

University of Bahrain

College of Engineering



**Department of
Electrical & Electronics
Engineering**

**Advanced Controller Design for D-FACTS Device in Grid
Connected PV System**

**A Thesis Submitted in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Renewable Energy Engineering**

Prepared by

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April 2023

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The student Ali Jaber Ali AlQattan, student ID 20070570, has defended the thesis entitled “Advanced Controller Design for D-FACTS Device in Grid Connected PV System” and by which he partially fulfilled the requirement for the degree of Master of science on 04/04/2023.

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Abstract

Photovoltaic (PV) solar energy is considered one of the highest renewable energy resources worldwide. Hence, PV system installation capacity is increasing, triggering new power quality problems in grid systems. Some examples of these problems include unbalanced voltages, fluctuating power levels and harmonic distortions. To mitigate these problems, a Distribution Flexible Alternating Current Transmission System (D-FACTS) is considered a viable solution that can be integrated into the distribution system. Moreover, to reduce the adverse impacts of PV integration on voltage regulation and harmonic distortion in electrical distribution systems, a Distribution Static Synchronous Compensation (D-STATCOM) is considered a solution. The thesis aims to mitigate power quality concerns related to PV integration by designing an advanced control system for the D-STATCOM. A simulation study is performed by modeling a power system model with an integrated PV system and D-STATCOM. Three control schemes, Proportional Integral (PI), Artificial Neural Network (ANN), and Adaptive Neuro-fuzzy Inference System (ANFIS), were applied within the internal control of D-STATCOM to enhance the power quality of the power system. Two different inverter configurations were adapted, a Sinusoidal Pulse Width Modulation (SPWM) and a Hysteresis Current Controller (HCC). Results are obtained as voltage profiles for all the considered control schemes with different inverter types under different contingency conditions. The performance is also evaluated by control characteristics evaluation for different controllers. Different scenarios were analyzed through graphical methods, Total Harmonic Distortion (THD), and Root Mean Squared Error (RMSE).

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Nomenclature

ANFIS	Adaptive neuro-fuzzy inference system
ANN	Adaptive Neural Network
BESS	Battery Energy Storage System
D-STATCOM	Distribution static synchronous compensation
DVR	Dynamic voltage restorers
FACTS	Flexible alternating current transmission system
GD	Gradient descent
GTO	Gate Turn off Thyristor
IPFC	Interline Power Flow Controller
IRP	Instantaneous reactive power
LSE	Least squares estimation
OLTC	On-load tap changer
PI	Proportional Integral
PLL	Phase Locked Loop
PSO	Particle swarm optimization
PV	Photovoltaic
PWM	Pulse-width modulation
RE	Renewable Energy
RMSE	Root Mean Square Error
SPWM	Sinusoidal pulse-width modulation
SRF	Synchronous Reference Frame
SSE _{Error}	Steady State Error
SSG	Static Synchronous Generator
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static voltage compensators
SVM	Supervised machine learning
TCR	Thyristor Controlled Reactors
TCSC	Thyristor Controlled Series Compensation

THD	Total harmonic distortion
TSC	Thyristor Switched Capacitor
UPFC	Unified Power Flow Controller
VSC	Voltage-Source Converter

Chapter 1: Introduction to the Study

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1.1. Introduction

The massive increase in power demand resulting from residential, industrial, and agricultural sector loads causes a significant demand increase in the power consumption. To mitigate power demand increase, several research is being conducted to meet the needs of renewable energy sources, reactive power compensation, and management at the consumer end of the grid (Martínez, Ebenhack, and Wagner 2019). Renewable energy (RE) sources such as solar photovoltaic (PV) power are increasingly popular used in different country. PV is considered among the fastest developing RE resources globally. Hence, it is rapidly integrated into power systems, and the capacity of PV system installations is growing. As a result, it has triggered new power quality concerns for grid systems, such as low inertia, unbalanced voltage or fluctuating power levels, harmonic distortion, and reverse power flow (Bisit et al. 2020).

Accordingly, the most recurrent problems in the power distribution system entailing poor power quality are due to the use of nonlinear loads operated by power electronics converters (Abas et al. 2020).

FACTS devices and reactive power assistance to improve power system performance have grown in popularity in recent years. The continual progress in power electronics has made it possible to increase the use of FACTS devices. If unanticipated power exchanges occur, some lines get clogged in practical systems. Several FACTS devices can help improve the security of the power system by redistributing power flow and regulating bus voltages (Mathad, Ronad, and Jangamshetti 2013). Distribution static synchronous compensation (D-STATCOM) is one of the shunt-connected FACTS controllers.

D-STATCOM is widely used to address power quality concerns and is considered an excellent shunt-connected custom power compensating device. It handles reactive power support at the load end, as described in these papers (Arulampalam et al. 2006; Kumar and Porate 2014; Rana et al. 2018a). D-STATCOM helps to alleviate the power quality issues in a distribution system, such as reactive power, harmonics, and unbalanced neutral current. D-STATCOM comprises three components: a voltage source converter (VSC), a DC link capacitor, and an interfacing inductor. For the possibility of operating D-STATCOM, different algorithms have been presented in the literature, including carrier-based algorithms such as Synchronous Reference Frame (SRF) (Singh, Jayaprakash, and Kothari 2011; Sree Jyothi, Venkatesh Kumar, and JayaKumar 2021a), Instantaneous Reactive Power Theory (IRPT) (Singh, Dube, and Arya 2015), carrier-free algorithms (Rana et al. 2016), and Power Balanced Theory (PBT) (Singh and Kumar 2010), fuzzy-PI based CSI control algorithm (Deben Singh, Mehta, and Singh 2016).

The sinusoidal pulse width modulation (SPWM) approach used for generating the VSC pulses and including the hysteresis controller PWM technique. D-STATCOM also uses a PI controller to sustain a stable voltage across a capacitor via a DC link capacitor. To some extent, the PI controller works well and provides superior results, but dynamic and highly nonlinear loads hinder the system's stability.

1.2. Static Shunt Compensators

The current vital manufacturing operations necessitate a consistent flow of electricity. The most common power quality issues are harmonics, flickering, swells, and sags (Abas et al. 2020).

The following are the functions of shunt compensators in a transmission system for increasing the transmitted power in the transmission lines by increasing the voltage across the transmission lines.

- Regulate the midpoint voltage of the line segmentation (two bus transmission lines in which a compensator is connected at the center of a transmission line) to improve the amount of transferable power available in the transmission network.
- Providing end-of-line voltage support, it is necessary to compensate loads with a low power factor. Hence, this improves the voltage instability limitations while simultaneously increasing the highest power supply capabilities of the transmission line.
- Improve the transient stability margin by enhancing the highest transferable power within the transmission line (A. R. Gidd et al. 2019).

Shunt compensators are applied in the distribution system to achieve the following objectives:

- Power factor improvement for loads with low power factor for achieving power factor values close to unity.
- Regulate the voltage for the loads caused by fluctuations within the supply voltage.
- solve the unbalanced load effect to achieve load balance.
- Filter out load harmonic, which allows the formation of an almost sinusoidal supply current.
- Exchange active power in a power system to dampen the oscillation.

According to Hingorani, Shunt Connected Reactive Power Compensators can be divided into two parts. The first part is devoted to Static VAR Compensators (SVC), while the other part is dedicated to Static Synchronous

Generators (SSG) (Hingorani NG 2000). SVC is a shunt-connected static var generator or absorber power, which its output is adjusted to exchange capacitive or inductive power to control reactive power flow. In the late 1960s, static VAR compensators were initially designed to compensate for substantial fluctuating loads, such as those produced by electric arc furnaces. Thyristor Controlled Reactors (TCR) or Thyristor Switched Capacitors (TSC) are used in SVC-based systems, along with fixed filters that utilize capacitive/inductive reactive power harmonic filtering to reduce noise (Hingorani NG 2000). SVC systems cause harmonic current issues as they simultaneously solve reactive power problems. It is necessary to have either constant shunt filters or special transformer connections for the systems to accomplish this (Hingorani NG 2000).

1.3. Motivation

Integration of PV power into the grid presents severe power quality challenges such as voltage and frequency variation; voltage sag; voltage surge; harmonics; reverse power flow; synchronization issues; and intermittent power flow (Karimi et al. 2016). Voltage fluctuation on the grid is caused by the intermittent nature of PV energy sources, which can worsen as PVs' penetration rises (Petinrin and Shaabanb 2016).

Another significant issue resulting from the increased penetration of PV energy sources is a harmonic distortion of current and voltage. The voltage or current harmonics are sinusoidal waveforms whose frequencies are integer multiples of fundamental frequencies, resulting in a distorted waveform. It occurs in a PV energy system due to power electronic components such as an inverter that converts the dc output of photovoltaic panels to alternating current signals (Karimi et al. 2016). Higher frequencies can cause circuit

breakers to trip, transformers to overheat, and equipment to wear out more quickly (Eltawil and Zhao 2010).

Similarly, as per IEEE standard 519 -1992, the Total Harmonic Distortion (THD) for the voltage waveform rate must be less than 5% of the fundamental frequency, and each particular harmonic distortion should not be more than 3% (Blooming and Carnovale 1992). If the THD exceeds the abovementioned limit, it will be considered a severe power quality concern. According to international standards, such systems are not recognized (IEEE 519-1992).

Harmonics in the system can be reduced with the help of passive filters, active filters, and FACT devices like the static synchronous compensator (Tran, Truong, and Le 2016). D-STATCOM can reduce energy flutter and tiny voltage instability, improving the quality of the power supplied to end-users. Staggered energies in distributed energy systems can ensure effectiveness using FACTS devices (Kobayashi et al. 2003).

D-STATCOM is now being used to compensate the power at the Sullivan Power station and Inuyama in Japan (Singh et al. 2009). The control of active power injection/absorption is the best solution for the power oscillation damping and can improve the transient stability. D-STATCOM itself cannot control the active power injection/absorption in the power system. A D-STATCOM with an energy storage system can control both the reactive and the active power injection/absorption, thus providing a more flexible power system operation. In a nutshell, D-STATCOM became an advantageous solution for several problems that are being faced by both electric utilities as well as industries. Its advantages could be summarized as follow:

1. It is essential to keep voltage levels in a safe range.

2. Improvement of the transient stability of the power system through reactive and active regulation of the system's output.
3. Increased power transfer capability.
4. Reduction of the power oscillations.
5. Unsymmetrical load balancing.
6. Reduction of transmission line losses.

1.4. Research Problem

PV is one of the fastest-growing renewable energy resources in the world. As the installed capacity of PV systems grows, new power quality concerns for the grid system are being raised, such as imbalanced voltage or fluctuation, harmonic distortion, reverse power flow, etc.

Voltage fluctuation on the grid is caused by the intermittent nature of PV energy sources, which can worsen as penetration of PV rises (Petinrin and Shaabanb 2016). It is characterized as "voltage fluctuations" when the amplitude of a voltage fluctuation is consistent and does not exceed the range stipulated in the ANSI C84.1 and IEEE std 1250-1995. Generally, the deviations from the nominal value do not exceed 0.9 to 1.1 percent. As a result, the lifespan of electronic equipment is shortened because of the harm done to its delicate components (Hossain et al. 2018).

Power quality affects both producers and consumers of electricity and grid operators. Power quality primarily concerns voltage and current deviations from their ideal waveforms. Examples of the power quality concerns entail long-duration voltage variations (sustained voltage oscillation and under voltage); oscillatory and impulsive transients, voltage flicker, short-duration voltage variations (dip or sag, interruption, and swell); waveform distortion (DC offset, notching, and harmonics), and voltage imbalance.

