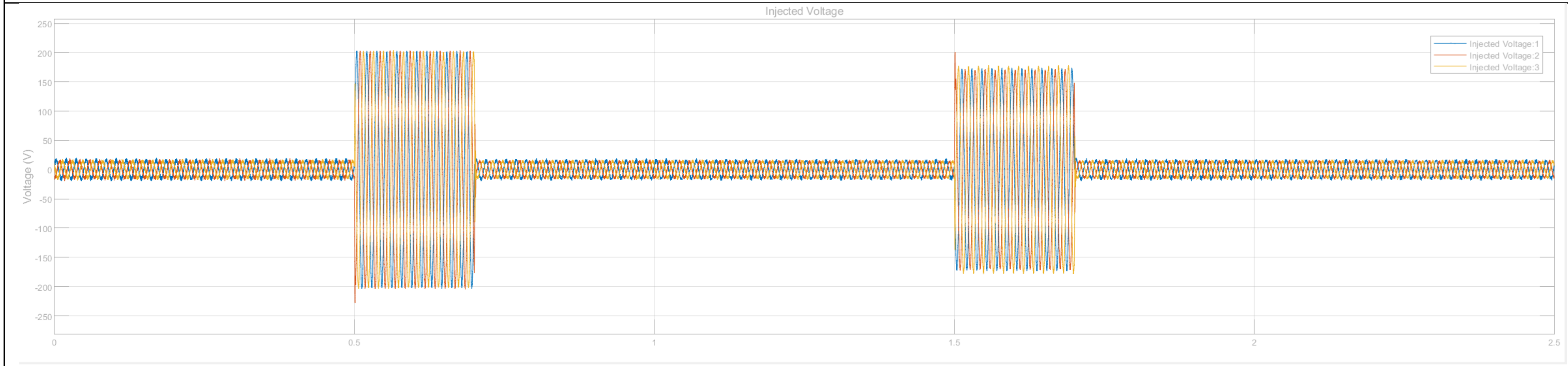


(c)

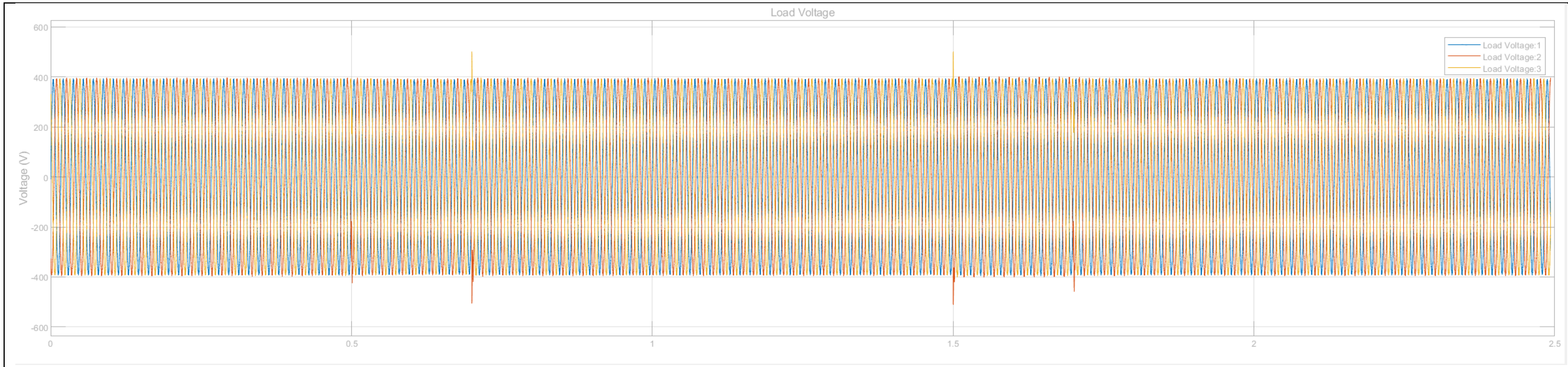
Figure 4.13 shows output signals for the grid, injected, and load voltage extracted from the buses after the integration of the solar PV system on the grid. The voltage for the sensitive load has been restored to normal for the full duration of the voltage sag and swell.


Bus 634 Voltage
Bus 634 Voltage:1
Bus 634 Voltage:2
Bus 634 Voltage:3
Voltage (V)
600
400
200
0
-200
-400
-600
0
0.5
1
1.5
2
2.5

(a)


Injected Voltage
Injected Voltage:1
Injected Voltage:2
Injected Voltage:3
Voltage (V)
250
200
150
100
50
0
-50
-100
-150
-200
-250
0
0.5
1
1.5
2
2.5

(b)



(c)

Figure 4.13: **DVR with solar PV for DC link storage support for compensation (a) Shows the Grid voltages where the voltage variation has been introduced, (b) illustrates the PV DVR voltage injected for the voltage sag compensation to protect restore the voltage supplied to the sensitive load connected at the end of the distribution line and (c) Shows the load voltage after the insufficient voltage injected by DVR to compensate for the voltage variations introduced by the Grid.**

The integration of the solar PV supported the DC Link voltage when it starts collapsing due to insufficient energy storage.

4.6. Discussion of the results

An examination of the dynamic and steady-state responses related to power quality in an IEEE 13 bus distribution network has been carried out utilizing the potent software tool, MATLAB/Simulink. This analysis concentrated on assessing power quality through the measurement of voltage and current parameters. The study considered typical and detrimental dynamic disturbances, including the introduction of variations in voltage supply from the source. The responses of each monitored variable are illustrated using MATLAB/Simulink scopes during this analysis.

A steady-state analysis of an IEEE13 bus radial distribution line with a non-linear load is connected at bus 634. THD analysis has been conducted to look at the voltage and current distortions at Bus 632 and 634 with the non-linear load connected. It has been noted that at bus 634 the voltage has not been disturbed while the current has a THD of 20.53% which is higher than the 5% regulated by IEEE 519.

Voltage sag and swell variations have been considered which are injected by the grid through the IEEE 13 bus system to the sensitive non-linear load. 50% variations at different time intervals with a duration of 0.1s. A DVR has been successfully proposed for the compensation of the variations with the calculated DC Link storage capacitor. When the value of the storage is reduced the DVR fails to compensate the voltage sag for the full duration. Solar PV has been proposed to support the DC link power storage by stabilising the storage. It has been realised that the DVR is unable to compensate for the current distortion made by the non-linear load connected. This meant an alternative solution needed to be proposed in addition to ensuring maximum protection of sensitive load.

4.7. Conclusion

Power Quality of the electrical network is very important to the utility and customers. Many strategies are used for compensation for power quality issues, it is important to understand the operation of these compensation devices and how best can they be optimised to get the power quality regulated within the standards at all times during the steady and dynamic state of the distribution system.

A DVR has been analysed in this study for compensation of voltage sag and swell for the sensitive non-linear load connected at the end of the distribution network, it works well when assuming enough DC Link capacitor storage as it would be able to re-inject and store power on the storage. However, this is not always the case as the storage could not be enough. It has been realised that when the DC link storage capacity is not enough the DVR fails to compensate for the voltage power quality for the total duration of the disturbance. An integration of Solar PV has been proposed to support the DC link power for the power required by the storage, compensation of the disturbance, and power demand. The solar PV is integrated on the DC side of the VSC with a DC-DC boost converter with Perturbation and Observe (P&O) MPPT used in between.

The use of DVR has challenges like not being able to compensate for current harmonics produced by the connection of non-linear load, which disturbs the current drawn from the utility. The THD of voltage and current drawn from the source as measured on the utility side needs to be less than 5% stipulated by IEEE 519. The harmonic current with THD more than 5% introduced using non-linear loads needs is not compensated by the DVR. A DSTATCOM is an APF that mitigates current related power quality issues.

CHAPTER FIVE
SIMULATION OF DSTATCOM FOR COMPENSATION OF POWER QUALITY ISSUES IN IEEE 13 BUS DISTRIBUTION NETWORK

5.1. Introduction

The two decades have seen a rise of interest in power quality for the end-users and utility due to ever-increasing developments in technology enabling the integration of non-conventional energy resources in all divisions of electrical power systems and the use of non-linear loads. Power quality is any current, voltage, or frequency variation from the values that are considered normal that causes equipment to malfunction or fail to operate.

The passive and active filters are used in the mitigation of power quality. A Distributed STATic COMpensator (DSTATCOM) is one of the Custom Power Devices (CPDs) or Distributed Flexible Alternating Current Transmission Systems (DFACTS) devices commonly used in the Low Voltage distribution network. A DSTATCOM is a shunt-connected Voltage Source Converter (VSC) with a short-time DC link capacitor stored energy. It is used to inject the required current to compensate for harmonic currents, variations, reactive power, and load unbalancing at the Point of Common Coupling (PCC). The optimisation of a DSTATCOM depends on the control algorithm used.

This chapter presents the implementation of DSTATCOM for harmonic power quality mitigation with control algorithms to optimise the use of this compensation device. The control strategy of the control algorithm is to ensure that the grid's current Total Harmonic Distortion (THD) is kept below 5%. A modified Dq-based control algorithm is used. Section 5.2 is about the test system configuration which provides the systems considered in this study and its parameters are covered in detail. Section 5.3 covers the details of the modified control algorithm used. In section 5.4 the results of case studies are presented considering before and after the connection of the utilised DSTATCOM with its control algorithm. Section 5.4 is about the controller's results after an SSEG integration in this case a PV.

5.2. Implementing Distribution Static Compensator (DSTATCOM) for Effective Compensation of harmonics injected by the connection of non-linear load

In this subsection, an IEEE 13 bus radial distribution network with the non-linear load connected at bus 634 of the network in Chapter 4 has also been considered for analysis in this chapter. Under steady state, it could be noted that the distribution network has current harmonics with a Total Harmonic Distortion (THD) being 20.53% which is not acceptable according to IEEE519 that the source voltage and current should have a THD of less than 5%. A DSTATCOM has been proposed for the mitigation of current related power quality issues and in this case to compensate for current THD to be less than 5%.

A shunt-connected DSTATCOM has been proposed between the source and load which will inject current into the system to maintain the power quality of the distribution grid on the source or the end-user side depending on the reference signal taken. The DSTATOM has been connected through a Passive Interfacing Circuit (PIC), a filter circuit used to suppress the unwanted noise on the signal injected into the system by the Voltage Source Converter (VSC).

Figure 5.1 shows a connection of DSTATCOM in a system with non-linear load connected. The DSTATCOM has been connected between the load and the source to ensure that the current distorted on the load side is compensated on the source side. A DSTATCOM has a shunt connected APF which is made of VSC and DC link capacitor for energy storage.

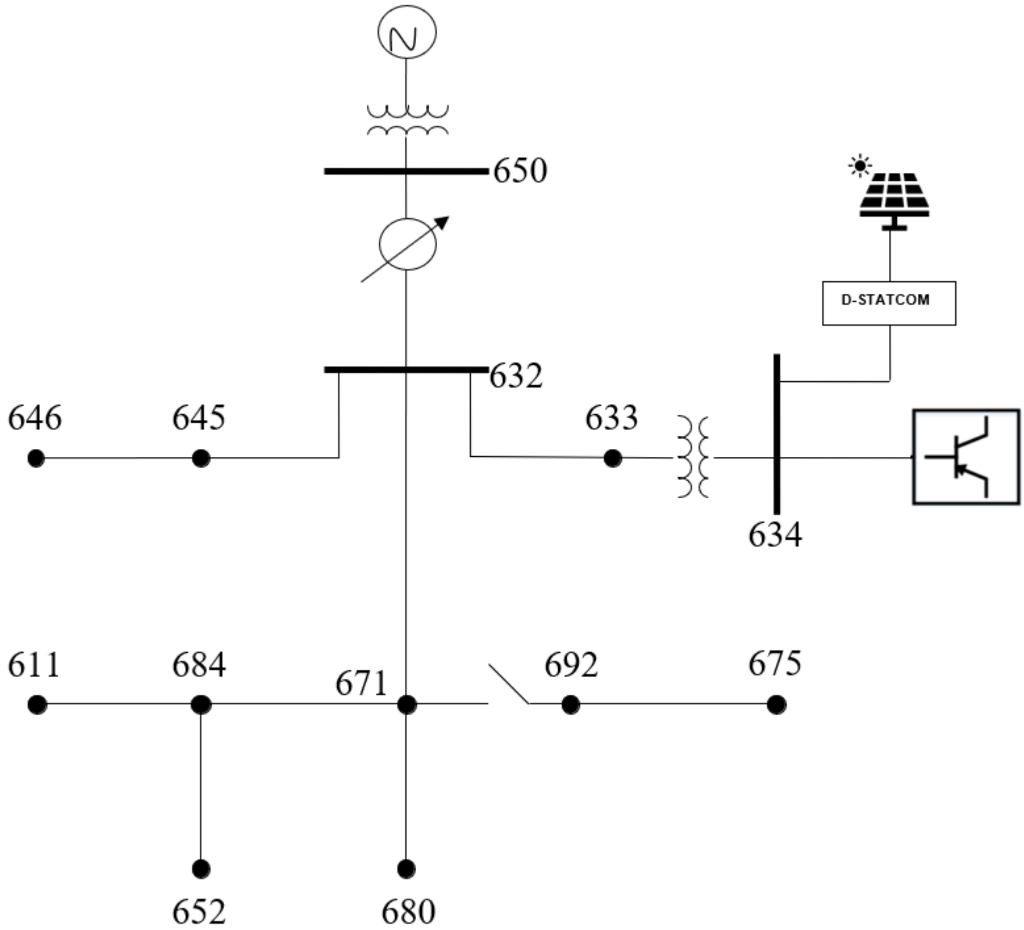


Figure 5.1: IEEE 13 Bus with DSTATCOM and solar PV Block diagram (Kersting, 2001)

The optimization of the DSTATCOM depends on the control algorithm used to control the DC link voltage. The elements of a DSTATCOM are VSC, DC link storage, and control algorithms which switch the 6 switches of a VSC using a PWM control for effective compensation. An SFRT control algorithm has been applied for the effective control of the VSC.

Figure 5.2 illustrates the computed THD results of the source current measured from bus 634 of the distribution network. The current signal is connected as a second signal of the scope, and it needs to be selected on the signals for correct analysis. The THD of the source current signal is 20.19%.

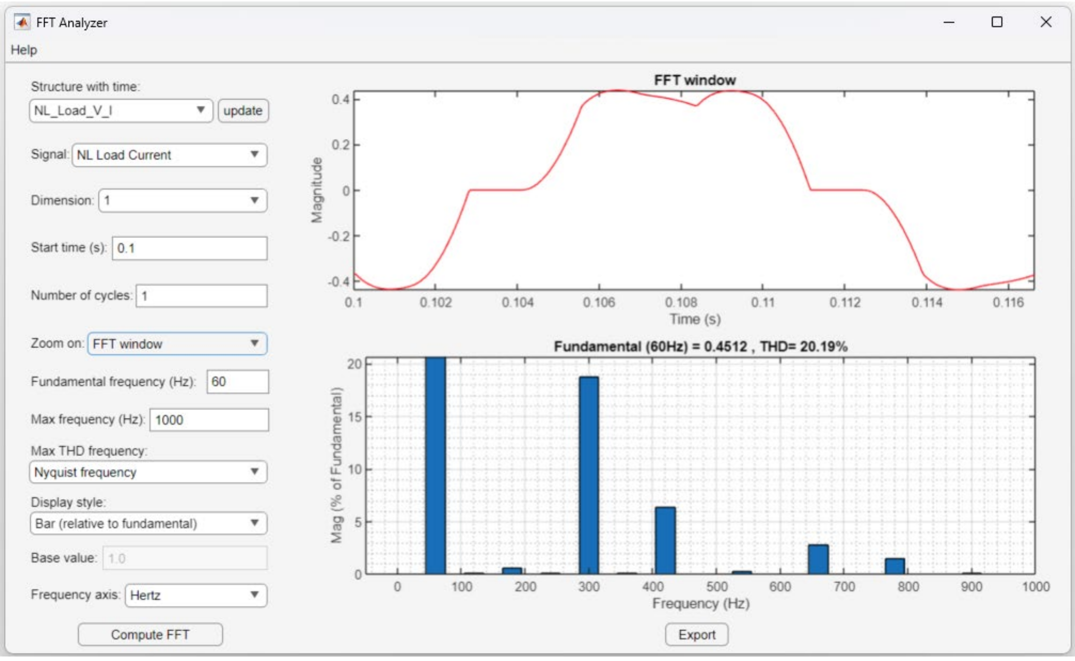


Figure 5.2: **Source current FFT analysis before connection of DSTATCOM**

Figure 5.3 illustrates a case where the DSTATCOM has been connected for compensation of harmonics introduced by the connection of non-linear load. A programmable voltage source has been used to represent a grid connection, the non-linear load has been modelled using a three-phase RL branch coupled with a universal bridge block with bridge diode rectification, and the DC side of the rectification circuit has been connected to the single-phase RL branch.