This study focuses solely on the voltage variations problem, one of the many other power quality issues discussed previously. Voltage variations can cause unwanted effects like flickering of lighting equipment. Electronics system intermittent lockup can result from voltage sag, leading to overloading issues such as surges. Voltage swell, on the other hand, can harm electrical equipment. Harmonics can also damage or destroy electrical equipment, transformers, and motors. Variations in power frequency have the most significant impact on the system motors and other frequency-sensitive components.

Voltage sag is a phenomenon used to describe a source of power quality issues because it comes under short-duration voltage change. This small voltage sag refers to any discrepancy in the supply voltage RMS (Root Mean Square). Voltage sag is a decrease in supply voltage RMS value at the fundamental frequency occurring for a short time. Depending on the voltage sag duration, it can last anywhere from five cycles to one minute.

Certain equipment pieces will trip if the RMS voltage falls under 90 percent throughout one or two cycles. Voltage sag is not detrimental to the end-user as the power interruption (long or short in duration), so the harm of voltage sags in some occurrence remain unknown to end-user. However, because substantially voltage sags exist higher than interruptions, the overall harm caused by voltage sags remains significantly greater.

Voltage regulation devices, capacitor bank devices, and overcurrent devices malfunction will generate power quality issues. As a result, the electric power system will eventually suffer from a lack of stability, dependability, efficiency, and security (Shafiullah et al. 2010).

It is essential to note that while the cause of a high number of the issues related to transmission systems is the interconnection of power systems or natural disasters, individual customers bear the responsibility for a significant proportion of the power quality issues on the supply point of the distribution grid. Techniques based on power electronics to combat power quality issues include FACTS devices. Besides voltage control, harmonic cancellation, and voltage balancing, this technology may be helpful in other areas.

The Distribution Flexible Alternating Current Transmission System (D-FACTS) is being investigated as a solution that experts can integrate into the distribution system through the use of Distribution Static Synchronous Compensation (D-STATCOM) to alleviate this problem (Deben Singh et al. 2016).

1.5. Research Objectives

This thesis aims to mitigate power quality problems related to PV integration by designing an advanced control system for the D-STATCOM to reduce the adverse impact of PV integration on the voltage regulation and harmonic distortion in the electrical distribution systems.

- These goals will be achieved by investigating different controllers for D-STATCOM such as Proportional Integral (PI), Artificial Neural Network (ANN), and Adaptive Neuro-Fuzzy Inference System (ANFIS), as well as different inverter types of Sinusoidal Pulse Width Modulation (SPWM) Controller and Hysteresis Current Controller (HCC). The results of this investigation would reveal the best kind of controller that will be proposed. This investigation will be carried out by developing the proposed controllers in MATLAB.

- The control schemes of PI, ANN, and ANFIS are applied with SPWM controller and hysteresis current controllers in D-STATCOM installed in the Study test system.
- The results are obtained as voltage profiles for all control schemes under different operating and fault scenarios. Further performance evaluation was performed by evaluating the control characteristics of different controllers in MATLAB/SIMULINK with different scenarios. In addition, analyzing all control schemes using total harmonic distortion (THD).

The following steps are put into consideration to fulfill the goal of the thesis:

1. The study created via designing a network combining PV and D-STATCOM.
2. Assessing the system's overall flexibility with different conditions via voltage measurement and scope monitoring on particular points of the system.
3. Analyzing the effectiveness of different D-STATCOM control designs.
4. More than one inverter modulation is considered while designing D-STATCOM controllers.

The results obtained are as voltage profiles for all control schemes under different scenarios. Further performance evaluation was done by applying the control characteristics evaluated by calculating Root Mean Square Error (RMSE), Steady State Error, Settling Time, Settling Average value, Rise time, and the peak value to explore an in-depth analysis of each controller type.

1.6. Research Questions

D-STATCOM used for improving electrical distribution systems is examined and practically implemented by simulation in this study. The study explores the integration systems among PV and D-STATCOM control systems that are part of this investigation. Multiple questions need to be answered, and this is related to (D-STATCOM) control system:

- 1- How can we mitigate power quality concerns to the grid system caused by the PV system?
- 2- What is the type of D-STATCOM controller?
- 3- Will the D-STATCOM controller be able to overcome different load changes?
- 4- Can the system reduce the THD to comply with standards?
- 5- How can different controllers be compared with other widely used topologies and control techniques?

1.7. Research Significance

The advanced controller for D-STATCOM will improve the power quality of a grid-connected PV system in terms of voltage regulation and harmonic distortion.

This research work has made the following original contributions to the area of D-STATCOM systems:

- Different controller techniques are applied to D-STATCOM and compared to achieve the best results.
- Grid voltage becomes balanced because of the selected control scheme.
- Investigation of the inverter type in D-STATCOM voltage converter.

- Optimization of the THD in a system by comparing different types of controllers

1.8. Thesis Plan

The Thesis is organized into five different chapters as follows:

- Chapter 1 introduces the study and covers the thesis questions, objectives, and significance.
- Chapter 2 provides the theoretical background on power system structure, PV system, PV system integration problems, power quality issues, different types of D-FACTS devices, D-STATCOM main components, and different configurations for D-STATCOM.
- Chapter 3 introduces the different D-STATCOM controller configurations and mathematical modeling of D-STATCOM and its internal control. It also explains the control algorithm and its types for D-STATCOM. The proposed controllers PI, ANN, and ANFIS, along with different inverter types such as SPWM and Hysteresis Current Controller.
- Chapter 4 explains the procedure of modeling and simulating the controllers with MATLAB/ SIMULINK. The distribution system in the study is always subject to different loading and varying operating conditions all the time. As a result, seven different scenarios are tested along with one fault to evaluate the performance of the control strategies. At the end of this chapter, the simulation results are analyzed.
- Chapter 5 concludes the thesis by analyzing the overall system's advantages and limitations. It also covers the final recommendations and future aspects of this work.

Chapter 2: Theoretical Framework and Literature Review

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2.1 Power System

The modern electric power system generates, transmits, and distributes electrical power in an electrical network that consists of alternators, transformers, transmission lines, sub-transmission lines, distribution lines, and various control and protective devices. Alternators at power plants generate electrical power. There are two sources for the generation of electrical power (i) conventional sources, which are high headwater (hydropower plant), nuclear fuel (nuclear power plant), combustion of coal, natural gas or oil (thermal power plant), etc., and (ii) non-conventional sources such as wind, solar, geothermal, tidal, biomass, etc. Power generation from conventional sources contributes a significant part of total electrical energy. Most of the power plants are located far away from the load centers. So, the generated electrical power must be transmitted to the load centers over a long distance through transmission lines. Transmission lines also connect one power system with another (grid or area), forming a complex electrical network called an interconnected power system (Machowski et al. 2020).

As the size of the power system increases in terms of the number of alternators, substations, transmission lines, switchgear, transformers, etc., their interaction, operation and maintenance become more complicated. Therefore, it is essential to simultaneously gather and monitor data of the interconnected power system at a particular point at what is known as the Energy Dispatch Centre. Various regional dispatch centers are interlinked to the national load dispatch center for properly coordinating, monitoring, and controlling the electrical power.

The generated voltage level is generally between 11-13.8 kV. This voltage level is stepped up to 132/220/400 kV for economical electrical power

transmission. Then the voltage level is stepped down to 66 kV (sub-transmission voltage level) or 33 kV (primary distribution voltage level) to supply electrical power to industrial loads. Again, the voltage level is stepped down to 11 kV (primary distribution)/400 V/220 V (secondary distribution) to meet the electrical power requirement of small-scale industries and domestic users, respectively (Machowski et al. 2020). Figure 2.1 shows a typical power generation, transmission, and distribution system.

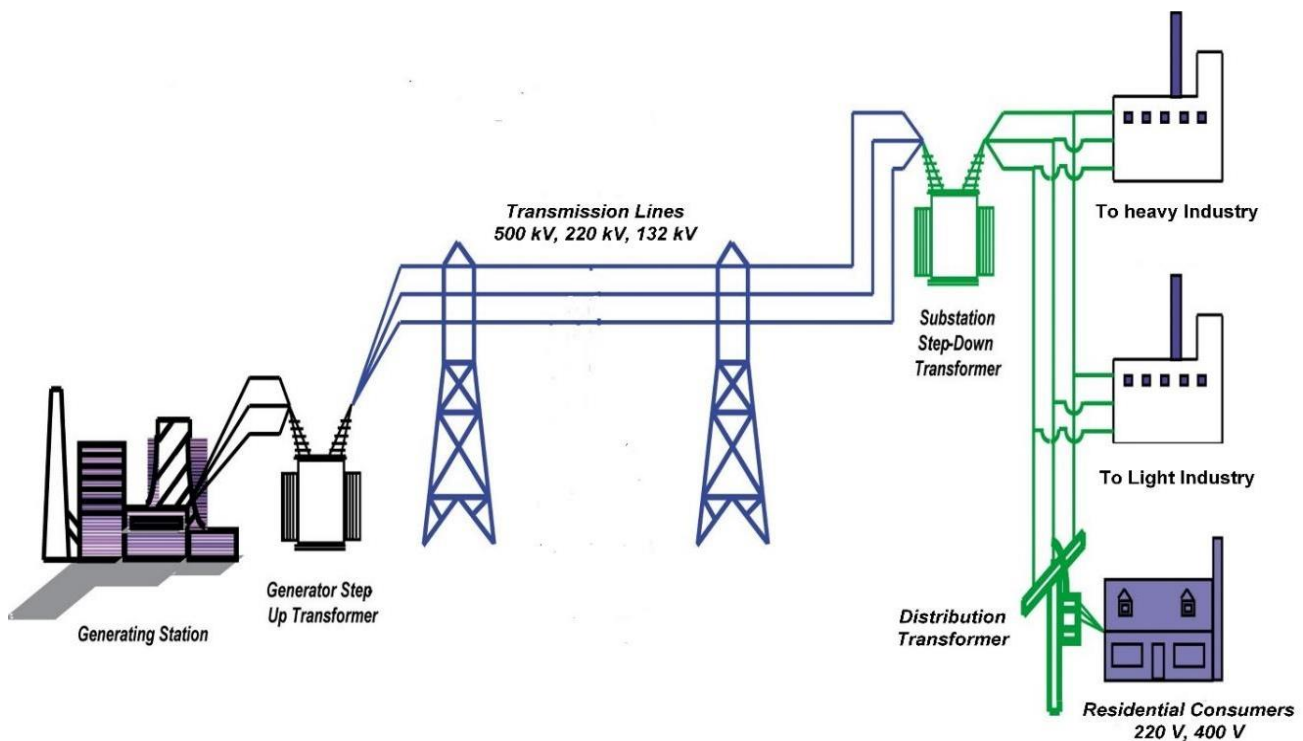


Figure 2.1. Electrical Power Transmission System (Machowski et al. 2020)

However, the interconnection of the power system increases the complexity due to the presence of a considerable number of components, each having its internal dynamics and may interact with each other to give rise to complex collective behavior. Further, the broad geographic spread of the electrical power system raises the system's complexity. As a result, the analysis and control problems become more critical. Power systems are generally subjected

to many disturbances during their operation. Some disturbances, like changes in load demands, constantly occur while the other disturbances rarely occur. However, the effects may be highly hazardous, like faults and physical changes such as tripping one or more transmission lines (Alvarado et al. 2001).

2.2 PV System

Human progress is dependent on the availability of energy. At the same time, fossil fuels have been the primary source of energy for the past two centuries (coal and, more recently, natural gas and oil). As societies and industries grow, the demand for energy increases. The world's population is expected to surpass 11.2 billion people by the end of the century, and a mathematical model that combined global population, wealth, and oil consumption recently estimated that global energy consumption should rise by about 1.7 billion tons of oil equivalent per year by 2025 to support natural growth in gross domestic product worldwide. This means that to retain a 33% oil energy share (as of 2015), existing oil output would have to be increased by about 11 million barrels per day (Meneguzzo et al. 2016).

Solar energy is the cleanest, most abundant, and renewable energy source on Earth and is also infinitely renewable. To put it another way, the sun is still strong at 6500 million years old and is still producing enough energy to power our planet. On the Earth's surface, solar irradiation reaches 120,000 terawatts, which is translated as 20000 times as much electricity as the entire globe needs. In just 18 days of solar radiation, the Earth receives energy comparable to that accumulated from the world's oil, coal, and natural gas reserves (López 2020).

When it comes to photovoltaics (PV), solar irradiation has been nicknamed the "fuel" because its characteristics serve as the foundation for all aspects of PV system design, from array building to the electric reliability of PV stand-alone systems. In 1839, Edmund Becquerel published his analysis of the photoelectric effect (Aruchamy, Aravamudan, and Subba Rao 1982), which was the first time that solar irradiation was recognized. Solar cells were invented in 1954 (Chapin, Fuller, and Pearson 1954) by Calvin Fuller, Daryl Chapin, and Gerald Pearson, who were responsible for creating the world's first solar cell (Hammad et al. 2017). However, even though it has been nearly 70 years since this discovery, the same solar cell design has been responsible for more than 940GW of global PV installation, with China claiming the top spot with around 305.9 GW cumulative capacity (Renewables Global Status Report 2022)

In grid-off PV systems, there are batteries employed for three primary purposes: (1) to serve as a store of excess power in case the PV array's output falls short of the load demand, (2) as a backup source of energy, and (3) prevents large and potentially harmful voltage fluctuations (Spiers 2012).

In addition to energy storage and variable transmission, power electronics converters also provide load control, which is a technological link between the electric power grid and the rest of the world (Timofejevs et al. 2013). Grid converters, which are sometimes referred to as "synchronous converters" when compared to the synchronous generator in centralized power systems, will play an essential role in future power systems based on smart grid technologies because distributed generation systems generate higher voltage levels that must be managed.

As stated previously, solar energy has been the topic of significant research and has seen a dramatic increase in growth in recent years, particularly for the conversion of solar energy into electrical energy or heat or for the generation of fuels through an artificial photosynthesis process. When compared to other forms of renewable energy, photovoltaics has a few distinct advantages:

- Solar energy is a renewable resource since it will continue to radiate on the Earth for millennia (100% renewable).
- It is environmentally friendly, as it produces no pollutants or greenhouse gasses.
- It can be utilized anywhere in the world because of its universal accessibility and the fact that it reaches areas where electricity lines cannot be installed.
- Everything from industrial plants to little homes can be included.
- Due to the lack of moving parts, photovoltaic panels are maintenance and noise free.

2.3 Power Quality Issues

The term "grid power quality" refers to a grid's ability to offer ideal power with a clean, noise-free sinusoidal wave shape and a steady voltage and frequency (Hossain et al. 2018). The overall system's efficiency will be harmed if there are any obstacles to retaining high-quality power. Power quality control is a term that relates only to voltage management because adjusting voltage in the system is more straightforward than regulating current. As a result of these economic and technical issues, power quality is becoming more critical. The waste of energy and the resulting financial impact on utilities and end-users of electricity are important considerations. The

voltage profiles for voltage sag, voltage swell and current profiles for harmonics are respectively shown in Figures 2.2, 2.3, and 2.4.

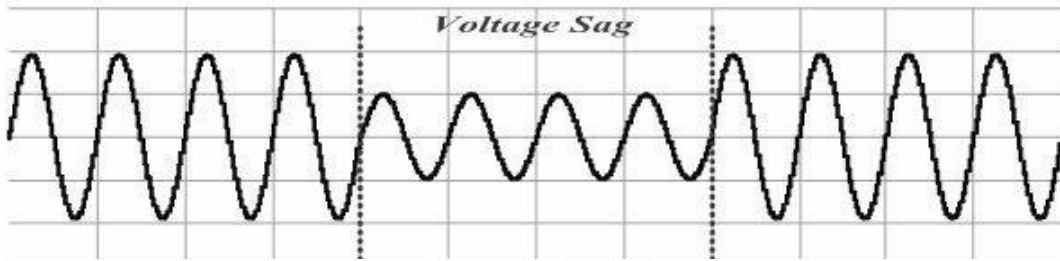


Figure 2.2. Waveform with Voltage Sag (Büyük, Inci, and Tümay 2017).

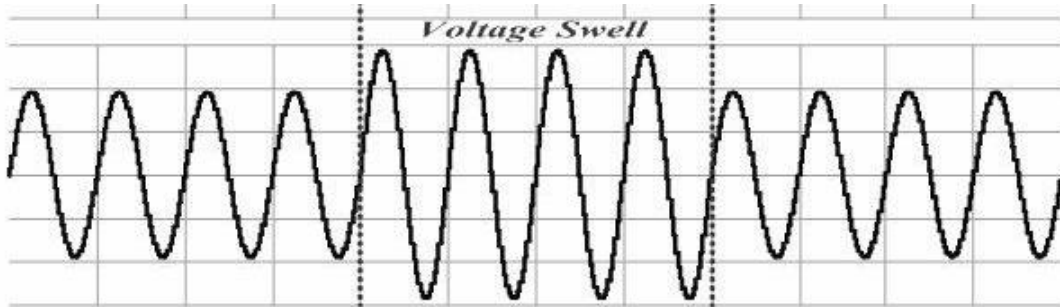


Figure 2.3. Waveform with Voltage Swell (Büyük et al. 2017)

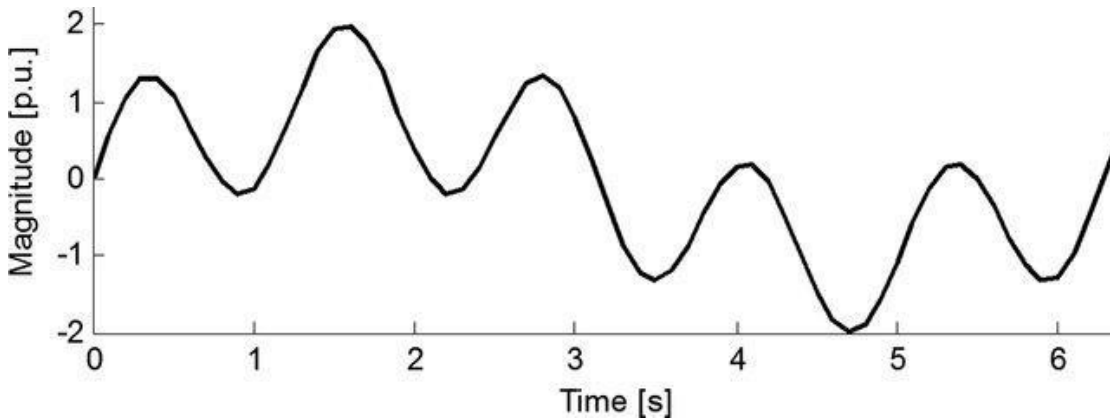


Figure 2.4. Wave Form with the harmonic current (Büyük et al. 2017)

There is complexity in the advanced power system where transmission and distribution networks connected with millions of loads are interconnected. The facility of a reliable and high-quality power supply is the primary concern

of customers. The performance quality of the power system is not good but reliable in developed countries. At steady voltage magnitude and frequency, the continual flow of power with smooth sinusoidal voltage without any interruption is customers' demand regarding the power supply.

Many causes affect the quality of the power system, such as voltage sags, voltage swells, voltage drop, disturbance in voltage, disruption, and harmonic problems. This may lead to the destruction of equipment from its breakdown to the complete closure of a plant. Load switching, startup of motors, unstable load demand, non-linear loads, sparking, etc., are the causes of voltage sags and wells. (Büyük et al. 2017).

2.4 Power Quality issues due to PV system

Integration of PV power into the grid presents severe power quality challenges such as voltage and frequency variation; voltage sag; voltage swell; harmonics; reverse power flow; synchronization issues; and intermittent power flow (Karimi et al. 2016). Voltage fluctuation on the grid is caused by the intermittent nature of PV energy sources, which can worsen as PV penetration rises (Petinrin and Shaabanb 2016). As a result, electronic equipment's lifespan is shortened because of the harm done to its delicate components (Hossain et al. 2018). The real and reactive power can be controlled to reduce voltage variations. Dynamic voltage restorers (DVRs), On-load tap changers (OLTCs), static voltage compensators (SVCs), and energy storage devices can all be used to mitigate variations (Petinrin and Shaabanb 2016). Another significant issue resulting from the increased penetration of PV energy sources is the harmonic distortion of current and voltage. It occurs in a PV energy system due to power electronic components such as an inverter that converts the dc output of photovoltaic panels to

alternating current signals (Karimi et al. 2016). Harmonics in the system can be reduced with the help of passive filters, active filters, and FACT devices like the static synchronous compensator (Tran et al. 2016). Voltage sag and swell are caused by the non-controllable of PV energy sources in the system. The voltage sag might occur for short periods (ranging from 500 milliseconds to 1 min). For more than 1 min, the voltage drops to an under-voltage situation, and for less than 500 milliseconds, the voltage drops to a transient condition (A R Gidd et al. 2019), as shown in Figure 2.5.

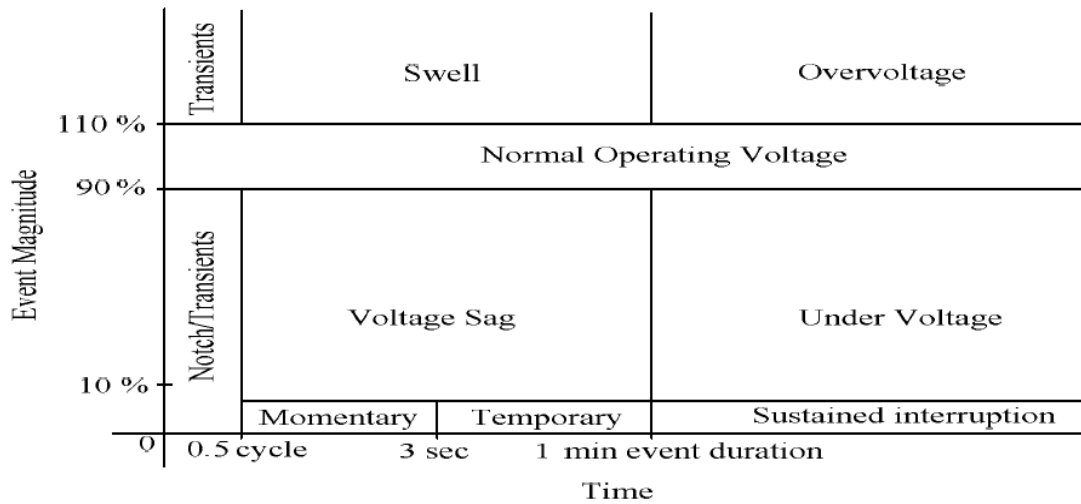


Figure 2.5. Classification of voltage sag and swell (A R Gidd et al. 2019)

Synchronization is a crucial consideration for integrating renewables into the grid. PV system output must be synchronized with the grid voltage in order to avoid system instability (Arrillaga and Watson 2004). The stability of the power system can be jeopardized if the power system is not correctly synchronized (Hirth and Ziegenhagen 2015). Because of this, the voltage, phase angle, and frequency differential between the renewable source and the grid must be minimized. Consequently, load compensation and reverse power flow are caused by the system's usage and integration of renewable energy. (Alpcan, Saha, and Aldeen 2014).