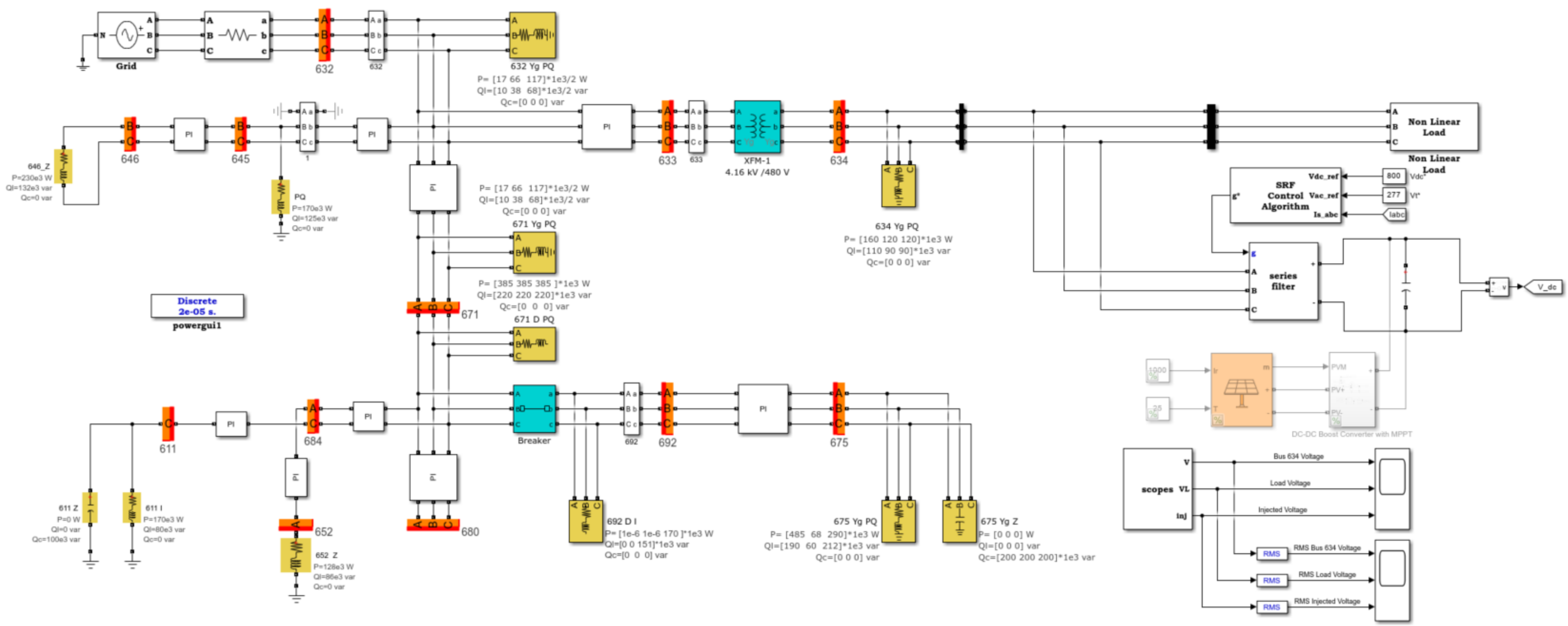


Figure 5.3: Simulink Diagram of a IEEE 13 Bus with Distribution Static Compensator (DSTATCOM)

Figure 5.4 shows an FFT analysis of the current signal at the connection point which is bus 634, THD of the bus 634 current has been measured after being distorted by the Non-Linear load and is now being compensated with the use of DSTATCOM with capacitor storage element which always compensate for the harmonics but can be replaced with Solar PV and get the same results.

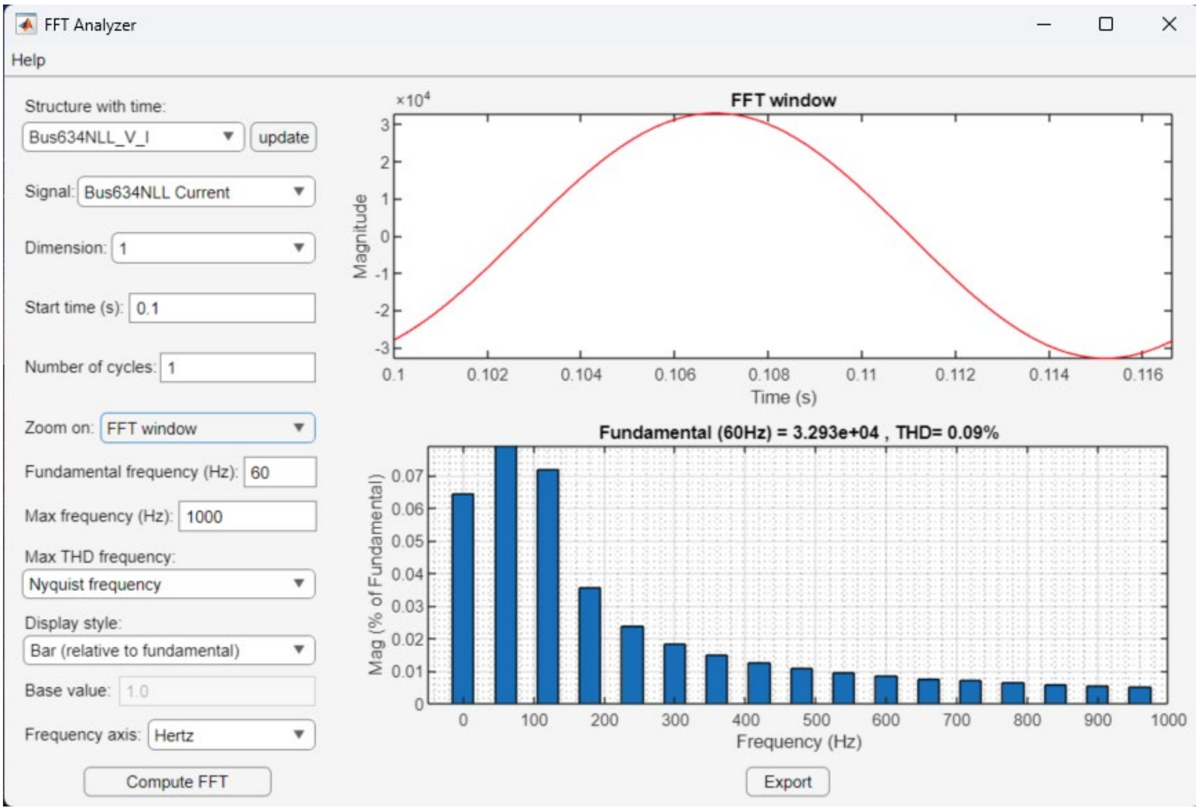


Figure 5.4: **IEEE 13 bus 634 current FFT analysis after connection of DSTATCOM with DC link storage or Solar PV**

In order to ensure that proper THD has been measured the starting time selected is 0.1 seconds to avail the switching ripples of the system as illustrated in the Figure above. The IEEE 13 bus system used for analysis and demonstration of the results uses 60Hz and has to be selected. The THD after connecting DSTATCOM with a DC Capacitor or Solar PV has yielded an improved current distortion of 0.09% which is with the 5% specified by IEEE519.

5.3. Discussion of the results

The power quality disturbances considered in this study are the connection of non-linear load and three-phase fault which gives power quality issues attributed to harmonics and voltage sag/swell respectively. The results for the connection of DSTATCOM with SRF/Dq control algorithms for compensation of the said power quality issues have been indicated in Figure 5.4. The results show that the harmonics that are introduced using non-linear load cause the source THD to be more than 5% stipulated by IEEE 519 and the measured is 20.19% which is compensated to 0.09%.

The response of DSTATCOM with SRF/Dq control algorithms has proved to be good for the mitigation of power quality issues and tested in this study with the current harmonics.

5.4. Conclusion

The Power Quality of a distribution network is very important, and if it is not being properly addressed may result in many issues like equipment failure/damage, data corruption, data loss, and system lock-up. The fast-growing technological advancements lead to new non-linear electronic devices being used where higher use of these devices will lead to harmonics into the system and needs to be addressed. The advancing technology enables the integration of solar PV where its high penetration has been reported by many studies to be causing voltage sag and swell into the overall system.

A SRF/Dq control algorithm has been developed for the control of DSTATCOM's VSC device in order to compensate for harmonics and voltage sag power quality issues. This is done by controlling the DC and AC voltage using a PI controller where the reference phase is extracted using phase locked loop from the AC source voltage and this is done to ensure the calculated compensation signal is in sync with the grid's signals. Solar PV has been considered for boosting and supporting the DC capacitor with charging even though this SSEG power can be exported for use by another load in the Microgrid.

CHAPTER SIX

SIMULATION OF UPQC FOR COMPENSATION FOR ALL POWER QUALITY ISSUES IN IEEE 13 BUS DISTRIBUTION NETWORK

6.1. Introduction

Electric utilities' primary goal is to provide their consumers with continuous, sinusoidal voltage at constant frequency and magnitude, along with sinusoidal balanced current at the AC mains (Kazmierkowski, 2015). However, there are significant power quality (PQ) issues with modern AC distribution systems, including high reactive power burden, imbalanced loads, harmonic-rich load currents, and an excessive neutral current. Furthermore, these utilities are unable to prevent harmonics, sag, swell, surges, flicker, imbalance, and notches in the supply voltages across the load end of their customers. Numerous delicate and important loads necessitate continuous sinusoidal balanced voltages with consistent magnitude and frequency; in the absence of these, power quality disruptions cause their protection mechanisms to activate (Kazmierkowski, 2015).

The abrupt rise in the use of non-linear loads in the distribution system has resulted in voltage and current-related power quality problems, raising severe concerns among experts. The main source of the current disruptions in the distributed system is the sophisticated semiconductor technology-based systems. Furthermore, when there are voltage fluctuations, these nonlinear loads react strangely (Dash & Ray, 2018). As a result, power quality enhancement applications have drawn a lot of attention to power quality enhancement devices or power conditioners. The previous Chapters 4 and 5 looked at individual mitigation of voltage and later the current harmonics power quality mitigation. Due to exceptional performance capabilities for reducing voltage and current disturbances in the distribution system, the Unified Power Quality Conditioner (UPQC) has attracted a lot of attention among different power types of conditioners (Dash & Ray, 2018).

This chapter examines the use of UPQC for the mitigation of voltage and current-related power quality issues in a Low Voltage (LV) distribution network with a non-linear load connected through MATLAB Simulink modelling and simulation. This analysis with dynamic disturbances like voltage sag, swells current harmonics in radial distribution networks with non-linear loads.

This chapter's organisation is as follows. Section 6.2 is about the system configuration which provides the systems considered for this study and its parameters are covered in detail. Section 6.3 is on simulation results when considering a steady state with and without connection of a three-phase balanced load. Section 6.4 focuses on the simulation and results of dynamic disturbances applied to the radial distribution network.

6.2. Implementing Unified Power Quality Conditioner (UPQC) for Effective Compensation of Voltage Sag, Swell and Harmonics in a Distribution Network

One approach for minimising numerous PQ difficulties is a UPQC, which is a combination of shunt and series compensators. A common DC link connects two VSCs that are connected back-to-back to form the power circuit of a UPQC. Positioned parallel to the consumer load, the Distribution Static Compensator (DSTATCOM) shunt device offers reactive power compensation, load balancing, neutral current compensation, and harmonic elimination. The load end voltage is kept insensitive to supply voltage quality issues including sag/swell, surges, spikes, notches, or unbalance by the series device known as the Dynamic Voltage Restorers (DVR). The load voltage is returned to its reference value by the DVR by injecting a compensating voltage between the supply and the consumer load (Kazmierkowski, 2015).

Figure 4.6 illustrates a basic schematic diagram of a right shunt UPQC which consists of two Active Power Filters (APFs) which are Voltage Source Converters (VSCs) coupled back-to-back by a common DC link capacitor. The first APF is connected in series to the network through injecting transformers this type of configuration is known as DVR on its own. It is used for compensation of voltage-related power quality issues like voltage sag and swell. The second APF is connected in parallel to the non-linear load. This connection on its own is known as DSTATCOM, its main function is for mitigation of current related power quality issues.

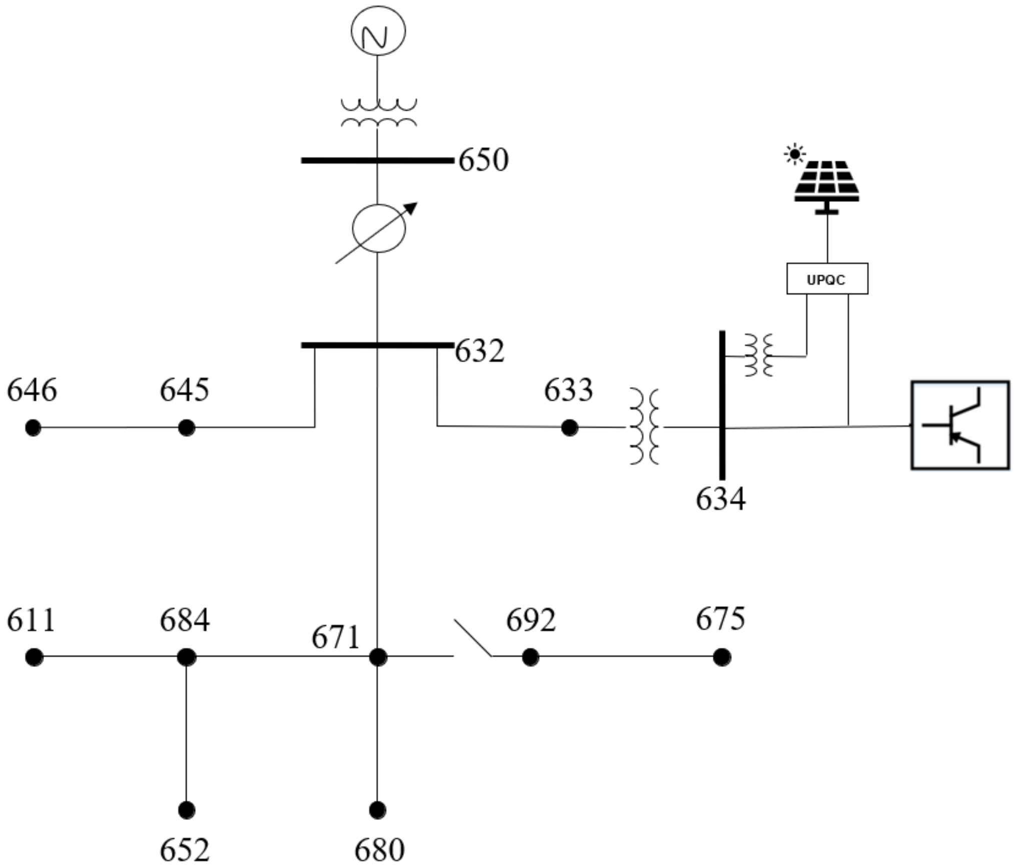


Figure 6.1: **Basic Schematic Diagram of UPQC** (Kersting, 2001)

The device is proposed for multiple power quality issues that may occur in a distribution network. In this study, the device is used for compensation of voltage sag and swell injected by the grid into the sensitive load. It does so by injecting/absorbing voltage to compensate for voltage supplied to a sensitive load which may be damaged by the voltage variation and should comply with IEEE 1159. This device is also used to compensate for current harmonics caused by the connection of non-linear load. The harmonics should be mitigated to be less than 5% specified by IEEE519.