2.5 Main Technologies to Mitigate These Challenges

FACTS devices and reactive power compensation to improve the power system performance have grown in popularity in recent years (Kang et al. 2017; Zhang, Tomsovic, and Dimitrovski 2016a). In 1988, Hingorani and Gyugyi introduced the FACTS concept. To manage electrical factors like the voltage, phase angle, impedance, current, and active and reactive power, power semiconductor devices are used in FACTS (Amaize et al. 2017). FACTS devices modify the line reactance, absorb or inject reactive power, or alter the phase angle between the receiving and sending end bus. High-speed power electronic controllers are used in the design of FACTS devices. Mechanically regulated AC power transmission system components' poor response time and wear and tear are no longer an issue (Zhang, Tomsovic, and Dimitrovski 2016b). The continual progress in power electronics has made it possible to increase the use of FACTS devices. Several FACTS devices can help improve the security of the power system by redistributing and regulating bus voltages (Mathad et al. 2013).

2.6 FACTS Devices

FACTS controller enhances power system stability of a system by maintaining active and reactive power compensation, voltage regulation, and others.

The IEEE definition of FACTS is *"Alternating current transmission system incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability."* Other static controllers are not power electronic based (Hingorani NG 2000).

Table (2.1) explains the FACTS devices categorized by their functions. STATCOM is a versatile FACT device used to mitigate the problems like

voltage control, damping oscillations, and voltage stability, which are the major problems nowadays. UPFC is the most reliable and versatile FACT device than other devices because it is a pack of both STATCOM and SSSC both. UPFC is used for many applications like power system stability and control of a system by adjusting reactive and active power, fault current mitigation, and voltage stability. IPFC FACTS is good in voltage stability, dynamic stability, and transient stability (Hingorani NG 2000). The detailed classification of FACTS devices is illustrated in Figure 2.6.

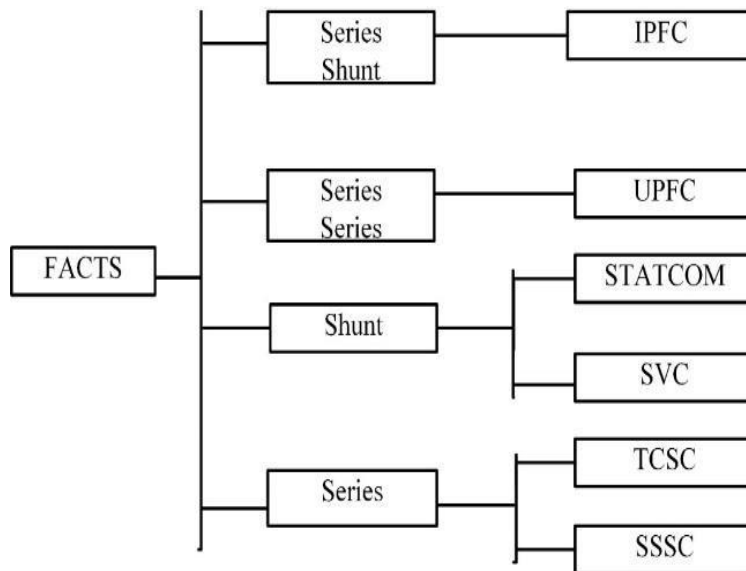


Figure 2.6. Classification of FACTS Devices (Hingorani NG 2000).

Table (2.1): FACTS and their control characteristics (Hingorani NG 2000)

Problems	Types											
	STATCOM (without storage)	STATCOM (With storage)	SVC	TCBRs	SSSC (without storage)	SSSC (with storage)	TCSC	TCPST	UPFC	TCVL	TCVR	IPFC
Voltage Control	✓	✓	✓								✓	✓
Var compensation	✓	✓	✓						✓			
Damping Oscillations	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓
Transient stability		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Dynamic stability		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Voltage stability	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Control on current					✓	✓	✓	✓				
Fault current mitigate					✓			✓	✓			
Active power control								✓	✓			
Control of reactive power									✓		✓	✓
Control of reactive power									✓		✓	✓

2.6.1. Static Synchronous Compensator (STATCOM)

STATCOM is a shunt controller, as shown in Figure 2.7, whose AC voltages control the capacitive and inductive output current. STATCOM is used as a current source and voltage source converter. STATCOM acts as a filter to absorb the system harmonics (Hingorani NG 2000). STATCOM is a voltage

source converter with a dynamic controller and power filters used to improve the power system stability, energy management, energy utilization, and improvement of the power factor in the smart grids when integrated with conventional power systems. STATCOM is the device that produces the active and reactive power at its terminal for compensation in a system. When an energy source of a specific rating relates to STATCOM, it produces active power. First, STATCOM was installed in Japan in 1991 providing voltage stabilization for a substation. The world's largest STATCOM installed in the United Kingdom (UK) in 2001. The main advantage of the STATCOM is that it requires a small area and gives higher reactive power where voltages are low. At the same time, STATCOM performs as a current source for grid voltage regulation (Gandoman et al. 2018). STATCOM has two possible modes. In the under-excited mode, STATCOM absorbs reactive power. In the over-excited state, STATCOM provides reactive power to mitigate voltage-related problems (Liu et al. 2017).

STATCOM absorbs power when the system voltages are high, and it generates power when system voltages are low (Raj and Waktola 2019). STATCOM is designed for reactive power compensation, a dc-link capacitor that receives the control pulse through which the STATCOM provides compensation of real and reactive power. STATCOM will absorb the reactive power if the terminal voltages are less than the system voltages. It has a smaller size, the cost is meager, and it can compensate for both the active and reactive power (Hossain et al. 2018).

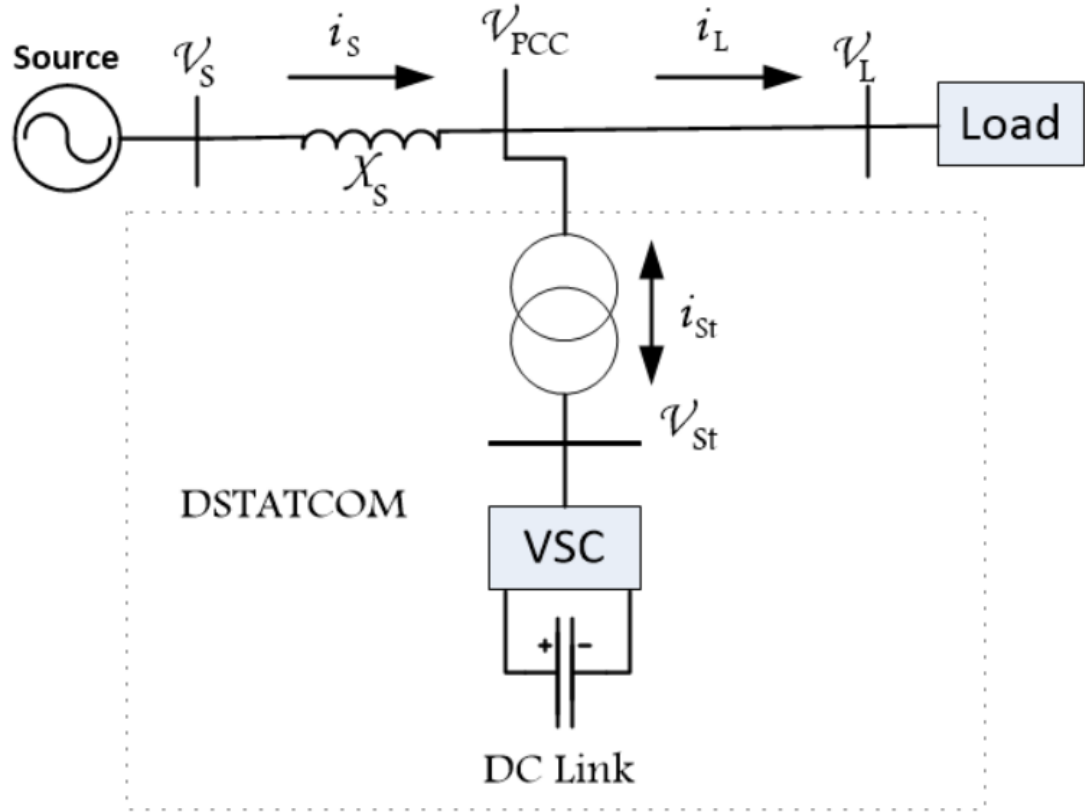


Figure 2.7. STATCOM connected with grid

2.6.2. Other Types of FACTS Devices

The first type, SVC (Static Var Compensator), is based on parallel capacitors and thyristor-controlled reactors. SVC is a shunt-connected device that injects or absorbs reactive power to regulate voltage. SVC is combined with capacitive and inductive components. SVC enhances power system stability, dynamic voltage control, power transfer, and mitigates fault impacts (Hemeida, Rezk, and Hamada 2018). The second type, BESS (Battery Energy Storage System), consists of chemical battery cells connected in either parallel or series to provide the power when linked with the voltage source converter like the STATCOM. Under discharging, mode BESS injects the energy into the power grid to compensate for active and reactive power. These methods

are used in voltage stability and frequency control (Liu et al. 2017). The third type, SSSC (Static Synchronous Series Compensator), contains an energy storage or captivating device to improve a system's active behavior by compensating power in a system to increase or decrease inclusive real voltage drop. The key objective of the SSSC is to reduce power system oscillations and deviation during fault cases (Al-Sarray and McCann 2017). The fourth type, Interline Power Flow Controller (IPFC), combines two or more SSSC interlined through a mutual dc link. For reactive power compensation, a bidirectional real power flow among SSSCs. IPFC provides or consumes active power (Hingorani NG 2000). IPFC can instantaneously control the power flow in two or many transmission lines. Last type, UPFC (Unified Power Flow Controller) which has shunt-connected STATCOM and a series-connected SSSC are coupled through a dc link, which permits the bidirectional power flow among the shunt terminals of STATCOM and series output terminals of SSSC. UPFC provides power compensation by using any electric energy source. UPFC injects the voltages for power system stability and control of a system by giving line impedance, voltage stability, and real power compensation (Hingorani NG 2000).

Table (2.2) shows that STATCOM and UPFC have the exact cost per KVAR. And SVC has a lower cost than the UPFC and STATCOM, but if we compare, SVC has no better performance than the UPFC and STATCOM. However, it is difficult to give a fixed cost figure because of many available criteria that must be considered, such as the voltage of the system and power rating.

Table (2.2): FACTS Devices Costs (Gandoman et al. 2018)

Types	Cost \$/KVAR
UPFC	40
TCSC	50
STATCOM	40
SVC	35

2.6.3. Advantages & Disadvantages of FACTS Technologies

FACTS System Advantages:

- Power flow control and enhancement in the loading capability.
- Intensification in the system security reduces short circuit currents and overloads, managing damping oscillations and blackouts.
- Provide safe line connections by providing reverse equipment.
- Reduce the amount of reactive power that flows through the line, allowing the line to accept more active power.
- Upsurge uses of low-cost generation (Hingorani NG 2000).

FACTS System Disadvantages:

- High power rating devices are required in high power rating systems, resulting in increased installation costs.
- Due to the lumped nature of FACTS devices, these are located at specific points (not in a wide area) of the transmission line. So, failure at that point leaves the entire system to shut down.
- A complex custom-engineered system requires on-site maintenance, which increases operating costs.

2.7 D-FACTS

Recently, the Distributed Flexible AC transmission system (D-FACTS) has been introduced to overcome most of the problems posed by FACTS devices but in distribution side . The concept of D-FACTS originates from the FACTS devices; these are miniaturized FACTS devices at a lower price and with a higher capability. D-FACTS devices are power modular, small in size, and light in weight. The distributed fashion of the D-FACTS contributes to more safety and improved controllability of the power system. The uniqueness of these devices is that they can be placed into a system at multiple positions. Each D-FACTS on different lines can be used to achieve a control objective by coordinating them to work together (Tambe and Joshi 2013).

There are numerous advantages to use D-FACTS devices in power system operations. The distributed architecture of D-FACTS adds to the power system's increased security and greater controllability. Because these devices can be used in various ways, they are an excellent fit for many applications. For multiple reasons, such as cost, dispersed nature, coordinated control, and a wide range of compensation, the concept of a distributive approach is required for the realization of FACTS devices (Tambe and Joshi 2013).

2.7.1. D-STATCOM

The Distribution Static Synchronous Compensator (D-STATCOM) is implemented dynamically to address power quality (PQ) issues in distribution side. To combat poor power quality, the distribution compensator stands head and shoulders above the rest of the controllers on the market. Conventional distribution techniques have declined in performance because of the rapid increase in the use of electrical power. Thus, better compensated strategies were developed by using D-STATCOM (Oda et al. 2021).

The D-STATCOM working principle is the same of STATCOM, but the only different is the rating and the size is smaller as D-STATCOM only used in distribution side to address power quality issue.

2.7.2. Components of D-STATCOM

A Voltage Source Converter (VSC) and the controller are the primary components of D-STATCOM. Using a voltage source inverter and a DC capacitor as the input to a D-STATCOM, a power system can generate a variable AC voltage source. A reactive and active power transfer occurs when a voltage differential across this reactance creates the D-STATCOM. The D-STATCOM is connected to power system networks to address voltage quality issues.

The D-STATCOM employs two primary methods of control. D-STATCOM power bus is coupled to an AC voltage regulating system. The D-STATCOM capacitor is controlled by a DC voltage control linked across it. A well-known technique for controlling the bus voltage is shunt reactive power injection. Both voltage regulators are commonly controlled by proportional-integral (PI) as internal controllers (Chakraborty, Mukhopadhyay, and Biswas 2022).

2.7.3. Configurations of D-STATCOM

It is possible to categorize D-STATCOM topologies based on how many switches are used. The most common configuration is the three-phase three-wire while other type is three-phase four-wire distribution systems D-STATCOMs (Sree Jyothi, Venkatesh Kumar, and JayaKumar 2021b).

2.7.4. Three-Phase Three-Wire D-STATCOM

The use of a three-phase, three-wire distribution model, as illustrated in Figure 2.8, compensates for consumer loads while also improving voltage stability on the grid and helps to improve the overall power quality of the system. Control and regulation of equal AC bus voltages and dc capacitors are challenging to control and regulate. It is preferable to use a three-phase, three-wire topology with a capacitor to reduce the number of switching devices. As illustrated in Figure 2.8, the three-phase grid voltages V_{sa} , V_{sb} , and V_{sc} , as well as the associated currents i_{sa} , i_{sb} , and i_{sc} . The corresponding load currents are i_{La} , i_{Lb} , and i_{Lc} . Due to the primary consideration of switching frequency and ripple current, the interfacing inductor is selected, and the design of the DC bus capacitor on the energy storage capacity needed. (Sree Jyothi et al. 2021a).

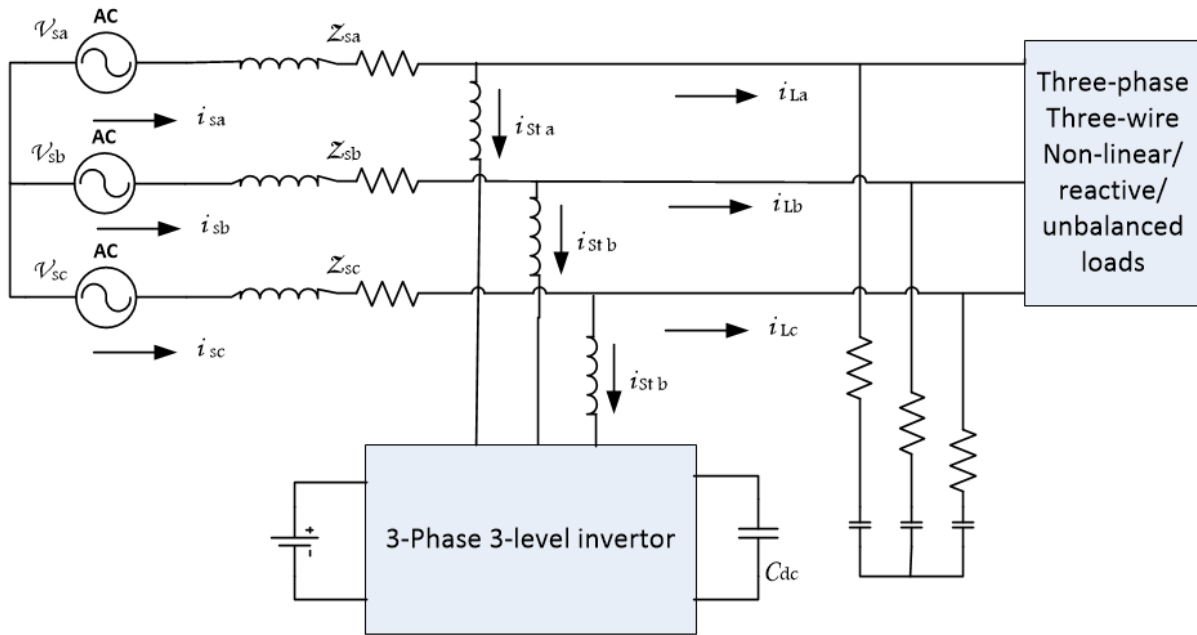


Figure 2.8. Three-phase three-wire D-STATCOM (Sree Jyothi et al. 2021a)

Chapter 3: Research Methodology

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3.1. D-STATCOM Controller Configuration

A distributed static compensator (D-STATCOM) configuration with a load for a three-wire 3- ϕ distribution system is illustrated in Figure 3.1. Using 3- ϕ transformers with voltage ratings of 11/0.415 kV, a 3- ϕ load can be connected to a 3- ϕ source voltage of 415V. The D-STATCOM is connected to the PCC for the harmonic's reduction and regulation of voltages at the bus interface. Six IGBTs power a three-legged voltage source inverter in the D-STATCOM. Six IGBTs power a three-legged voltage source inverter in the D-STATCOM.

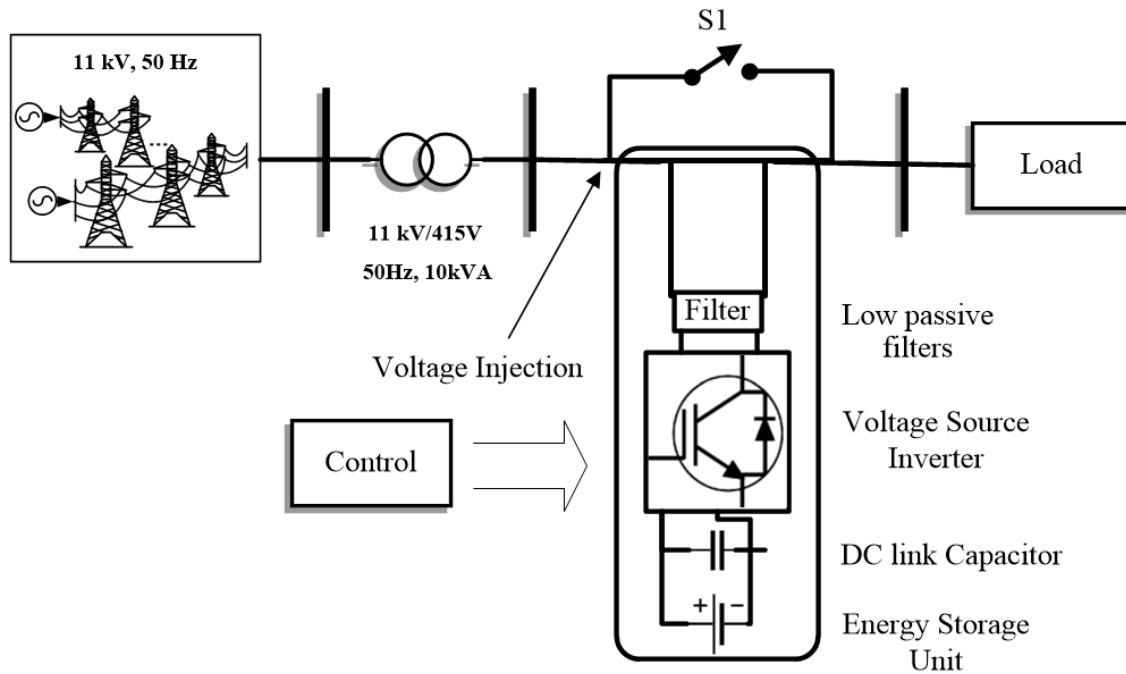


Figure 3.1. Distribution static compensator (D-STATCOM) configuration.

3.1.1. System Configuration

Figure 3.2 depicts a single-line diagram of the study system for this research. The reason behind selecting this simulation model is that it consolidates the research objective and scope to have the correct simulation that will describe the effects of different controllers. A typical distribution system with 11 kV,

50 Hz voltage rating is used, and a step-down transformer is employed to feed the different load types. The distribution line voltage to the consumer-end is 415V, which is a standard rating in Bahrain. VSI-based D-STATCOM switching is used for voltage compensation under different load situations, and the controller obtains the fundamental reference control signals for switching. Study work done in MATLAB/Simulink, the D-STATCOM Simulink model was used to build the suggested approach and run simulations.

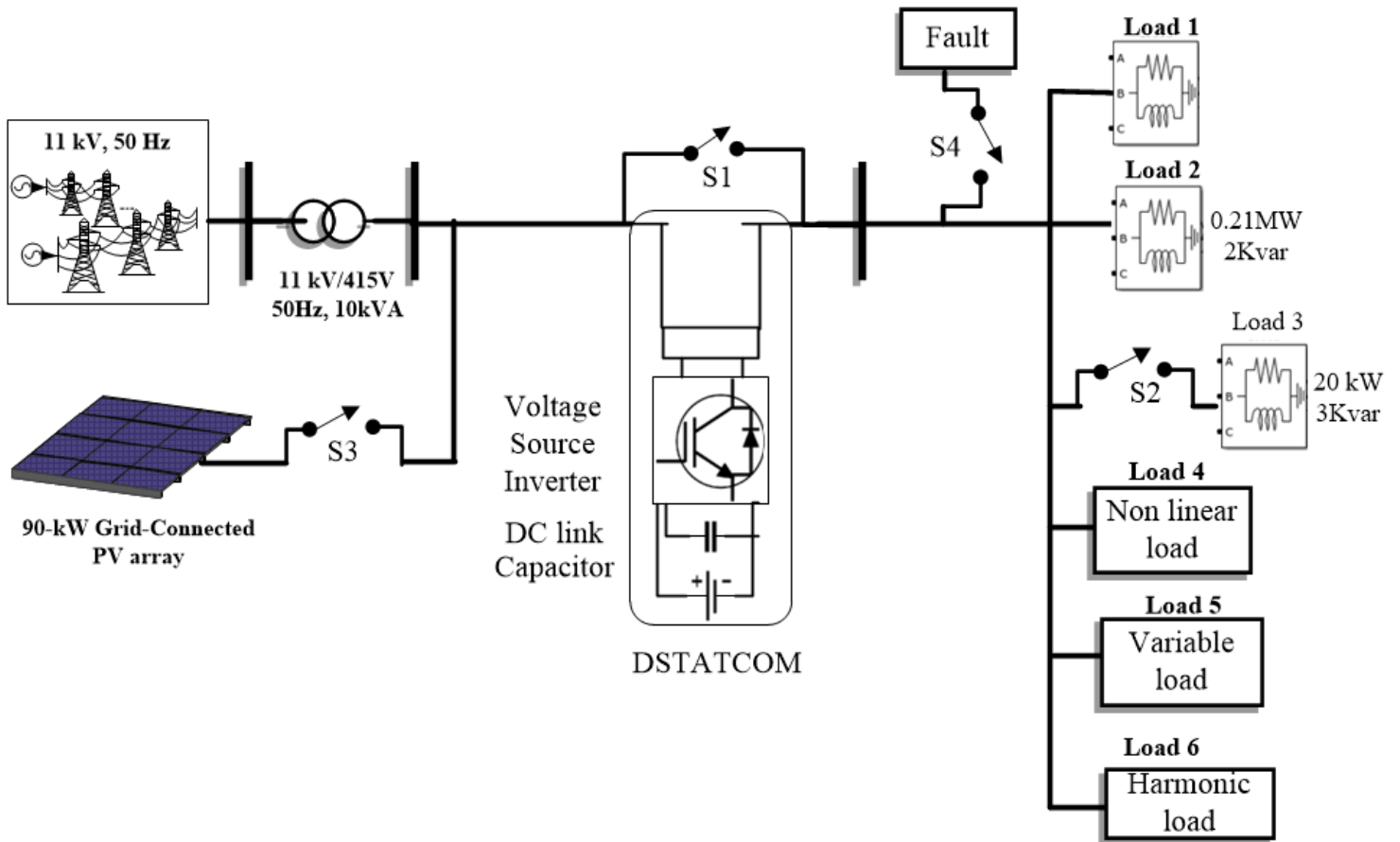


Figure 3.2. Single line diagram of the proposed test system for this research.