Figure 6.2 shows a Simulink block for a right shunt UPQC, the Grid connection is represented with a programmable voltage source which enables the introduction of grid variable voltages like voltage sag and swell. A non-linear load has been connected on this radial feeder as load protected, it is represented with a three-phase RL load coupled with universal bridge diode rectification with an RL load connected on the DC side. Two APFs are constructed from IGBT bridge VSC, the first one is connected in series to the network using three single-phase injecting transformers, and the second APF is connected in shunt to the load through a

Passive Interfacing Circuit (PIC) filter. The gate signals of the VSCs are driven by control algorithms that employ PWM voltage and current control for switching.

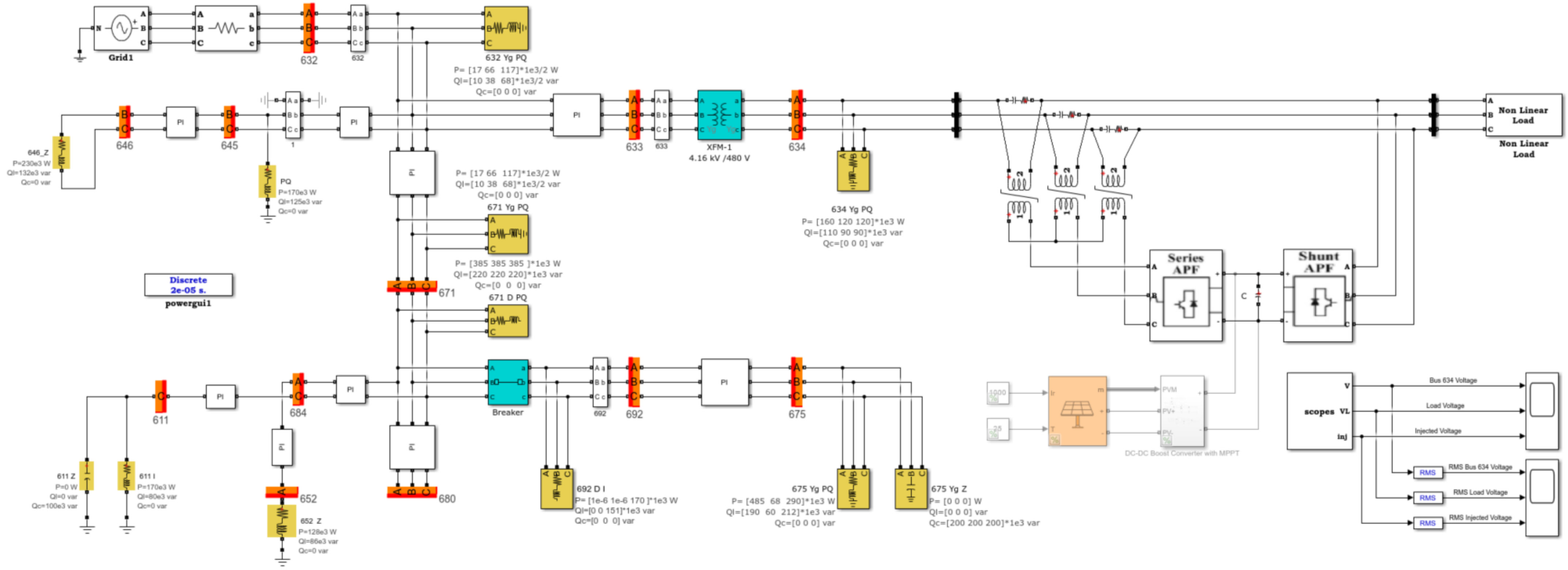


Figure 6.2: Simulink Diagram of a Unified Power Quality Conditioner (UPQC)

The optimization of the two APFs for effective compensation depends on two control algorithms which are used for calculating the reference current or voltage for the PWM control. In this study, the series active filter is controlled using power vectorial theory to calculate the reference voltage which is added to the load voltage in the hysteresis PWM voltage control to produce the gate control signal of the VSC. The shunt active filter is controlled using an Instantaneous Reactive Power Theory (IRPT) based control algorithm.

6.2.1. Control algorithms for the Series Active Power Filter

Figure 6.3 is MATLAB Simulink block for the control of the series active which is used to calculate the amount of voltage distorted in the distribution network and protect the sensitive load connected at the end. This is done by compensating the load voltage to ensure it with the 415*sqrt(2/3) which gives a 339.8V maximum. The load voltage should always be restored to this maximum voltage. A hysteresis compared the calculated to the reference AC voltage.

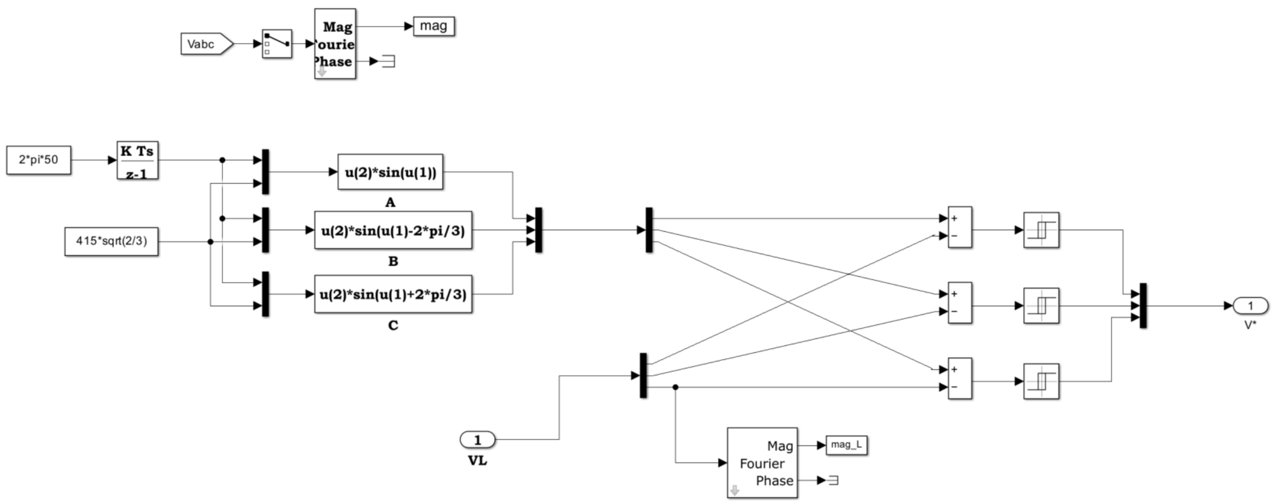


Figure 6.3: **Simulink block of the control algorithm for Series APF**

6.2.2. Control algorithms for the Shunt Active Power Filter

An Instantaneous Reactive Power Theory (IRPT) based control algorithm also known as PQ theory has been employed for control of the shunt active filter. The power circuit of the connection is responsible for synthesizing the required compensation current. It is made up of a DC-link capacitor to store energy and a PWM-based voltage source inverter (VSI) to maintain and control the DC voltage. Additionally, the power circuit is precisely controlled by the control circuit to synthesise the necessary harmonic current by continually tracking the variation of the harmonic current to determine the instantaneous reference compensation current. The methods used for harmonic extraction and current management largely determine how effective the harmonic current compensation process is (Imam et al., 2020). The current flow on the shunt side can be calculated as follows:

$$\boldsymbol{I_s = I_L = [I_{1L} + I_H] - I_c + I_{dc}} \qquad (6.1)$$

Where:

I_s - Source current,

I_L – Load current

I_{1L} – Fundamental component of the load current

I_H - Harmonic component of the load current

I_c – Injected compensation current

I_{dc} – DC-link current

The voltage across the DC-link capacitor is thought to control the harmonic compensation current. The generated harmonic compensation current and the harmonic current drawn by the non-linear load will exactly match when the voltage across the DC link capacitor is kept at the predefined level, where they will cancel each other out (Imam et al., 2020). Figure 6.4 illustrates a block diagram of the IRPT control which is a power theory based on the a-b-c stationary reference to the 0-α-β rotating coordinate which is known as Clarke transformation.

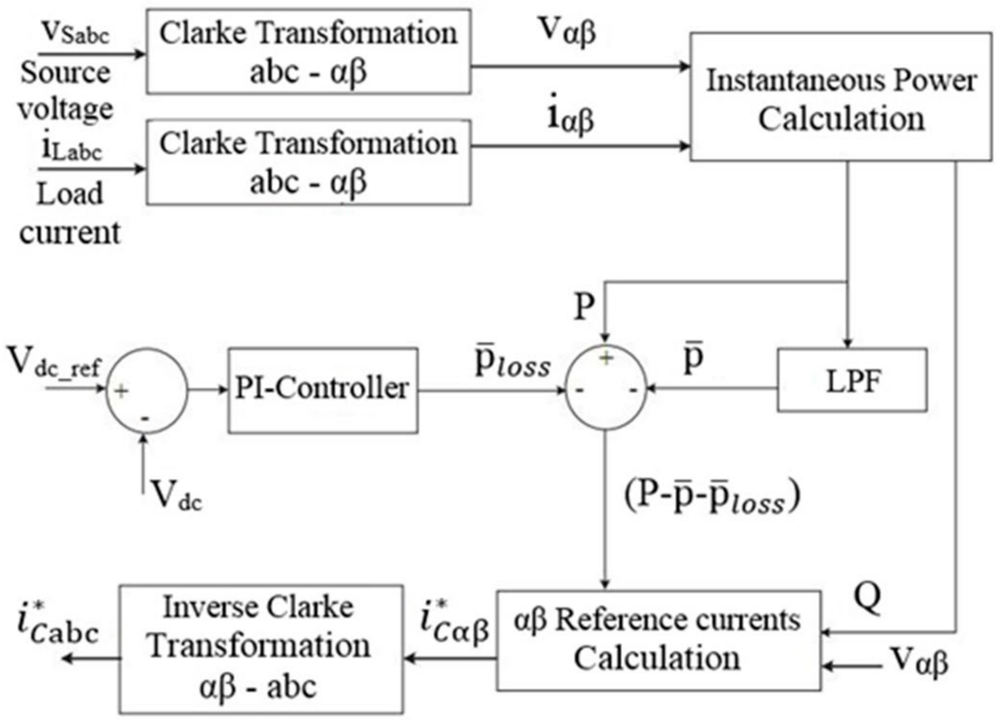


Figure 6.4: Block diagram of the active and reactive power theory (Imam et al., 2020)

The voltages and current are transformed into 0-α-β using equations 6.2 and 6.3.

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{6.2}$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{6.3}$$

Where v_a,, v_b, v_c and i_a, i_b i_c are the three-phase voltages and current respectively at the a-b-c coordinate which are transformed to 0-α-β.
The system is a three phase three wire which does not consider zero-sequence components. The real and reactive power in this theorem can be calculated using the equations 6.4 and 6.5 below:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \times \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{6.4}$$

$$\begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \frac{1}{i_\alpha^2 + i_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \times \begin{bmatrix} \tilde{p} \\ Q \end{bmatrix} \tag{6.5}$$

Where $\tilde{p} = P - \bar{p} + \bar{p}_{loss}$, $\tilde{p}$ represents AC active power component, $\bar{p}_{loss}$ is the amount of real power consumed by the APF. Equation 6.6 is used to inverse the reference current which is sent to the PWM current control.

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} \tag{6.6}$$

Figure 6.5 illustrates the inner current control loop and the outer voltage control of the DC voltage PI controller. The gains $G_{PI}(s)$ and G_{VSI} are the transfer function for the PI controller and VSI respectively.

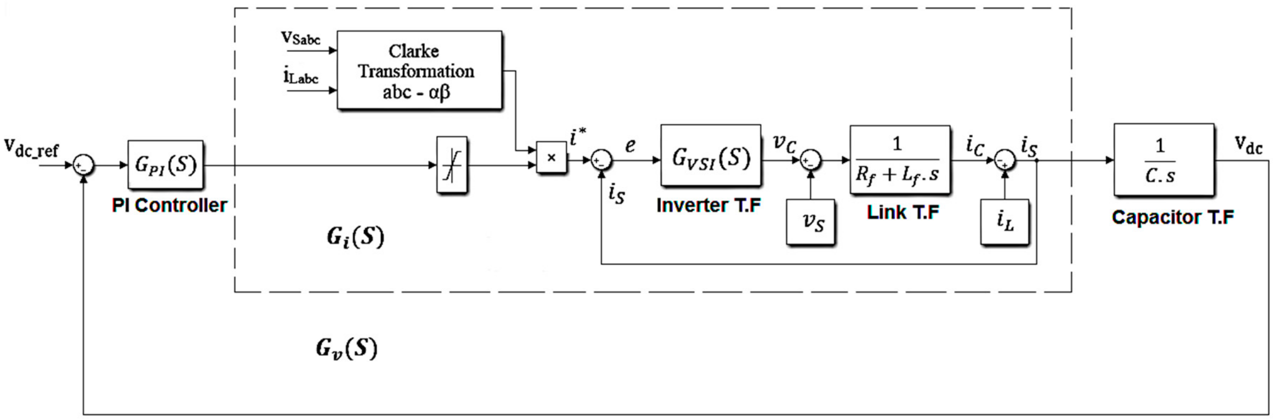


Figure 6.5: Cascade closed loops of current and voltage(Imam et al., 2020)

The proportional gain (K_p) and integral (K_i) gains can be calculated using the step response equation below for the closed loop represented in Figure 6.6:

$$\frac{v_{dc}}{v_{dc\_ref}} = \frac{\frac{K_p.K_i}{C}}{s^2 + \frac{K_p}{C}s + \frac{K_p.K_i}{C}} \tag{6.7}$$

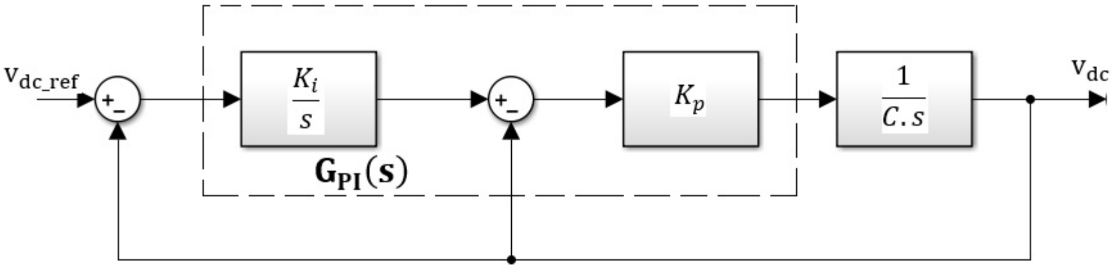


Figure 6.6: **DC voltage control closed-loop** (Imam et al., 2020)

Where, v_{dc} is the DC voltage, v_{dc_ref} represents DC reference voltage. Figure 6.7 illustrates an implementation block of the control algorithm on Simulink with all the critical components further clarified in the following Figure like the PI controller and compensating current calculations.

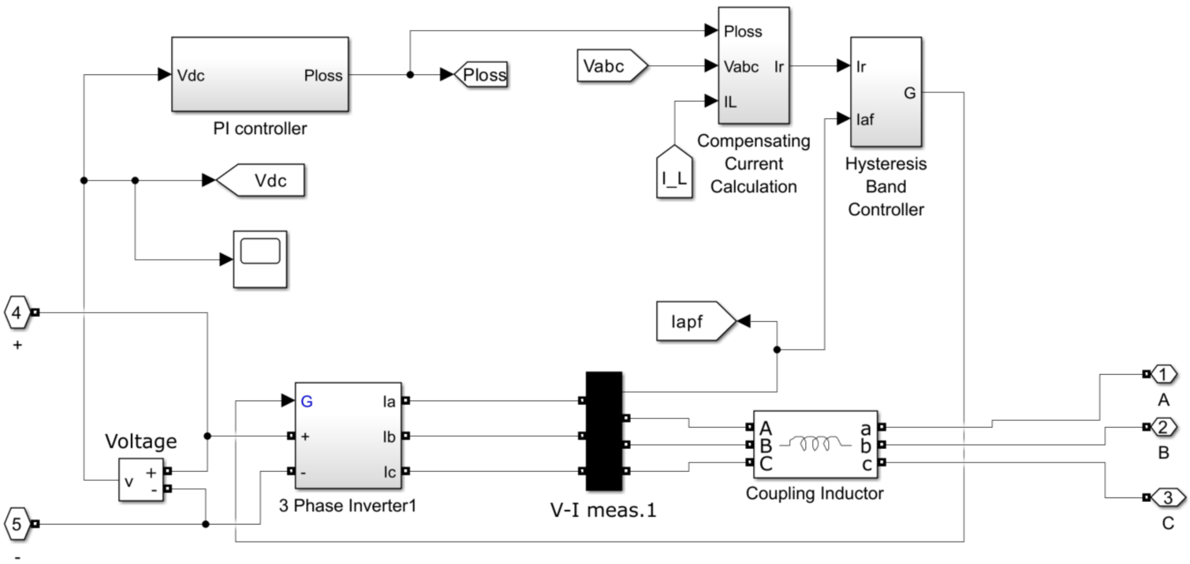


Figure 6.7: **Simulink block of the control algorithm for Shunt APF**

Figure 6.8 shows a DC PI controller block which is used to regulate the error of actual DC voltage to the constant reference voltage of 700V. The loss with a gain applied using the PI is sent to the IRPT transform for calculating power and switching pulses of the converter.

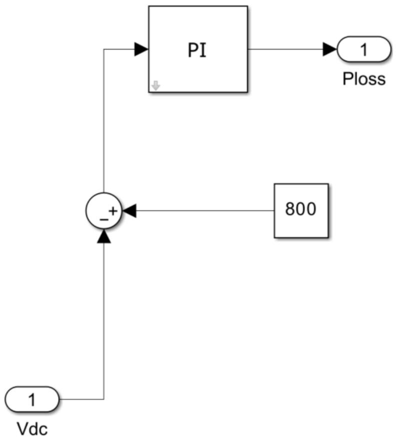


Figure 6.8: DC PI control block of the IRPT control

MATLAB Function blocks are used to implement the equation for Clarke transformation and inverse transformer as shown in Figure 6.9 below. The Simulink block is there to perform current compensating calculations.

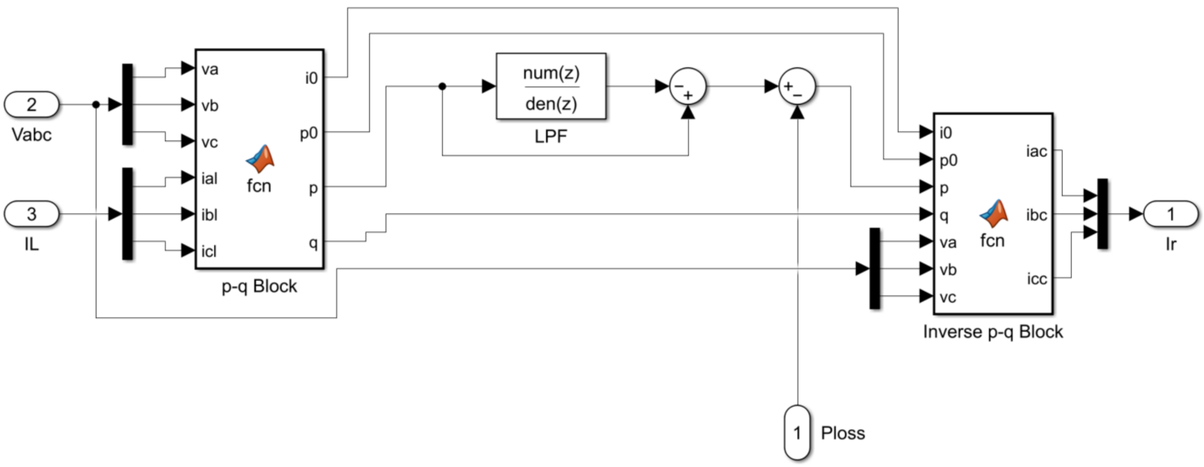


Figure 6.9: Compensating current calculation

ANMlamla_UPQC_R3 ▸ ▸ Compensating Current Calculation ▸ p-q Block

```
function [i0,p0,p,q]= fcn(va,vb,vc,ial,ibl,icl)
%#codegen
v_zero=(va+vb+vc)/sqrt(3);
v_alpha=(va-vb/2-vc/2)*sqrt(2/3);
v_beta=(vb-vc)/sqrt(2);
il_zero=(ial+ibl+icl)/sqrt(3);
il_alpha=(ial-ibl/2-icl/2)*sqrt(2/3);
il_beta=(ibl-icl)/sqrt(2);
i0=il_zero;
p0=v_zero.*il_zero;
p=v_alpha.*il_alpha+v_beta.*il_beta;
q=v_beta.*il_alpha-v_alpha.*il_beta;
```

Figure 6.10: PQ calculation code

ANMlamla_UPQC_R3 ▸ ▸ Compensating Current Calculation ▸ Inverse p-q Block

```
function [iac,ibc,icc]= fcn(i0,p0,p,q,va,vb,vc)
%#codegen
v_zero=(va+vb+vc)/sqrt(3);
v_alpha=(va-vb/2-vc/2)*sqrt(2/3);
v_beta=(vb-vc)/sqrt(2);
i_zero=i0;
i_alpha=(v_alpha.*p+v_beta.*q)/(v_alpha.^2+v_beta.^2);
i_beta=(v_beta.*p-v_alpha.*q)/(v_alpha.^2+v_beta.^2);
iac=sqrt(2/3)*(i_zero/sqrt(2)+i_alpha);
ibc=sqrt(2/3)*(i_zero./sqrt(2)-i_alpha/2+sqrt(3)*i_beta/2);
icc=sqrt(2/3)*(i_zero./sqrt(2)-i_alpha/2-i_beta*sqrt(3)/2);
```

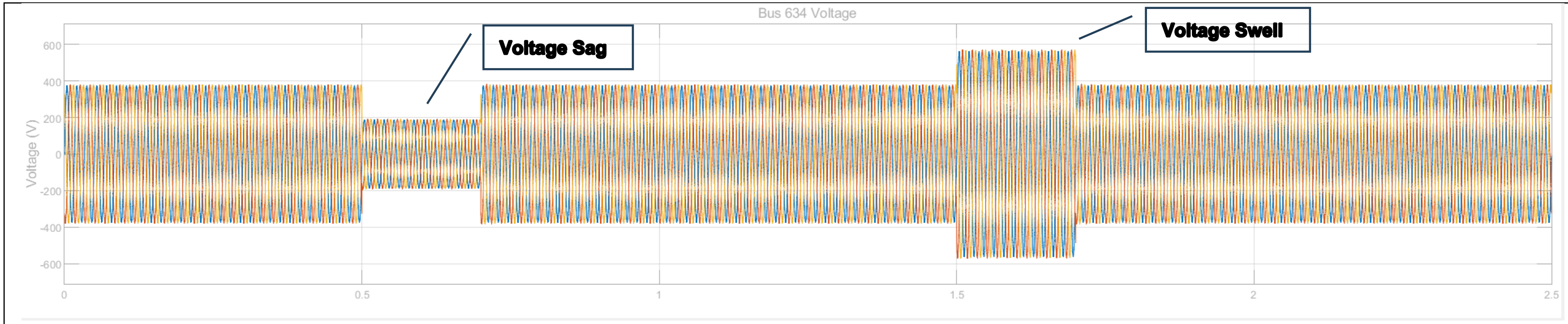
Figure 6.11: Inverse PQ calculation code

The control algorithms should be able to work together to achieve multiple voltage and current power quality mitigations.

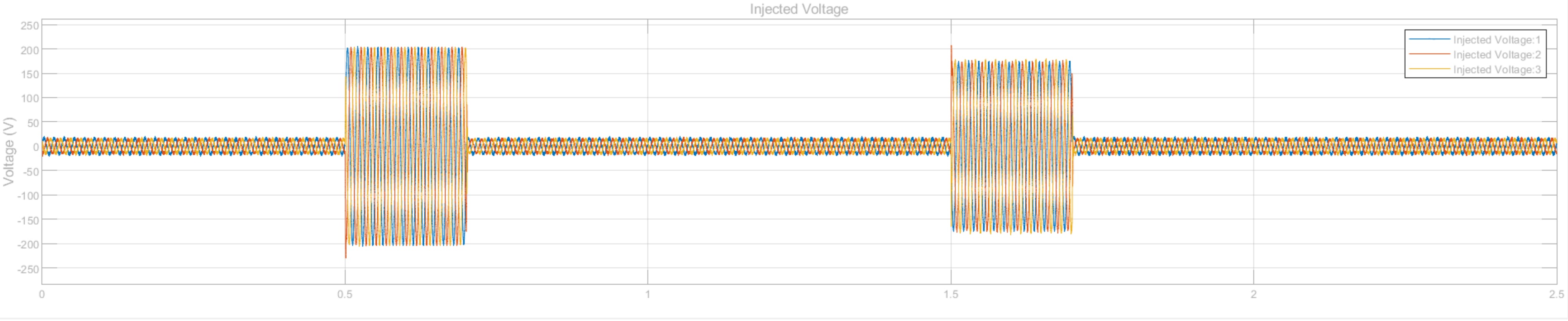
6.2.3. Case study: mitigation of voltage sag, and swell using UPQC

In this case, study the UPQC has been analysed for effective compensation of voltage sag, swell, and current harmonics. A trace selection for cursor measurements has been conducted where the signal maximum voltage is measured to be 375.5V.

The voltage sag variation of 187.8V (At 50% of Supply Bus 632) has been compensated at Bus 634 by injecting a positive signal of 201.1V which is added to the already distorted voltage to retain the 100% voltage magnitude that is supposed to be supplied by the system before the variation. Voltage swells of 563.6V (At 150% of Supply Bus 632) are compensated at Bus 634 by injecting a voltage signal with magnitude -170.9V (in the opposite direction) to reduce the magnitude of the swell voltage which retains the load voltage to the nominal safe magnitude for the load. Figure 6.12 (c) indicates the load voltage after the variation has been compensated by the UPQC.


Bus 634 Voltage
Voltage Sag
Voltage Swell
Voltage (V)
600
400
200
0
-200
-400
-600
0
0.5
1
1.5
2
2.5

(a)


Injected Voltage
Injected Voltage:1
Injected Voltage:2
Injected Voltage:3
Voltage (V)
250
200
150
100
50
0
-50
-100
-150
-200
-250
0
0.5
1
1.5
2
2.5

(b)

(c)

Figure 6.12: **UPQC used for voltage variation (a) Shows the Grid voltages where the voltage variation has been introduced, (b) illustrates the voltage injected by the UPQC to restore the voltage supplied to the sensitive load connected at the end of the distribution line and (c) Shows the load voltage after the voltage injected by UPQC to compensate for the voltage variations introduced by the Grid.**

The voltage injection by the UPQC in the figures considers a scenario in which the VSC's DC link storage and supply are sufficient to restore the variance. But sometimes the DC link capacitor has a tiny storage capacity, which means the UPQC doesn't have enough power saved on the DC Link storage element and can't restore the voltage for the duration of the variation. This isn't always the case, though. In the analysis conducted with results shown in Figure 6.12, the DC link capacitor value is enough to store energy for compensation.

Figure 6.13 illustrates the THD analysis of the grid current which has been compensated from 20.19% to 0.09% by the UPQC controller to ensure it is less than the THD specified by IEEE 519 which is to ensure the grid has THD less than 5%. During this analysis, one needs to ensure all the settings highlighted are set properly. It has also been noted that the signal that must be selected is after 0.1 seconds which is where the system controller stabilises the system to a steady signal.