The D-STATCOM compensator performs a reactive power compensation and offers voltage support without requiring massive capacitor banks. At a common coupling node, it absorbs or generates reactive power.

3.2. Modeling of D-STATCOM's Control Architecture

The single-phase synchronous D-Q frame theory-based control technique for the three-phase D-STATCOM is shown in Figure 3.3. A D-Q frame theory-based control was used to create switching pulses for the three-phase D-STATCOM. In three-phase system, the $3-\phi$ (in abc frame) currents or voltages are transformed to a stationary $\alpha - \beta$ frame and subsequently to a D-Q spinning frame. Thus, at least two phases are required to convert a signal to a stationary $\alpha - \beta$ frame. The α -axis components are represented by the original signal, whereas the stationary reference component is β -axis frame and lags by 90° . Input signals such as the voltages at the PCC (V_a, V_b, V_c), and the voltages at the dc bus (V_{dc}) and the load current (i_l), are all monitored and used as signal to the system. Using balanced and sinusoidal PCC voltages, the system voltage amplitude is computed as (Ponnananthi and Kumar 2015).

$$V_{rms} = \frac{\sqrt{2}}{\sqrt{3}} \sqrt{(V_a^2 + V_b^2 + V_c^2)} \quad (1)$$

The conversion of a phase current and voltage into an $\alpha - \beta$ stationary frame is done by using a Clark's transformation on three-phase currents and voltages. Then, in the stationary $\alpha - \beta$ frame, the current of the load and PCC voltages are characterized as: (Ponnananthi and Kumar 2015).

$$\begin{aligned} V_{a\alpha}(t) &= V_a(t) \\ V_{b\alpha}(t) &= V_b(t) \\ V_{c\alpha}(t) &= V_c(t) \end{aligned} \quad (2)$$

$$\begin{aligned}
V_{a\beta}(t) &= V_a \left(t - \frac{T}{4} \right) \\
V_{b\beta}(t) &= V_b \left(t - \frac{T}{4} \right) \\
V_{c\beta}(t) &= V_c \left(t - \frac{T}{4} \right)
\end{aligned} \tag{3}$$

$$\begin{aligned}
i_{l\alpha}(t) &= i_l(t) \\
i_{l\beta}(t) &= i_l \left(t - \frac{T}{4} \right)
\end{aligned} \tag{4}$$

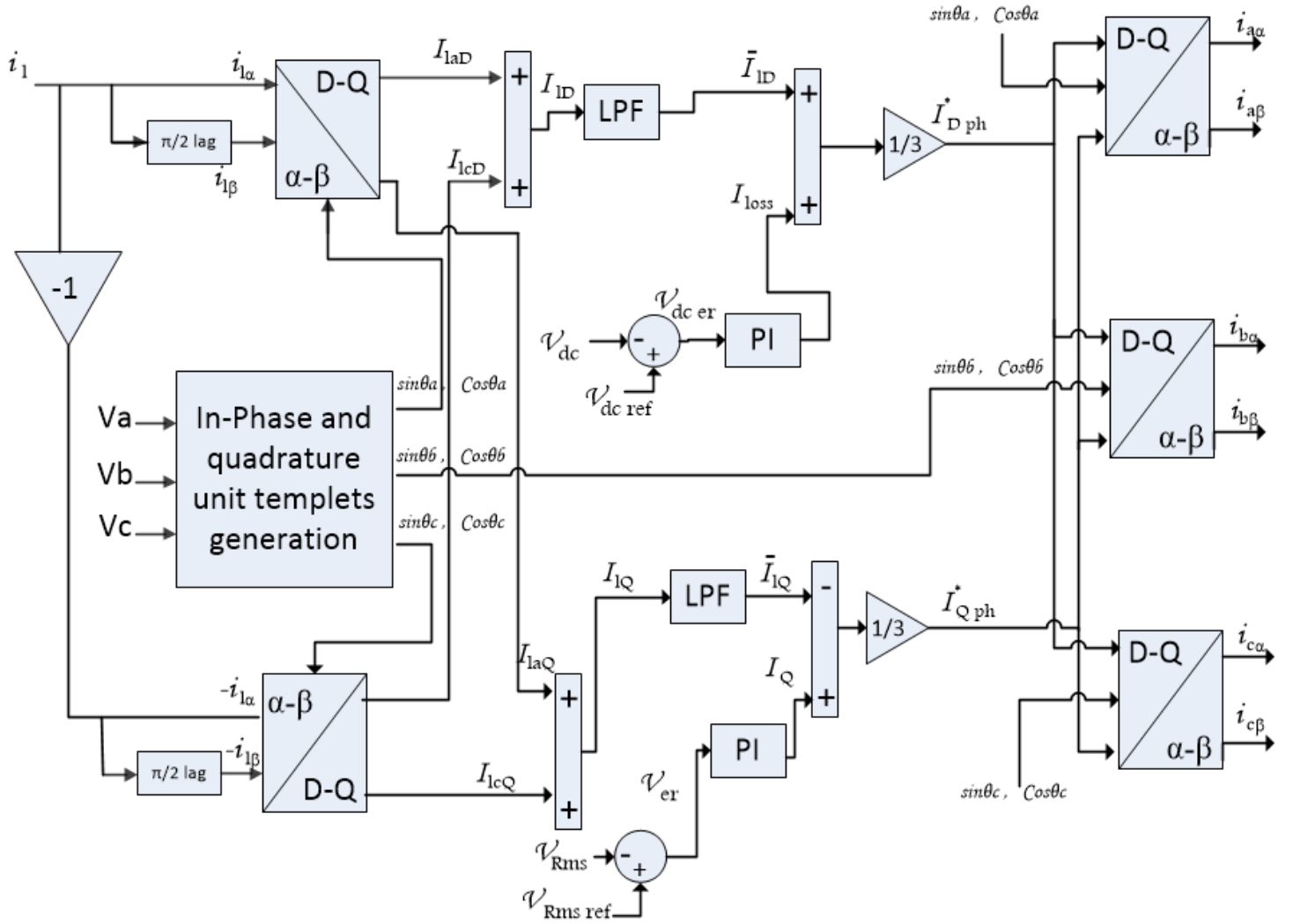


Figure 3.3. D-Q frame theory is shown as a block diagram (Ponnananthi and Kumar 2015).

Now consider a phase a whose direction is similar to $V_a(t)$ that rotates synchronously with DQ-frame. Therefore, in phase a , the components of the D-axis and load current of the Q-axis can be calculated as follow:

$$\begin{bmatrix} I_{laD} \\ I_{laQ} \end{bmatrix} = \begin{bmatrix} \cos \vartheta_a & \sin \vartheta_a \\ -\sin \vartheta_a & \cos \vartheta_a \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{l\beta} \end{bmatrix} \quad (5)$$

Where, $v_{a\beta}$ and $v_{a\alpha}$ are used to estimate the values of $\sin \vartheta_a$ and $\cos \vartheta_a$ by the following equations: (Ponnananthi and Kumar 2015).

$$\begin{bmatrix} \cos \vartheta_a \\ \sin \vartheta_a \end{bmatrix} = \frac{1}{\sqrt{(v_{a\alpha}^2 + v_{a\beta}^2)}} \begin{bmatrix} V_{a\alpha} \\ V_{a\beta} \end{bmatrix} \quad (6)$$

Estimating the ϑ can be by using the PLL (Phase Locked Loop). The PLL determines the utility phase angle, frequency, and amplitude. The basic structure of PLL is illustrated in Figure 3.4.

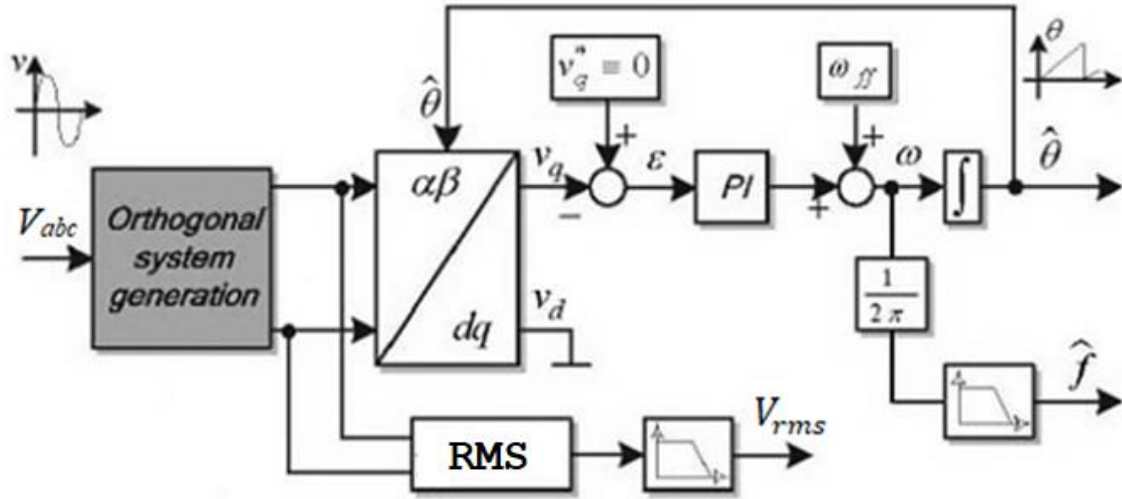


Figure 3.4. PLL basic structure (Ponnananthi and Kumar 2015).

From Equ. (5) the load current D-axis components are estimated I_{laD} and the Q-axis the load current reactive component is represented by I_{laQ} . A similar

estimation is made for the load current components on the D- and Q-axes in phase "c".

$$\begin{bmatrix} I_{icD} \\ I_{icQ} \end{bmatrix} = \begin{bmatrix} \cos \vartheta_c & \sin \vartheta_c \\ -\sin \vartheta_c & \cos \vartheta_c \end{bmatrix} \begin{bmatrix} -i_{l\alpha} \\ -i_{l\beta} \end{bmatrix} \quad (7)$$

The current in phase c is identical to the current in phase a , but they are 180 degrees change different . (Ponnananthi and Kumar 2015).