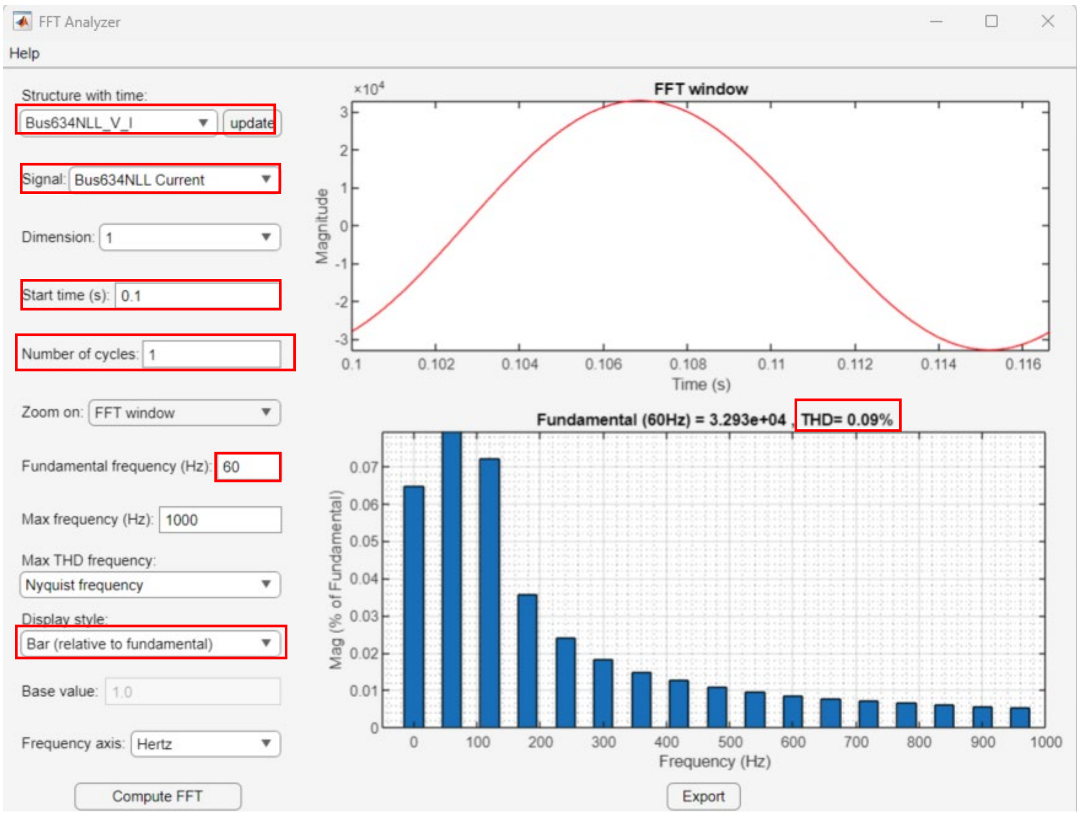


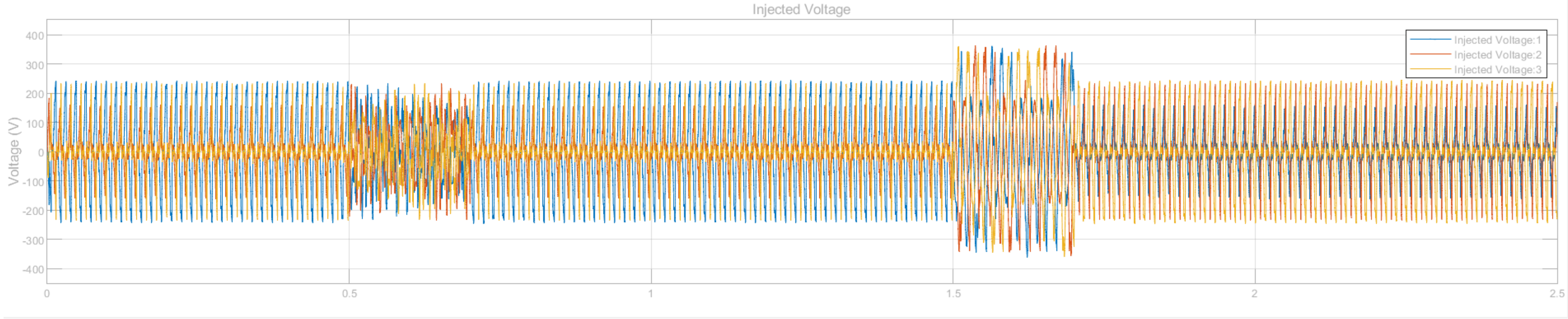
Figure 6.13: **THD analysis of the grid current**

An analysis was conducted when the DC link capacitor was reduced to 1μF. Figure 6.14 shows voltage signals when the DC link capacitor size has been reduced.

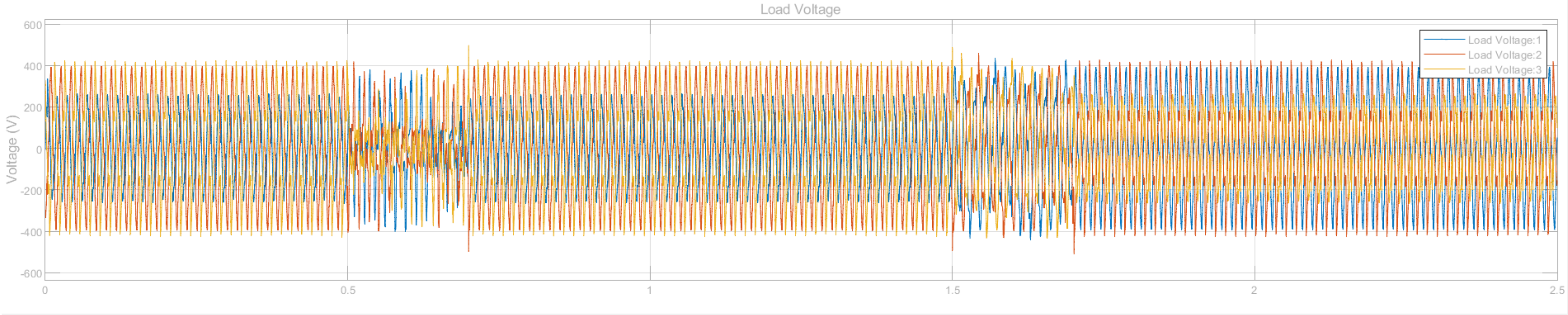
Figure 6.14 (a) shows the same variation considered in Figure 6.12 (a). Figure 6.14 (b) illustrates the voltage injected by the UPQC to compensate for the voltage sag injected by the Grid. It has been noted that in this case, the UPQC is not able to compensate for the voltage sag and the injected sign is not sinusoidal for the whole duration and this is mainly because the controller used for the shunt APF tries to restore the DC link voltage but because it not enough its does not win. Figure 6.14 (c) shows the load voltage signal which is not compensated by the UPQC for the whole duration of the variation.


Bus 634 Voltage
Bus 634 Voltage:1
Bus 634 Voltage:2
Bus 634 Voltage:3
Voltage (V)
600
400
200
0
-200
-400
-600
0
0.5
1
1.5
2
2.5

(a)


Injected Voltage
Injected Voltage:1
Injected Voltage:2
Injected Voltage:3
Voltage (V)
400
300
200
100
0
-100
-200
-300
-400
0
0.5
1
1.5
2
2.5

(b)



(c)

Figure 6.14: **UPQC with insufficient DC link storage for compensation (a) Shows the Grid voltages where the voltage variation has been introduced, (b) illustrates the insufficient voltage injected for the voltage sag duration by the UPQC to restore the voltage supplied to the sensitive load connected at the end of the distribution line and (c) Shows the load voltage after the insufficient voltage injected by UPQC to compensate for the voltage variations introduced by the Grid.**

Figure 6.15 illustrates a DC link voltage signal when the DC link storage element has been reduced. The charges stored in the capacitor collapse to a point where the UPQC is not able to compensate for the voltage variations. The DC Link voltage of the UPQC VSC collapses and the DC link controller tries to control and balance but this does not assist as it only distorts the voltage signals further.

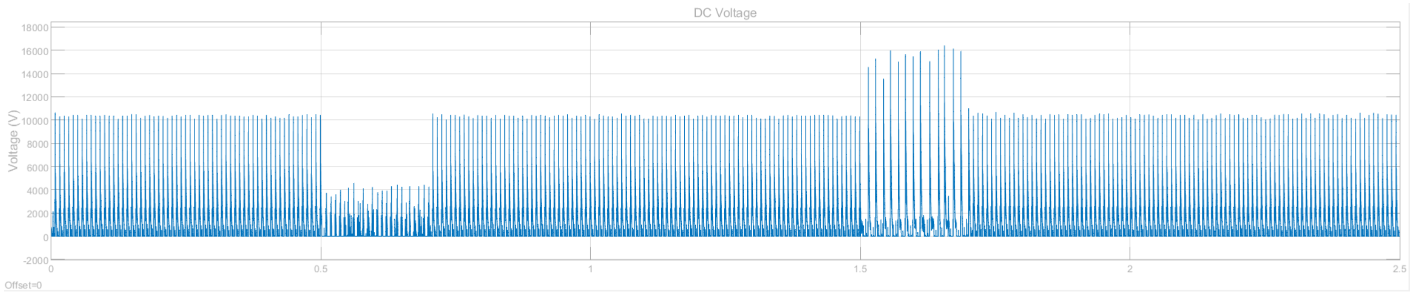


Figure 6.15: UPQC voltage signal when the DC link capacitor is reduced.

In the Figure above the period where there is a voltage sag and swell the UPQC controller is not able to restore the voltage power quality issues and instead, it further distorts the voltages.

Solar Photovoltaic (PV) system can be utilised to stabilize the DC link voltage which will assist the UPQC to continue compensating and restoring by injecting necessary voltage into the distribution system for the full duration of the variations.

6.3. Integration of Solar PV to improve UPQC compensation

Small-Scale Embedded Generation (SSEG) is becoming widely used in many parts of the world. The consumer generates and uses the SSEG power. Customers can also use this to reinterpret their place in the value chain of electricity. The SSEGs are classified as Category A Renewable electricity Producing (RPP) generators, meaning that they have a voltage range of -15% to +10% around nominal voltage at the Point of Connection (POC) and can produce no more than 1MVA of electricity. Given their widespread usage on the low-voltage distribution network, solar PV SSEG generators are taken into consideration in this study. To improve UPQC compensation under changing DC storage, integration of Solar PV SSEG on the DC Link side of the VSC for the UPQC connection has been investigated in this subsection. The study's primary focus is on how solar PV systems can sustain power quality when DC storage varies and the UPQC is unable to make up for the loss in power quality.

Figure 4.11 shows a UPQC with solar PV integrated on the DC side of the VSC across the DC Link capacitor storage.

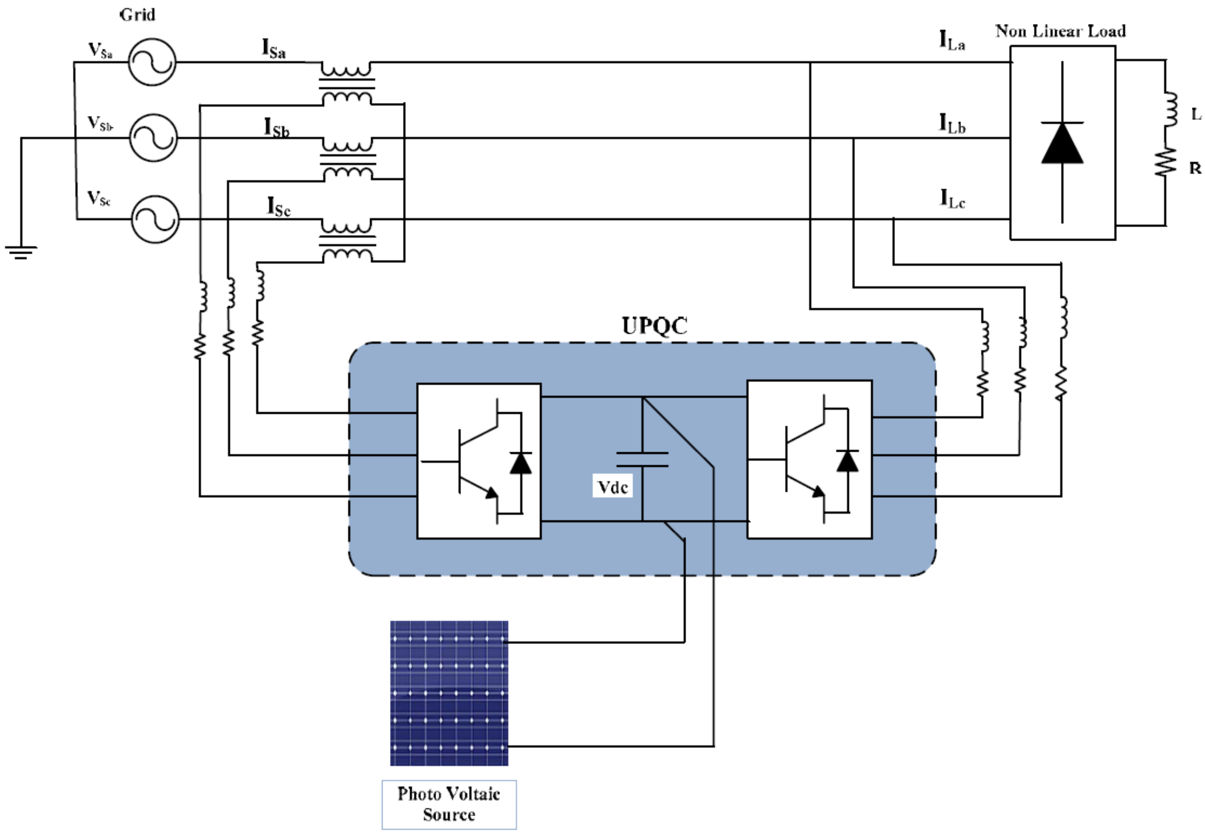


Figure 6.16: Basic Block Diagram of a UPQC with solar PV integration (Dash et al., 2017)

The modelling of small-scale Solar PV requires the expected DC voltage, the power system's nominal voltage, and the intended outpower. Most of the time, the remaining parameters are calculated during the modelling process. The software offered by PV system engineers makes it simple to ascertain the characteristics needed for solar power plant design. Figure 4.12 is a MATLAB Simulink diagram with solar PV connected on the DC side. The integration of solar PV requires a Maximum Power Point Tracking (MPPT) and DC-DC boost converter.

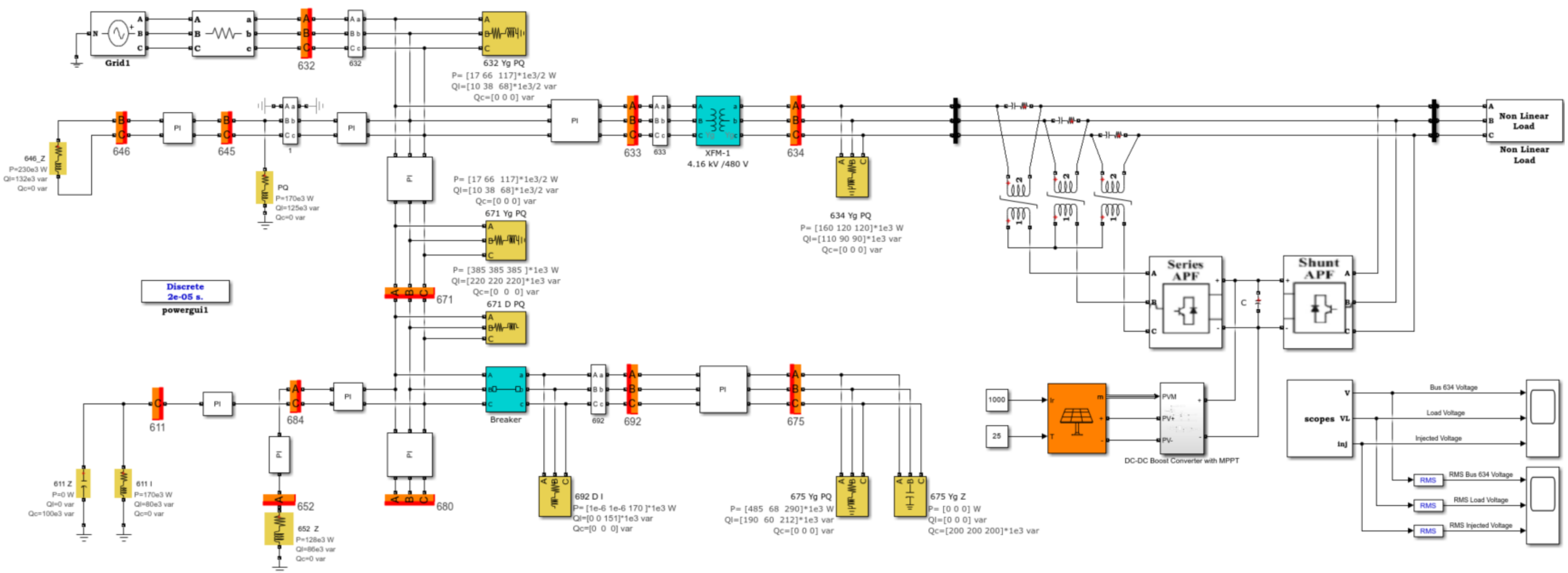
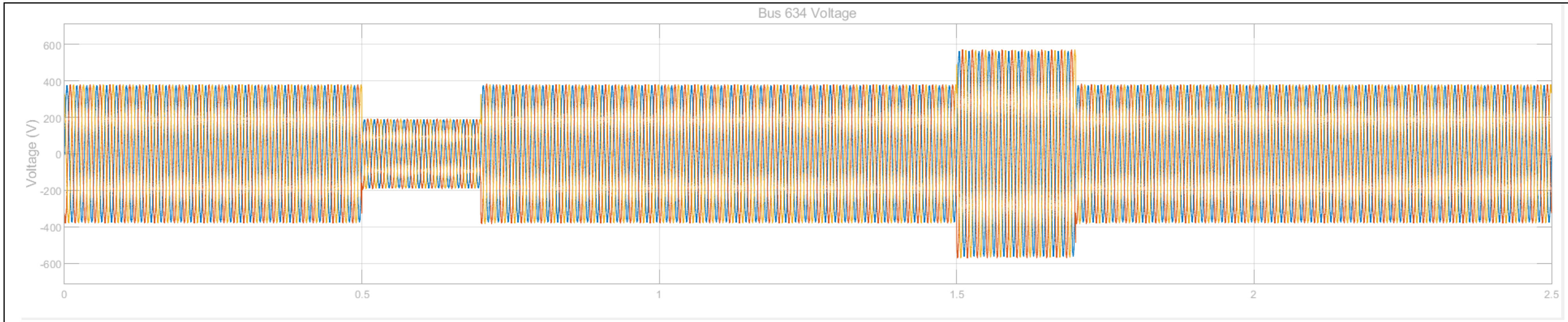


Figure 6.17: Simulink Diagram of a Dynamic Voltage Restorer with solar PV

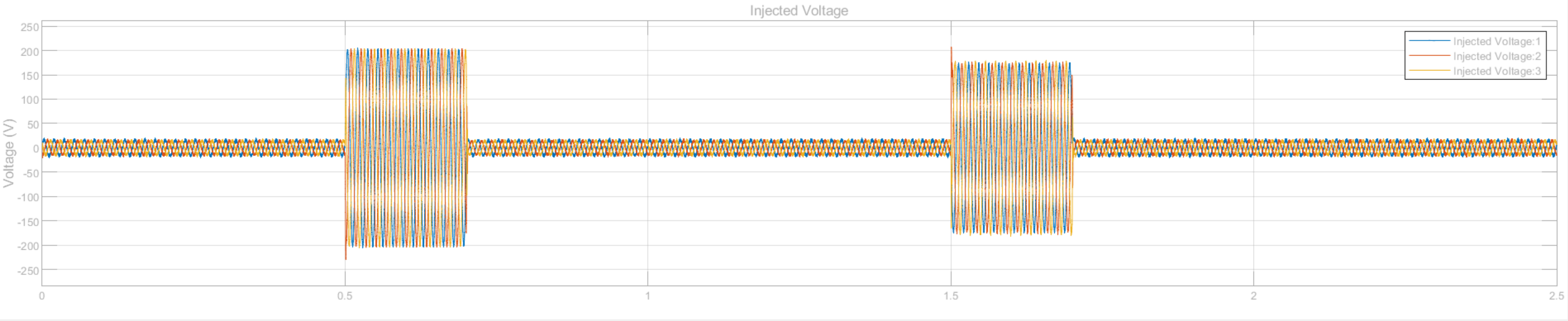
MATLAB Simulink software has already built a model for PV where module data in terms of the type of a module or user-defined, Maximum power, cells per module, open circuit voltage, short circuit current…., and array data in terms of parallel strings and series-connected modules per string is defined. The selected solar PV module at Trina Solar TSM-250PA05A.08 The other data are predefined for this module like maximum power being 250.1W. To have the power produced by the PV not more than 1MW for SSEG, 47 parallel strings and 10 series-connected modules per string are selected.

The estimated DC output power is 118kW (110kW actual) and the irradiance of 1000 $W/m2$ at 25℃. The control of the Solar PV is considered by having a DC-DC boost converter with Maximum Power Point Tracking (MMPT) which is used for stabilizing and optimising the power produced by the solar PV. This information is further detailed in Annexure A.4.1.

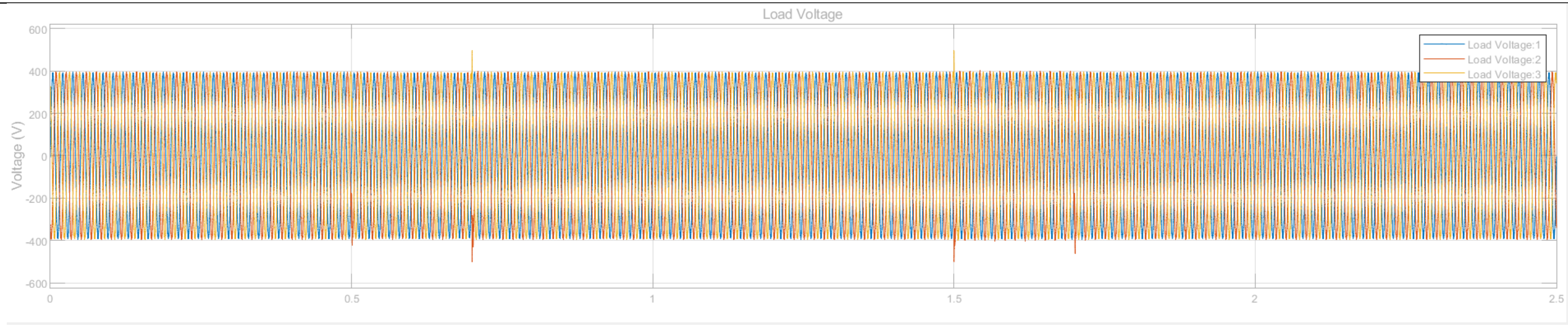
Figure 6.18 shows output signals for the grid (IEEE13 bus 634), injected, and load voltage extracted from the buses after integrating the solar PV system on the grid. The voltage for the sensitive load has been restored to normal for the full duration of the voltage sag and swell. UPQC with Solar PV ensured the distorted supply voltage was restored even when the DC link storage was insufficient.


Bus 634 Voltage
Voltage (V)
600
400
200
0
-200
-400
-600
0
0.5
1
1.5
2
2.5

(a)


Injected Voltage
Voltage (V)
250
200
150
100
50
0
-50
-100
-150
-200
-250
0
0.5
1
1.5
2
2.5
Injected Voltage:1
Injected Voltage:2
Injected Voltage:3

(b)



(c)

Figure 6.18: UPQC with solar PV for DC link storage support for compensation (a) Shows the Grid voltages where the voltage variation has been introduced, (b) illustrates the PV UPQC voltage injected for the voltage sag compensation to protect restore the voltage supplied to the sensitive load connected at the end of the distribution line and (c) Shows the load voltage after the insufficient voltage injected by UPQC to compensate for the voltage variations introduced by the Grid.

The integration of the solar PV supported the DC Link voltage when it starts collapsing due to insufficient energy storage.

6.4. Discussion of the results

An examination of the dynamic responses related to power quality in a distribution network has been carried out utilizing the potent software tool, MATLAB/Simulink. This analysis concentrated on assessing power quality through the measurement of voltage and current parameters. The study considered typical and detrimental dynamic disturbances, including the introduction of variations in voltage supply from the source. The responses of each monitored variable are illustrated using MATLAB/Simulink scopes during this analysis.

Voltage sag and swell variations have been considered which are injected by the grid to the sensitive load. 50% variations at different time intervals with a duration of 0.1s. A UPQC has been successfully proposed for the compensation of the variations with the calculated DC Link storage capacitor. It has also been noted that the THD of the grid current signal has been improved from 20.19% to 0.09% which is less than the 5% specified by IEEE 519. When the value of the storage is reduced the UPQC fails to compensate for the voltage sag and produces harmonics in the voltage and current of the system. Solar PV has been proposed to support the DC link power storage by stabilising the storage.

6.5. Conclusion

For both the utility and the consumers, the electrical network's power quality is crucial. Power quality problems can be compensated for using a variety of tactics. It's critical to comprehend how these compensation devices work and how to best optimise them to maintain a standard level of power quality control throughout the distribution system's dynamic state.

A UPQC which can compensate for voltage and current-related power quality issues has been analysed in this study for compensation of voltage sag, swell, and current harmonics for the sensitive non-linear load connected at the end of the distribution network, it works well when assuming enough DC Link capacitor storage as it would be able to re-inject and store power on the storage. However, this is not always the case as the storage could not be enough. It has been realised that when the DC link storage capacity is not enough the UPQC fails to compensate for the voltage power quality. An integration of Solar PV has been proposed to support the DC link power for the power required by the storage, compensation of the disturbance, and power demand. The solar PV is integrated on the DC side of the VSC with a DC-DC boost converter with Perturbation and Observe (P&O) MPPT used in between.

CHAPTER SEVEN
CONCLUSIONS AND RECOMMENDATIONS

7.1. Introduction

There are many factors, including the economy of other nations and the daily operations of customers, depending on the power system's power quality.
In addition to these, technological advancements, and integration of renewable energy resources (RES) are always accelerating, which leads to a rise in the use of power electronic-based devices because of their inherent benefits in a variety of household and commercial applications, including compressors, large air conditioning systems, arc furnaces, power supplies, low-power lamps, and adjustable speed drives (ASDs). Unfortunately, it is thought that the widespread usage of these devices and the integration of RES are among the primary factors causing several power quality issues, including voltage sag/swell and the creation of various harmonic components that are causing several major issues.

Various studies have been conducted to mitigate power quality issues hence restoring the power to an acceptable range as stipulated in the standards. One of many ways is the use of an Active Power Filter (APF) which is a Dynamic Voltage Restorer (DVR) for voltage-related and Distributed STATic COMpensator (DSTATCOM) for current-related PQ issues and finally the combination of the two Unified Power Quality Conditioner (UPQC) with their control algorithms for optimisation. The UPQC which is a combination of series and shunt-connected APFs absorbs and injects the difference in the opposite phase and should continuously track the system for all the disturbances. The problem of power quality has grown to be a significant one that is receiving increased attention from researchers, consumers, and suppliers of electrical energy these days.

This thesis focuses on the development of control algorithms to mitigate voltage sag/swell and harmonics power quality issues of the power system in the event of non-linear load connection, three-phase fault, and integration of PV source for support of DC link voltage. A radial Low Voltage (LV) distribution network has been considered and modelled on MATLAB Simulink. A Power Vectorial control algorithm has been considered for series APF while an IRPT-based control algorithm has been used for gate firing of APF of the Shunt APF to mitigate Total Harmonics Distortion (THD) and voltage sag/swell.

In this chapter, the work done to fulfill the thesis's goal and objective is briefly described. It is organised as follows. Section 7.2 is the thesis deliverables. Section 7.3 is the application of the thesis for academic and industrial. Section 7.4 is the future work that can be done in extension to this study. Section 7.5 indicates the publication of the researcher.

7.2. Thesis delivery

The work done to fulfill the thesis's purpose and objectives is summarised in this section as detailed in the subsections that follow.

7.1.1. Literature review

A detailed literature review has been conducted to ascertain and present progress made in voltage sag/swell and Harmonics power quality mitigation control algorithms before and after the integration of Photovoltaic (PV) systems for DC voltage link mitigation.

7.1.2. Theoretical aspect

Digital libraries such as IEEE Xplore, ResearchGate, ScienceDirect, and Winley have been used to gather conference articles, journals, and textbooks to develop theoretical background on the power quality mitigation strategies used before and after the integration of SEGs. They also assisted in getting detailed theoretical on individual components that are utilised in this study like DVR, DSTATCOM, and UPQC.

7.1.3. Test system analysis

An IEEE13 bus highly radial distribution system modelled on MATLAB Simulink has been utilised for the study. An analysis of THD for sources voltages and current when a non-linear load is connected. Voltage variation supplied by grid with voltage sag and swell has been proposed as case studies. An impact analysis of the integration of the PV system has been conducted for the support of the DC voltage link of the DVR, DTSTACOM, and UPQC when the DC link storage is not sufficient. The THD analysis is conducted by extracting the data for all the scopes for the data of interest and has been logged to the workspace for further analysis in an FFT analysis of Powergui. The connection of non-linear load causes the source & load current to have a THD that is more than 5% maximum specified by IEEE 519. A

UPQC has been proposed for multiple PQ issues with a gate signal of the VSC driven by a control algorithm that considers the mentioned scenarios.

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

A UPQC is implemented as compensation for the multiple power quality issues that are introduced using non-linear loads and the application of a three-phase fault on the load side. The optimisation of the UPQC depends on the control algorithm used for switching the gate pulses of the VSC used in the controller. The VSC considered uses Insulated Gate Bi-polar Transistor (IGBT) switches. A power vectorial and IRPT-based control algorithm has been applied for gate switches of the two VSCs to mitigate harmonics and voltage sag/swell power quality disturbances. The control algorithm managed to restore the THD harmonics of the source current which was way above the limits stipulated by IEEE 519 to an acceptable value which is less than 5%.

The algorithm in addition was tested in dealing with the voltage sag, it managed to restore the voltage to the nominal voltage. The UPQC does this by storing energy on the DC link capacitor which absorbs and re-injects the power into the system when required in the event of disturbances. The ability of the UPQc to restore/mitigate power quality issues also depends on the size of the DC storage which can be boosted by the connection of the solar PV.

7.1.5. Integration of solar photovoltaic system into a grid

The integration of solar photovoltaic power in this study has been considered for mitigating the DC voltage link of the voltage source converter (VSC). The power generated by solar PV also assists in the load demand.

7.3. Application of power quality control algorithms

The ideas presented in the thesis can be referred to for practical applications in university education and research, industry, and research labs. The subsections below detail the few possible uses of the proposed ideas.

7.1.6. Industrial application

The industries struggle with power quality such as voltage sag/swell, harmonics, power factor correction, and other power quality issues. These power quality issues have a great impact as they result in the equipment used being damaged and there would be a need to buy expensive protection devices like the installation of capacitor banks which are difficult to attenuate. As part of green energy and meeting energy demand with installation of the solar, this can also be taken as a gap to buy APF devices that implement the mentioned control algorithms to also deal with the power quality issues of the network.

7.1.7. Academic application

In academic institutions, the proposed ideas are detailed and can easily be referred to. A prototype can also be built which can practically demonstrate the use of the algorithms and show how important the control of power quality issues is.

7.4. Future Work

The thesis investigates algorithms implemented on a UPQC APF that could be used to mitigate voltage sag/swell and harmonics in power distribution networks and integration of PV systems to support DC voltage Link in case when the storage is not sufficient for compensation. The following are the studies that can be further conducted from this study:

- A laboratory-based prototype of the study can be conducted and experimentally verified.
- The controller can also be tested considering other power quality issues in the power system like voltage flicker, transients, other waveform distortion other than harmonics, Power Factor Correction, Frequency variations, voltage imbalance, and long-duration voltage variations.
- Impact of high penetration of Small-Scale Embedded Generations (SSEG) PV system microgrid.
- Investigation of an IEC61850 APF implementing the same control algorithms or modified.
- Investigation of IEC 61850 transformer data concentrator for coordination power quality control algorithms of IEC 61850-based APFs.