The load D-axis and Q-axis components to load current are expressed by (8) and (9), respectively.

$$I_{lD} = I_{laD} + I_{lcD} \quad (8)$$

$$I_{lQ} = I_{laQ} + I_{lcQ} \quad (9)$$

Similarly, the entire load is equivalent to the D-Q axis component of the current and is broken down into oscillatory and fundamental components as follows, (Ponnananthi and Kumar 2015).

$$\bar{I}_{lD} = I_{lD} - \tilde{I}_{lD} \quad (10)$$

$$\bar{I}_{lQ} = I_{lQ} - \tilde{I}_{lQ} \quad (11)$$

The nonlinear nature of the coupled loads in the system is the cause for the existence of the oscillatory component. To ensure power quality, oscillatory components must not be present in the D-Q reference axis of source currents. To remove oscillatory components, a filter of low-pass is used.

The voltage error is handled through a PI controller when the dc-bus voltage capacitor is monitored and matched to a reference value. At the k^{th} sampling moment, the voltage error of the D-STATCOM $V_{dc_{er}}$ is stated as follows:

$$V_{dc_er}(k) = V_{dc_ref}(k) - V_{dc}(k) \quad (12)$$

In this equation, $V_{dc}(k)$ and $V_{dc_ref}(k)$ are the D-STATCOM's reference and measured dc bus voltages, respectively.

To keep the steady voltages of D-STATCOM's dc bus at sampling moment k , the output of the PI controller is expressed as:

$$I_{loss}(k) = I_{loss}(k-1) + K_{pd}\{V_{dc_er}(k) + V_{dc_er}(k-1)\} + K_{id}V_{dc_er}(k) \quad (13)$$

where I_{loss} is the current component of active power required to compensate for losses of the D-STATCOM. The PI controller's integral and proportional gain constants for the dc -bus voltage are K_{id} and K_{pd} , respectively. The current loss (I_{loss}) should be supplied by the source in addition to the equivalent filtered D-axis current component computed in equation (10). As a result, I_{ld} is added to I_{loss} and distributed evenly throughout the phases to produce the D-axis component of the reference source current in each phase to ensure that the currents are completely sinusoidal and symmetrical with no ripple in the currents generated due to this. I_{ld} is thus added to I_{loss} and distributed uniformly throughout the phases, resulting in the generation of the reference source current's D-axis component in each phase. (Ponnananthi and Kumar 2015).

$$I_{D\ ph}^* = \frac{\overline{I_{ld}} + I_{loss}}{3} \quad (14)$$

Where $I_{D\ ph}^*$ reflects the active power component after adjustment that needed for compensation. for regulating PCC voltage, it is necessary to inject the current component of reactive power to meet the load demand for reactive power. The AC PI voltage controller estimates the D-STATCOM's reactive power injection currents, which is described as a reactive power component.

The PCC voltage amplitude is compared to the reference voltage determined in Equation (15). The k^{th} sampling moment of the PCC voltage error is represented as $V_{er}(k)$:

$$V_{er}(k) = V_{rms_ref}(k) - V_{rms}(k) \quad (15)$$

If we use V_{rms_ref} as a baseline and $V_{rms}(k)$ as a measure of the amplitude of the ac three-phase voltages at the terminals of PCC k^{th} instant. PCC voltage is expressed as k^{th} sampling instant PI controller's output for reference value:

$$I_Q(k) = I_Q(k-1) + K_{pa}\{V_{er}(k) + V_{er}(k-1)\} + K_{ia}V_{er}(k) \quad (16)$$

where integral and proportional gains of PI controllers are K_{ia} and K_{pa} . The errors at $(k-1)$ and k^{th} instant are $V_{er}(k-1)$ and $V_{er}(k)$, respectively. where current $I_Q(k)$ supplied by the D-STATCOM for the load equivalent to the requirement for reactive power (or Q-axis component). Reference source current required for the system voltage regulation is defined as:

$$I_{Q\ ph}^* = \frac{I_Q - \overline{I_Q}}{3} \quad (17)$$

where $I_{Q\ ph}^*$ stands for the amount of reactive power component. Each phase of the source must be provided with a reactive power component equal to or greater than $I_{Q\ ph}^*$ for the voltage at the reference terminal to be maintained at the desired level. Depending on the loading, $I_{Q\ ph}^*$ might have a negative or positive value. The components of the D-Q-axis of the current generated in Equation (14) and Equation (17) can be used to compute the phases α , α - axis and β -axis of the reference source current. (Ponnananthi and Kumar 2015).

$$\begin{bmatrix} i_{a\alpha}^* \\ i_{a\beta}^* \end{bmatrix} = \begin{bmatrix} \cos \vartheta_a & -\sin \vartheta_a \\ \sin \vartheta_a & \cos \vartheta_a \end{bmatrix} \begin{bmatrix} i_{D\ ph}^* \\ i_{Q\ ph}^* \end{bmatrix} \quad (18)$$

The reference source current is represented by the current on the a -axis of phase a , whereas the current on the b -axis indicates the current at $\pi/2$ phase lag, which corresponds to the fictitious phase. Thus, reference current for phase a , phases b and c is estimate as :

$$I_a^* = I_{D\ ph}^* \cos \vartheta_a - I_{Q\ ph}^* \sin \vartheta_a \quad (19)$$

$$I_b^* = I_{D\ ph}^* \cos \vartheta_b - I_{Q\ ph}^* \sin \vartheta_b \quad (20)$$

$$I_c^* = I_{D\ ph}^* \cos \vartheta_c - I_{Q\ ph}^* \sin \vartheta_c \quad (21)$$

For each phase, the source current (i_{sa} , i_{sb} and i_{sc}) and source reference currents (i_{sa}^* , i_{sb}^* , and i_{sc}^*) are measured and then compared to determine the current error. (Ponnananthi and Kumar 2015).

$$i_{a_err} = i_{sa}^* - i_{sa} \quad (22a)$$

$$i_{b_err} = i_{sb}^* - i_{sb} \quad (22b)$$

$$i_{c_err} = i_{sc}^* - i_{sc} \quad (22c)$$

The D-STATCOM's IGBTs are switched using the PWM pulse generator, receiving these error signals. As a result of the D-STATCOM being pulsed, sinusoidal source currents and a desirable voltage are generated.

3.3. Control Algorithm

3.3.1. SRF D-Q Theory

Theory of instantaneous reactive power (IRP), immediate symmetrical components, Synchronous Reference Frame (SRF) theories, and neural network approaches have all been utilized to control D-STATCOM controllers in various ways. SRF theory, on the other hand, is the commonly utilized control algorithm for 3- ϕ systems. The D-STATCOM's performance is primarily determined by the control method used to retrieve the reference signal. This section extracted the reference signals using SRF or d-q theory. D-STATCOM's performance depends on the way the reference signal is extracted. The *d-q* theory is illustrated in a simplified block diagram in Figure(3.5), which shows how reference source currents can be gleaned.

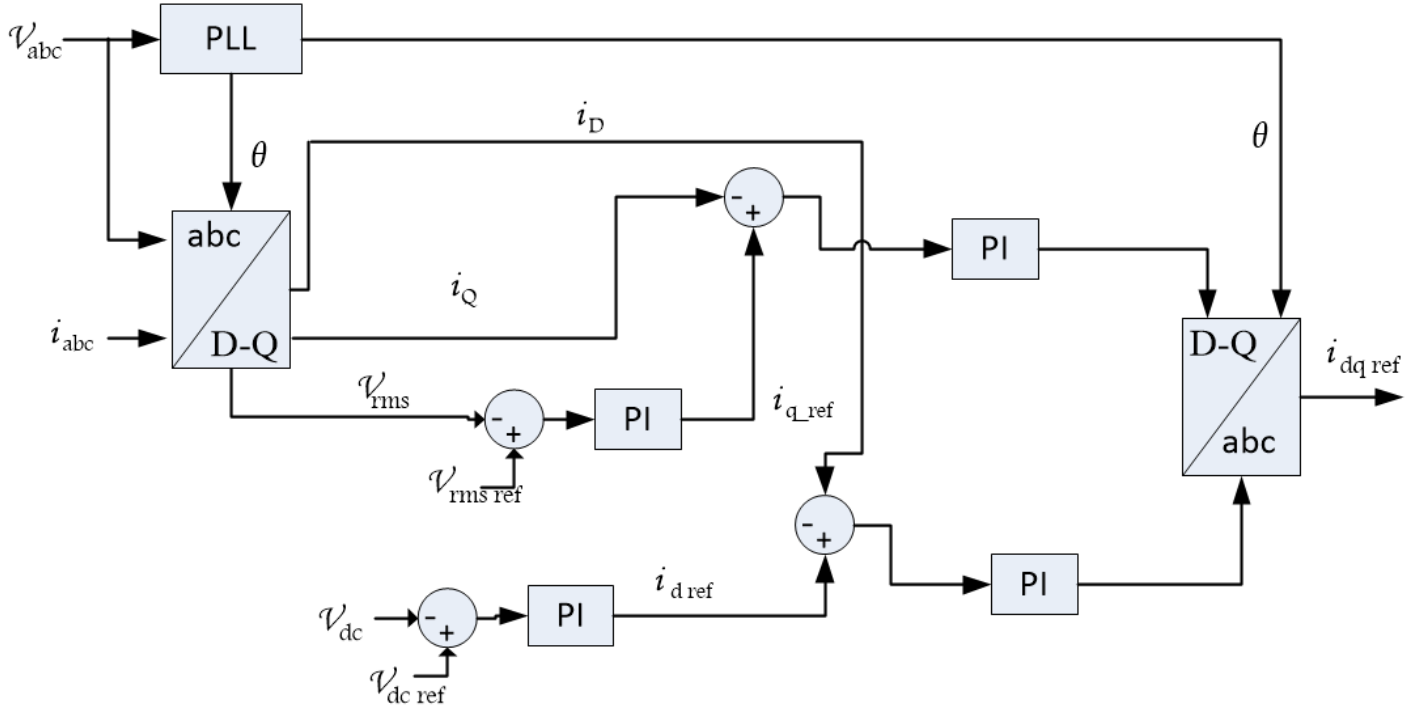


Figure 3.5. Using d-q theory, a simplified block diagram can be used to derive reference source currents.

3.3.2. SPWM Controller and Hysteresis Current Controller

The hysteresis technique is used for current regulation in the inverter since it is easy to implement (Salimi and Zakipour 2012). The control mechanism of Hysteresis Current-Controlled (HCC) pulse-width modulated inverters is the most significant aspect of high-efficiency reactive power compensation systems and AC drives (Salimi & Zakipour, 2012). HCC is a well-known technology due to its ease of development, adaptability to a wide range of load parameters, high current limit, as well as its quick dynamic response and high maximum current. Because the 3- ϕ HCCs are not coordinated, a high switching frequency is still conceivable.

The inverter output voltage can be nearly sinusoidal if the inverter is controlled using SPWM control (Salimi and Zakipour 2012). Where, the Pulse widths vary in proportion to a sine wave amplitude in the center of each pulse, rather than maintaining the same length for all pulses as in multiple pulse width modulation. The distortion factor, as well as the lower order harmonics, have been expressively minimized. A sinusoidal reference signal is compared to a triangular wave of the carrier frequency to generate gating signals. As the frequency of the reference signal determines the inverter's peak amplitude and output frequency, so are the inverter's modulation index M and V_{rms} output voltage V_o , while the modulation index M is used to control the modulation. It is determined by the carrier frequency how many pulses are produced in a half cycle. The input voltage is often stable for inverters that use PWM switching (Maheshri and Khampariya 2014).

AC power can be generated in various ways using pulse-width modulation (PWM). When a sinusoidal control signal and a triangle waveform are combined, the result is a sinusoidal waveform with the desired frequency. Once the inverter detects the triangle wave, it switches on and off at the wave's frequency.