7.5. Publication

A.N. Mlamla, M.E.S. Mnguni, Impact analysis of non-linear load on the Low Voltage distribution network. International Journal of Electrical Engineering and Applied Sciences (IJEEAS) 2024. (under review)

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APPENDICES

APPENDIX A: MATLAB Simulink distribution network and its parameters

A.1. Power System

A.1.1. IEEE 13 Distribution bus system with UPQC

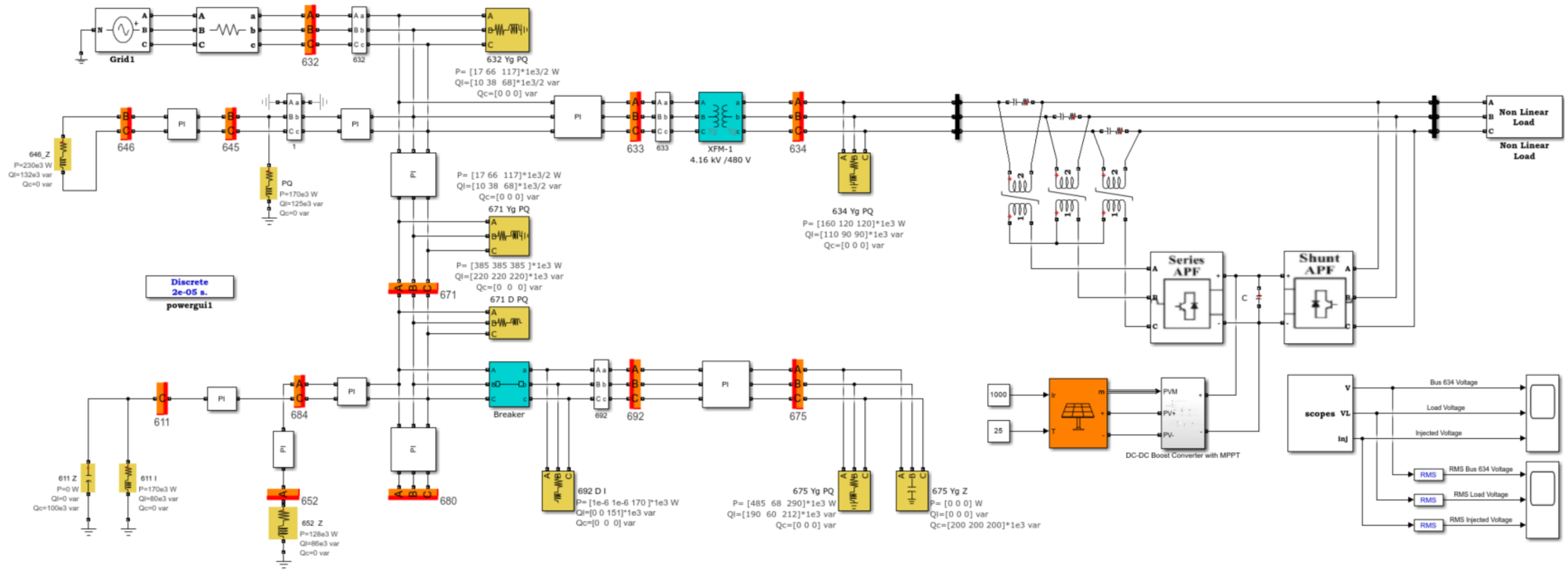

Figure A.1: UPQC Power System MATLAB Simulink Block

A.2. Network Parameters

A.2.1. Source, Non-Linear Load, Series and Shunt APF PIC Filters

Table A.1: Simulation parameters

Simulation Components Parameters					
Item	**Group**	**Description**	**Nomenclature**	**Expression**	**Magnitude**
1	Power Supply	Supply Voltage (L-L)	v_s	-	4.16kV
2		Supply Frequency	f_s	-	60Hz
3	Non-Linear Load AC side	Load AC Resistance	R_{NL_AC}	-	0.4Ω
4		Load AC Inductance	L_{NL_AC}	-	015mH
5	Non-Linear Load DC side	Load DC Resistance	R_{NL_DC}	-	60Ω
6		Load DC Inductance	L_{NL_DC}	-	0.15mH
7	Series APF PIC filter	Series APF Resistance	R_{PIC}	-	1Ω
8		Series APF Capacitance	C_{PIC}	-	100μF
10	Shunt APF PIC filter	Shunt APF Inductance	L_{PIC}	-	10mH

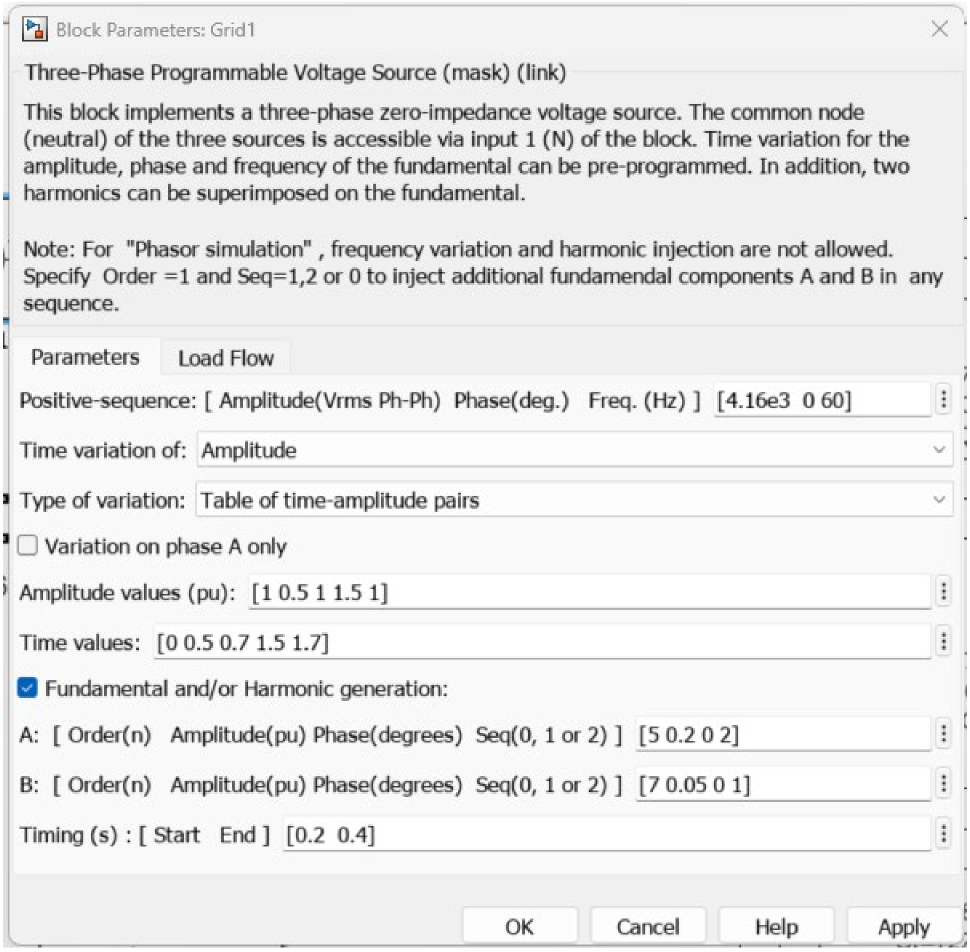

Figure A.2: Series injection Transformer MATLAB Simulink Block data

A.2.2. IEEE 13 Distribution bus system parameters

Table A.2: Underground Cable Configuration data (Kersting, 2001)

Config.	Phasing	Cable	Neutral	Space ID
606	A B C N	250,000 AA, CN	None	515
607	A N	1/0 AA, TS	1/0 Cu	520

Table A.3: Overhead Line Configuration data (Kersting, 2001)

Config.	Phasing	Phase	Neutral	Space ID
		ACSR	ACSR	
601	B A C N	556,500 26.7	4/0 6/1	500
602	C A B N	4/0 6/1	4/0 6/1	500
603	C B N	1/0	1/0	505
604	A C N	1/0	1/0	505
605	C N	1/0	1/0	510

Table A.4: Feeder Line Segment data (Kersting, 2001)

Node		Lenth (km)	Config
A	B		
632	645	0.1524	603

632	633	0.1524	602
633	634	0	XFM-1
645	646	0.0914	603
650	632	0.6096	601
684	652	0.2438	607
632	671	0.6096	601
671	684	0.0914	604
671	680	0.3048	601
671	692	0	Switch
684	611	0.0914	605
692	675	0.1524	606

Table A.5: Capacitor data (Kersting, 2001)

Node	Ph-A	Ph-B	Ph-C
	kVar	kVar	kVar
675	200	200	200
611	0	0	100
Total	**200**	**200**	**300**

Table A.6: Regulator data (Kersting, 2001)

Regulator ID:	1		
Line Segment:	650 - 632		
Location:	50		
Phases:	A - B -C		
Connection:	3-Ph,LG		
Monitoring Phase:	A-B-C		
Bandwidth:	2.0 volts		
PT Ratio:	20		
Primary CT Rating:	700		
Compensator Settings:	Ph-A	Ph-B	Ph-C
R - Setting:	3	3	3
X - Setting:	9	9	9
Volltage Level:	122	122	122

Table A.7: Transformer data (Kersting, 2001)

Node	kVA	kV-high	kV-low	R - %	X - %
Substation	5,000	115 - D	4.16 Gr.Y	1	8
XFM-1	500	4.16 – Gr.W	0.48 – Gr.W	1.1	2

Table A.8: Spot Load data

Node	Load Model	Real Power (kW)			Reactive Power (kVar)		
		Ph-1	Ph-2	Ph-3	Ph-1	Ph-2	Ph-3
634	Y-PQ	160	120	120	110	90	90
645	Y-PQ	0	170	0	0	125	0
646	D-Z	0	230	0	0	132	0
652	Y-Z	128	0	0	86	0	0
671	D-PQ	385	385	385	220	220	220
675	Y-PQ	485	68	290	190	60	212
692	D-I	0	0	170	0	0	151
611	Y-I	0	0	170	0	0	80
Total		**1158**	**973**	**1135**	**606**	**627**	**753**
		3266			**1986**		
PF		**0.85**					

Table A.9: Distributed Load data (Kersting, 2001)

Node A	Node B	Load Model	Real Power (kW)			Reactive Power (kVar)		
			Ph-1	Ph-2	Ph-3	Ph-1	Ph-2	Ph-3
632	671	Y-PQ	17	66	117	10	38	68
Total			**17**	**66**	**117**	**10**	**38**	**68**
			200			**116**		
PF			**0.87**					

B.2. Voltage Source Converter

A Voltage Source Converter (VSC) An which is active power filter for the Distributed Static Compensator (DSTATCOM) has been represented using the Universal Bridge mask. Figure A.3 shows the parameters for the VSC where their number of bridge arms, default snubber resistance value, capacitance and all parameters are used. The Power electronic Device assumed are the IGBT/Diodes which are the mostly used due to their good power handling, speed and other advantages.

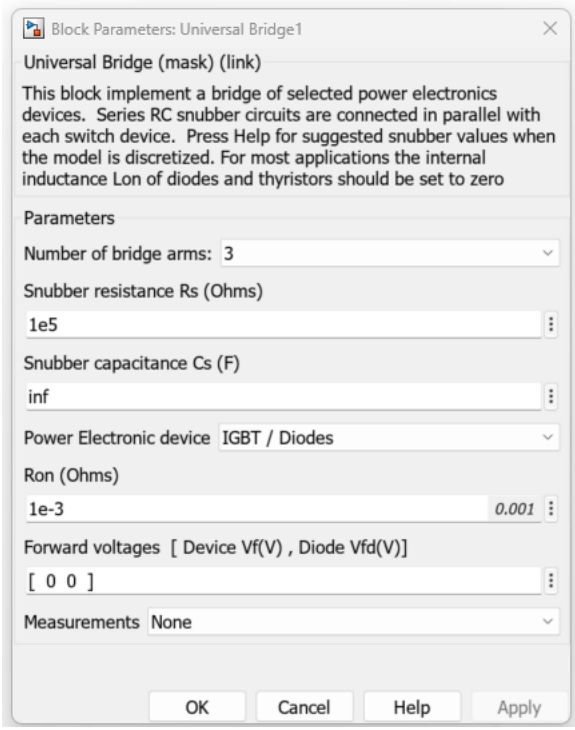

Figure A.3: Simulink Block

B.3. SRF Control algorithms

B.3.1. DC Voltage control

The voltage on the DC side of the VSC needs to be controlled to a certain value to ensure the system injects the necessary current into the system from the DC capacity/storage/PV connected. Figure A.4 depicts DC voltage control block where the measured DC voltage is controlled using PI controller with the Proportional (P) parameter being 0.2 and the Integral (I) parameter being 0.1 and a saturation of ±700V. The target is to maintain the DC voltage to the reference voltage of 700V.

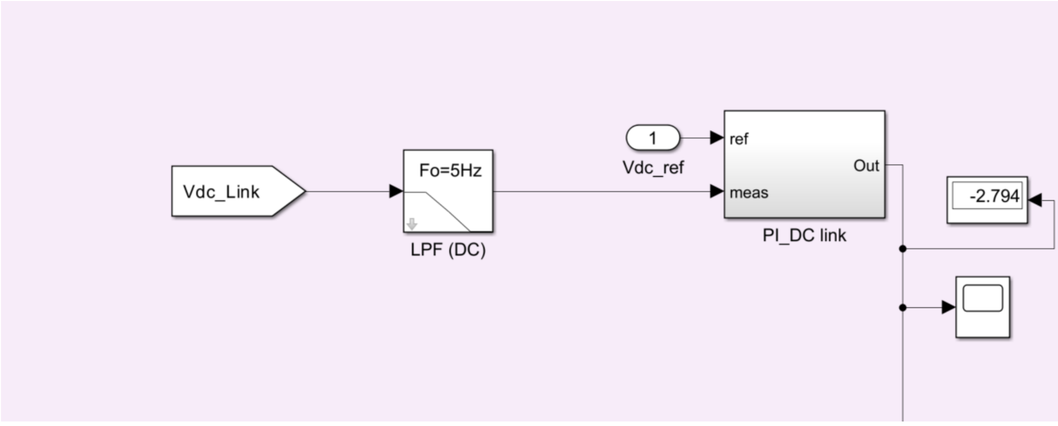

Figure A.4: **Simulink Block**

B.3.2. AC Load current extraction block

The load current is extracted from the load side of the system to view the disturbance that occurred because of different types of loads and faults that may occur as disturbances. Figure A.5 shows ABC to Dq0 frame logic block which is used to extract the load currents and the synchronised source voltage phase angles and frequency from the PLL block (sin_cos). When the source currents are in the rotation frame Dq, they are both taken through a Low Pass Filter (LPF) to extract the DC components of each which will are easy to control.

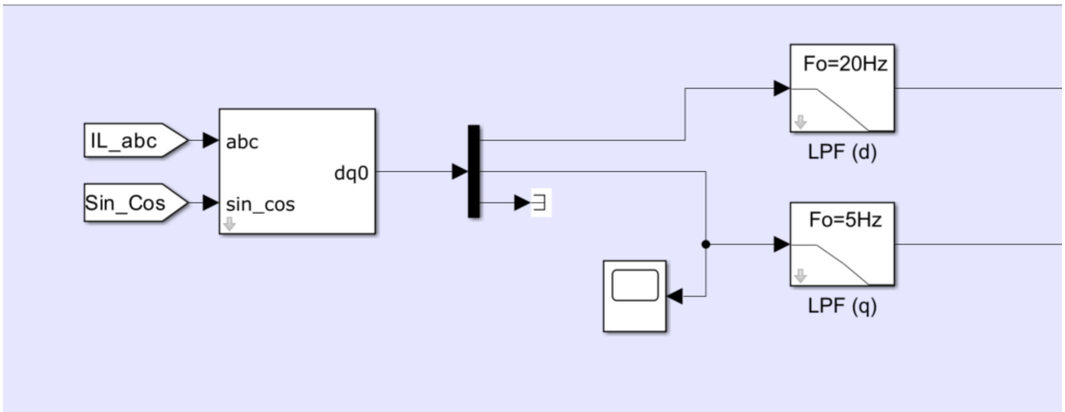

Figure A.5: **Load Current extraction using ABC – Dq0 frame logic block**

B.3.3. AC Voltage control

The AC voltage is also controlled by a PI controller which rectifies the error between the reference/desired voltage signal and the measured source voltage. The actual measured source voltage has been put through Low Pass Filter (LPF).

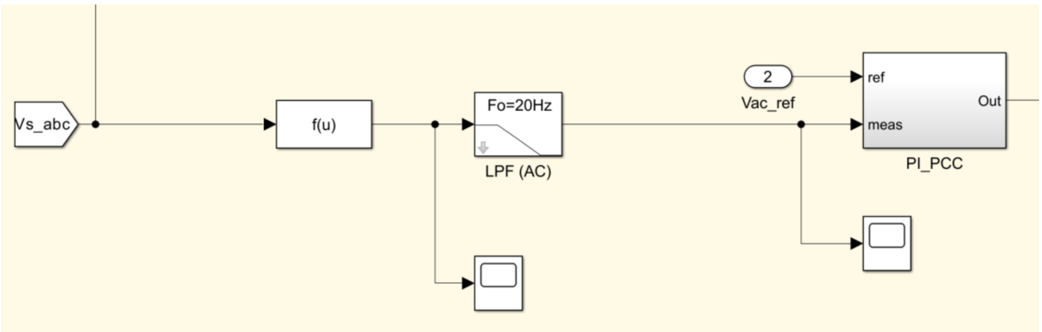

Figure A.6: **AC Voltage control block**

B.3.4. Phase Locked Loop

Park transforms requires phase and angular information, which are measured by the Phase Locked Look (PLL) block. Figure A.7 displays the PLL block controller. The PLL block in MATLAB Simulink is configured by default. **Error! Reference source not found.** presents these configurations. The PLL block extracts three-phase input voltages into phase angle and frequency outputs. In addition, the block has a Park transform block (also known as the ABC to DQ block) inside the block mask that changes the three-phase voltages into matching d-q axis currents. Utilising the angular information, the Park transform block applies the Park transform matrix to the three-phase quantities to achieve this.

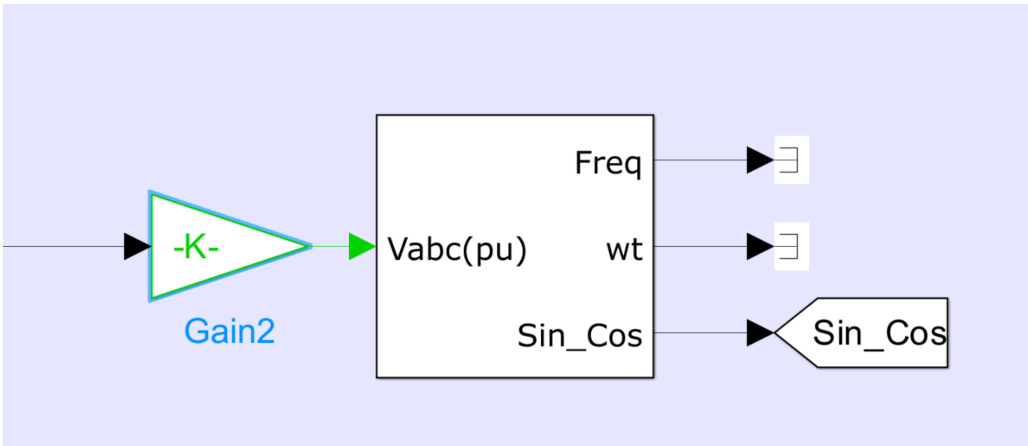

Figure A.7: **Discrete PLL Block model**

The model uses a three-phase maximum value, and they are converted using the gain to per units system by applying a base voltage of 340V.

Table B.1: **Simulation parameters**

Item	Description	Nomenclature	Value
1	Minimum frequency		60Hz
2	Initial inputs [Phase (degrees), Frequency (Hz)]		[0 60]
3	Regulator gains	$[K_P\ K_i\ K_d]$	[180 3200 1]

4	Sampling Time	Ts	Ts
4	Time constant for derivative action		10^{-4}
5	Maximum rate of change of frequency		12 Hz/s
6	Filter cut-off frequency for frequency measurement (Hz)		30Hz

B.3.5. Dqo to ABC

This block is used to calculate back the reference signal from Dq to ABC using the inverse parks theorem as shown in the block below. The block also needs the reference phase angle form the PLL block.

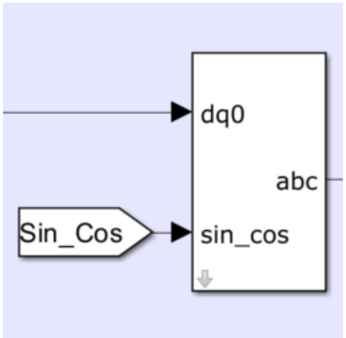

Figure A.8: Simulink Block

B.3.6. VSC Current Control (Hysteresis PWM)

The VSC's gate switching uses Pulse Width Modulation (PWM) to inject the necessary power into the system as when required. A reference source current as calculated after the DC voltage control, AC voltage control calculated from the AC load current measured is used with measured AC source current to define the upper and lower tolerance limits of the hysteresis current control. The control of conversion to PWM signals is done by turning off the VSC when the upper limit is reached until it reaches the lower limit and is switched on. This continues in trying the ensure the real output current is within the tolerance (hysteresis) band between the upper and lower limit in trying to find the reference.

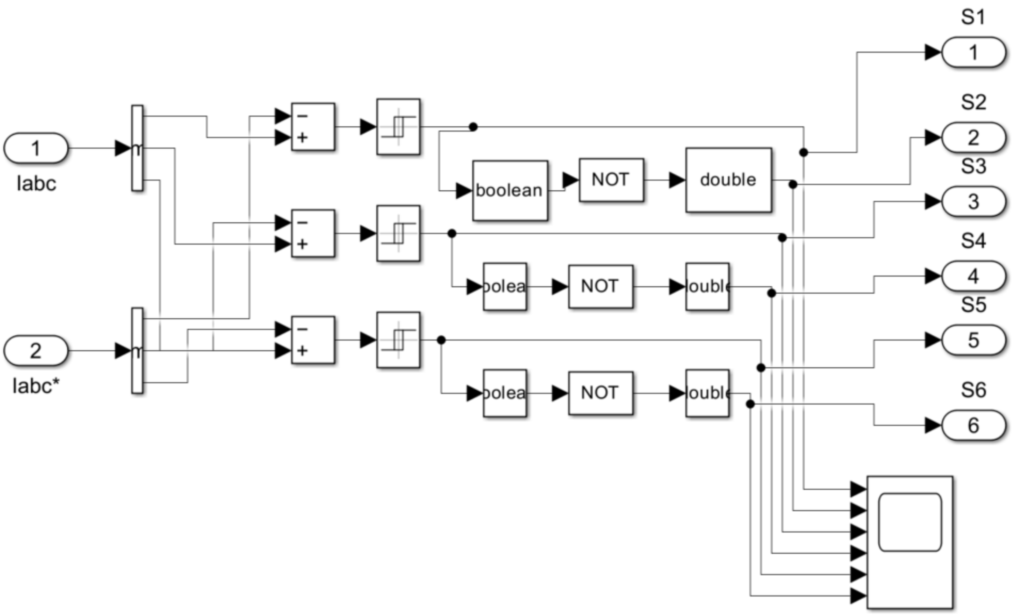

Figure A.9: **PWM (Hysteresis) block**

B.4. DC Link source side

The power quality compensation depends on the injection of power from the DC side of the VSC and at times the power injected is not enough to compensate for the power quality issue. The use of DC storage elements like DC capacitors and DC batteries has some limitations as they only rely on the power absorbed by the VSC to charge the elements which means if the system in a certain period only experiences power quality issues on the AC side, then the VSC will not function as it would run out of the fixed storage elements. The use of PV on the DC side can be very useful in dealing with power quality issues as it would assist in supplying power to the DC storage elements used whilst also some surplus power gets integrated into the system for mitigation of power demands from the Grid.

B.4.1. PV Array

The PV array, which is a connection of many PV modules, its parameters are indicated in the Figure below.

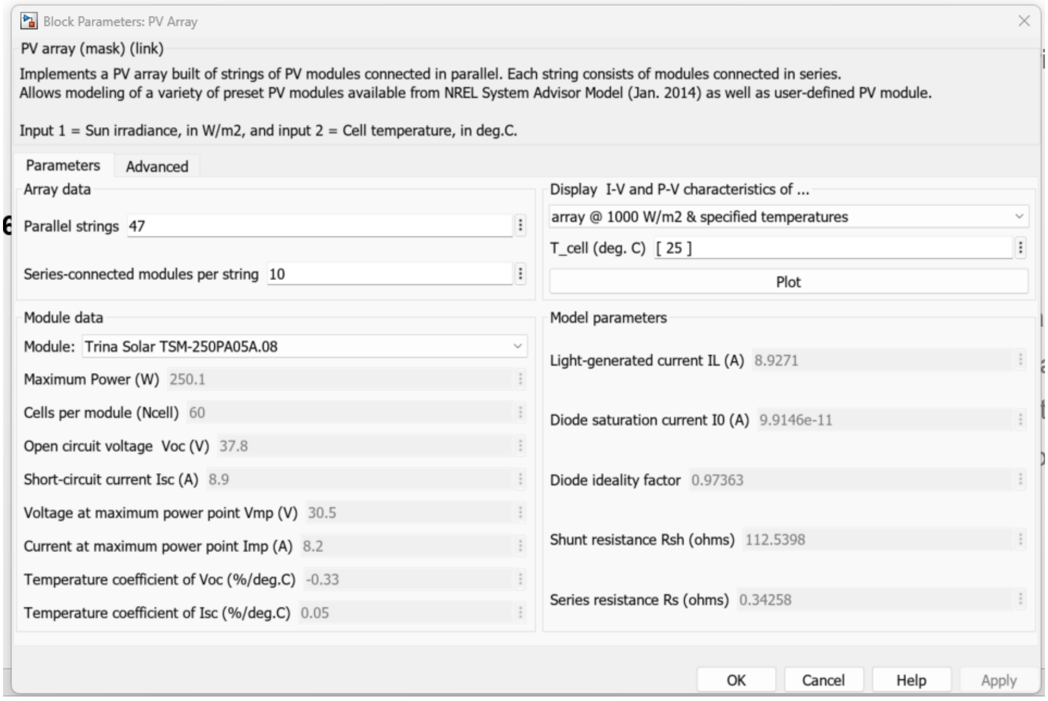

Figure A.10: Simulink Block

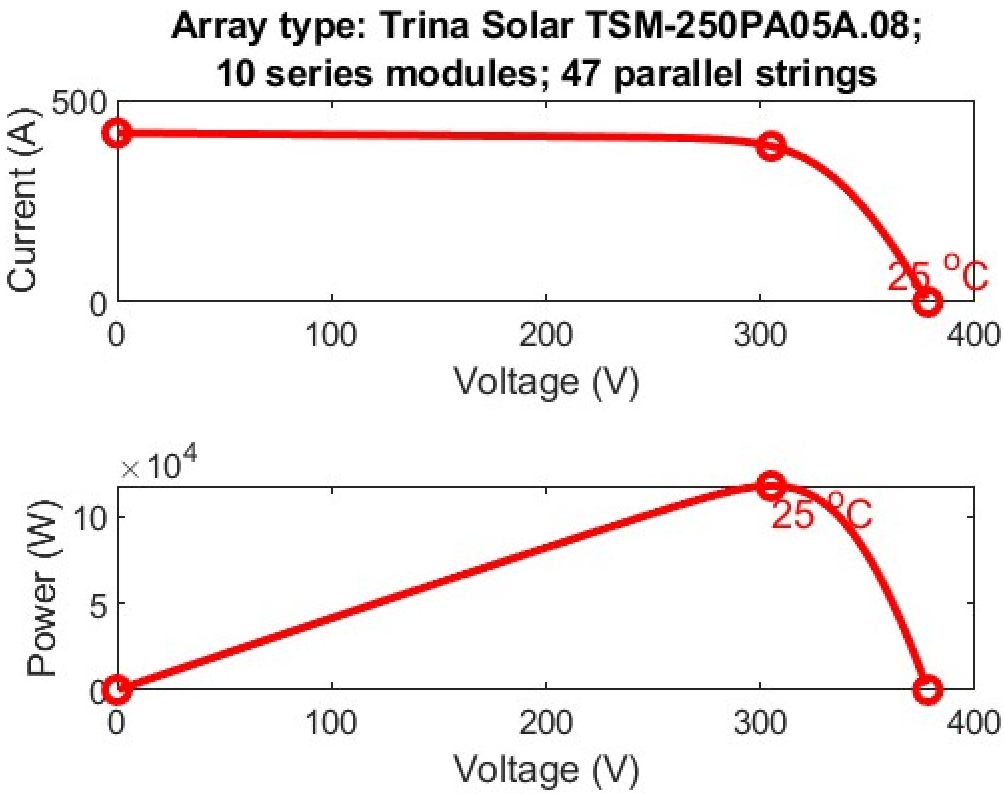

Figure A.11: Simulink Block

B.4.2. DC-DC Boost Converter and Maximum Power Point Tracking

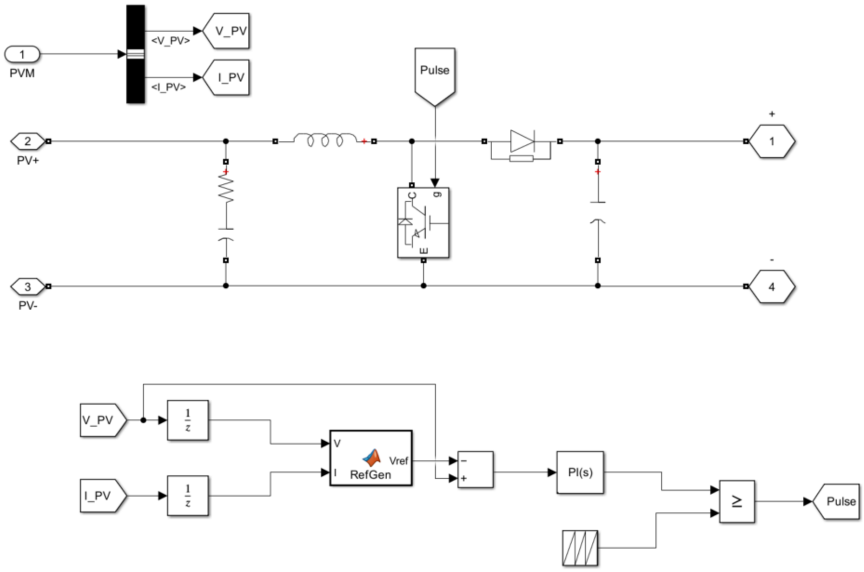

Figure A.12: DC to DC boost converter boost and MPPT function

ANMFinal_sim_R0 ▸ DC-DC Boost Converter with MPPT ▸ MPPT

```
function Vref=RefGen(V,I)

Vrefmax = 363;
Vrefmin = 0;
Vrefinit = 300;
deltaVref = 5;

persistent Vold Pold Vrefold;

dataType='double';

if isempty(Vold);

Vold=0;
Pold=0;
Vrefold=Vrefinit;
end

P=V*I;
dV=V-Vold;
dP=P-Pold;

if dP ~= 0
    if dP < 0
        if dV < 0
            Vref = Vrefold + deltaVref;
        else
            Vref = Vrefold - deltaVref;
        end
    else
        if dV < 0
            Vref = Vrefold - deltaVref;
        else
            Vref = Vrefold + deltaVref;
        end
    end
else
    Vref = Vrefold;
end

if Vref >= Vrefmax || Vref <= Vrefmin

    Vref = Vrefold;
end
Vrefold = Vref;
Vold = V;
Pold = P;
```

Figure A.13: MPPT m-file script of a function