As previously established, the inverter's transient responsiveness and current spectrum are two essential parameters for comparing voltage control and current control. Additional analogies that could be made include:

- a. It is not necessary to have additional equipment to prevent over-currents when using current-controlled inverters, but it is essential for voltage-controlled inverters.
- b. The dc-link voltage must be greater than the highest peak grid voltage to ensure proper current control operation. Voltage control, on the other hand, does not demand this condition.
- c. The dc-link voltage is employed exclusively to define the slope of the increase and decrease in output current during the current control process. Therefore, any fluctuations in the dc-link voltage or harmonic distortion will be disregarded.
- d. It is feasible to generate sinusoidal grid current by inverting harmonic nonlinear load currents in current control (active power filtering).
- e. To achieve voltage balancing across these several dc lines, additional hardware is often necessary for the current control circuit (Salimi and Zakipour 2012).

3.4. Control Configuration

SRF algorithm implementation for extracting reference signals utilized to generate pulses that used in inverter of the D-STATCOM VSC is depicted in Figure 3.6.

3.4.1. SRF D-Q Controller Theory

As described in an earlier section, synchronous reference frame theory (SRF) governs VSC control based on an estimation of the current reference. A simplified explanation for SRF theory can be expressed as follows, based on the transformation of load currents in a synchronously rotating DQ frame. The measured signals for this control system are illustrated in Figure 3.6.

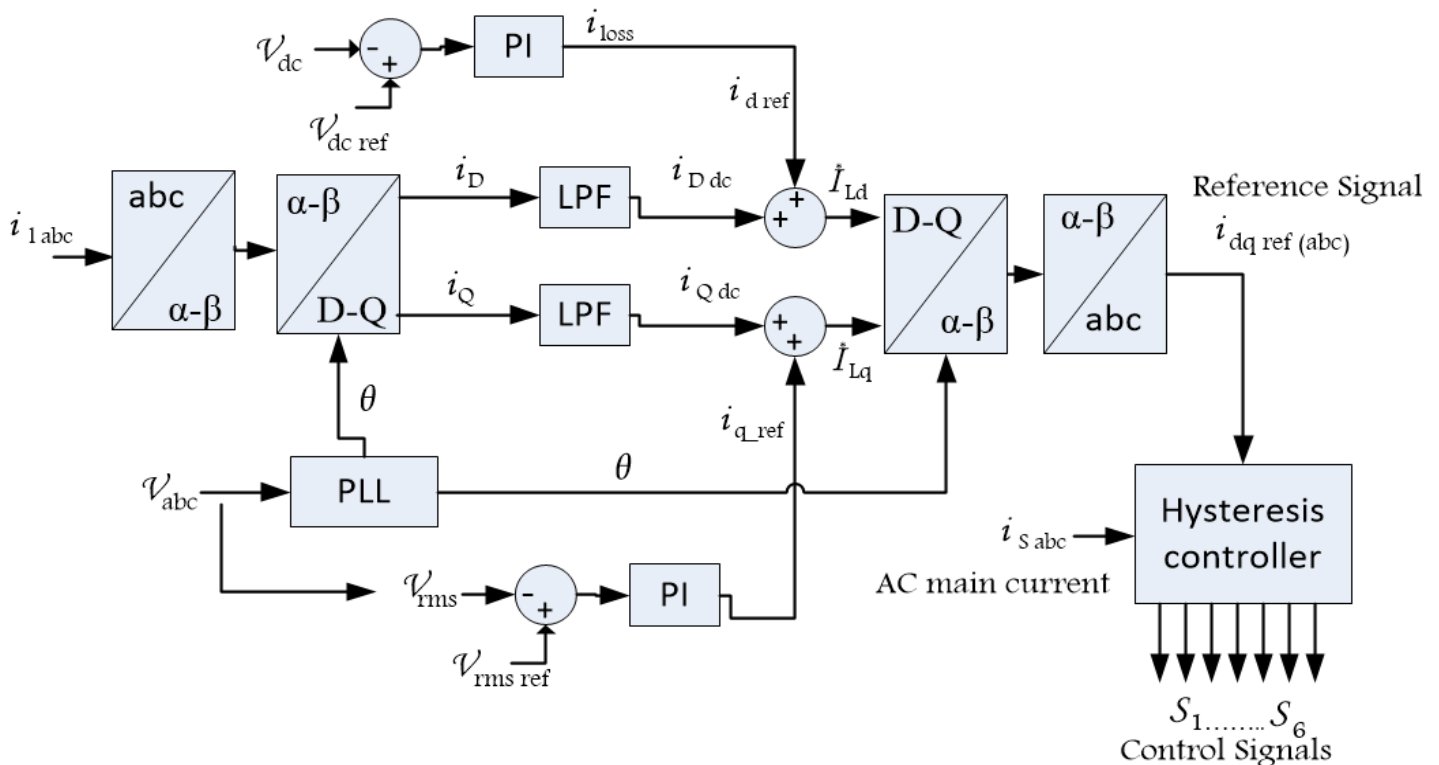


Figure 3.6. Diagrammatic representation of a control technique based on SRF for obtaining reference source currents (Reddy, Prasad, and Srinivas 2018)

Voltages at PCC (V_{abc}), the load currents ($i_{l\ abc}$), and voltages at DC bus (V_{dc}) of VSC are sensed as input signals. The control approach for reactive power compensation assumes that the supply must deliver both the dc and active components of the direct-axis component of load current (i_{d_DC}) to keep the dc bus satisfying the losses (i_{loss}). A PI controller maintains the VSC dc-link voltage at a predetermined level. As a result, the PI controller creates a compensatory current signal. (Reddy et al. 2018)

$$i_{loss} = K_{id}v_{dc_er}(n) + \{v_{dc_er}(n) - v_{dc_er}(n-1)K_{pd}\} + i_{loss}(n-1)$$

where $v_{dc_er}(n) = v_{DC_ref}(n) - v_{DC}(n)$ is the error due to the difference between the sensed value and referenced DC voltage values at the n^{th} iteration. K_{pd} and K_{id} denote the PI controller's proportional and integral gain constants for DC bus voltage and that can be calculated by

$$K_{pd} = 2\delta C_{Dc} \text{ and } K_{id} = w_n^2 C_{Dc} \quad (23)$$

$$\text{Where } w_n = \frac{f_c}{5\delta} \text{ and } \delta = tg^{-1}\left(\frac{v_q}{v_d}\right) \quad (24)$$

where f_c is modulation frequency, v_q and v_d is D-STATCOM D-Q voltage, C_{Dc} is D-STATCOM DC capacitor (Kerrouche et al. 2020), (Application Note 2009).

Figure 3.6 depicts the SRF control algorithm's block diagram. The control algorithm obtains fundamental reference control signals from the VSI-based D-STATCOM for use in voltage regulation.

In a $3-\phi$ system, for compensation purposes, active and the reactive components of currents are separated. The Equation of Clark's

transformation converts the 3- ϕ load currents into a two-phase stationary $\alpha - \beta - 0$ axis. (Reddy et al. 2018)

$$\begin{bmatrix} i_{L0} \\ i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (25)$$

Park's transformation equation transforms the α - β -0 stationary current axis into a spinning d - q -0 frame reference.

$$\begin{bmatrix} i_0 \\ i_D \\ i_Q \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \vartheta & \sin \vartheta \\ 0 & -\sin \vartheta & \cos \vartheta \end{bmatrix} \begin{bmatrix} i_{L0} \\ i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \quad (26)$$

The angle of transformation is denoted by ϑ . A voltage source's 3- ϕ PLL block (phase-locked loop) yields $\sin \vartheta$ and $\cos \vartheta$, which are used to synchronize current and voltage. (Reddy et al. 2018)

The terms "instantaneous reactive and active load current components" refer to the i_Q and i_D current components. Each component of current has an oscillating value (the alternating component) and an average value (the dc component), as defined by the equations (27) and (28).

$$i_D = i_{D_{dc}} + i_{d_{ac}} \quad (27)$$

$$i_Q = i_{Q_{dc}} + i_{q_{ac}} \quad (28)$$

The dc component is represented by $i_{d_{dc}}$ and $i_{q_{dc}}$ and i_{Lq} and oscillating or the ac component is represented by $i_{d_{ac}}$ and $i_{q_{ac}}$.

It appears as ripples when the oscillatory or harmonic component is present. After removing the oscillatory current component by the use of a low pass

filter, the reactive current and average active components are given in equations (29) and (30).

$$i_{Ld} = i_{D_dc} \quad (29)$$

$$i_{Lq} = i_{q_dc} \quad (30)$$

The PI controller output current is taken as the component of the loss current (i_{Loss}). This component is added to the active reference current component of the d- axis in the D-Q frame. A power source is utilized to maintain a steady DC link voltage and supply power to the D-STATCOM system's losses. Then the current component of the active reference is (Reddy et al. 2018)

$$i_{Loss} = I_{Ld}^* - i_{D_dc} \quad (31)$$

An analogous source of reactive current (i_{q_ref}) is required to regulate the voltage at PCCs in the same way that direct current (i_{Q_dc}) has to deliver reactive current (i_{q_ref}). It is applied to a reference component of average reactive current (i_{q_dc}) for use in *D-Q* frames. The reactive component of reference current that results, as a result, is then

$$i_{q_ref} = i_{Lq}^* - i_{Q_dc} \quad (32)$$

A controller's PI output is utilized to figure out reactive currents (i_{q_ref}), and the amplitude of the voltage V_{rms} is subtracted from V_{rms_ref} before being sent into the PI controller. The PCC voltage's amplitude is denoted by: (Reddy et al. 2018)

$$V_{rms} = \sqrt{\frac{2(V_a^2 + V_b^2 + V_c^2)}{3}}$$

The symbol represents the PI controller's output:

$$i_{q_ref}(n) = i_{q_ref}(n-1) + K_{pq} \left(V_{rms_er}(n) - V_{rms_er}(n-1) \right) + K_{iq} V_{rms_er}(n)$$

where $V_{rms_er}(n) = V_{rms_ref}(n) - V_{rms}(n)$ is the error due to the difference between the sensed value and referenced of PCC voltage amplitude at the n^{th} iteration. K_{pq} and K_{iq} denote the PI controller's proportional and integral gain constants and that can be calculated by

$$K_{pq} = 2\delta - \frac{R_{st}}{L_{st}} \text{ and } K_{iq} = w_n^2 \quad (33)$$

$$\text{Where } w_n = \frac{f_c}{5\delta} \text{ and } \delta = tg^{-1} \left(\frac{v_q}{v_d} \right) \quad (34)$$

where f_c is modulation frequency, v_q and v_d is D-STATCOM D-Q voltage R_{st} and L_{st} D-STATCOM impedance (Kerrouche et al. 2020), (Application Note 2009).

For the PCC voltages and the active power component of reference AC currents to be in phase, there has to be a phase difference. This is accomplished by reversing Park's change. (Reddy et al. 2018)

$$\begin{bmatrix} i_{dq_ref\ a} \\ i_{dq_ref\ b} \\ i_{dq_ref\ c} \end{bmatrix} = \begin{bmatrix} \cos \vartheta & \sin \vartheta & 1 \\ \cos \left(\vartheta - \frac{2\pi}{3} \right) & \sin \left(\vartheta - \frac{2\pi}{3} \right) & 1 \\ \cos \left(\vartheta + \frac{2\pi}{3} \right) & \sin \left(\vartheta + \frac{2\pi}{3} \right) & 1 \end{bmatrix} \begin{bmatrix} i_{Ld}^* \\ i_{Lq}^* \\ i_o^* \end{bmatrix} \quad (35)$$

The proportional controller amplifies the current error in each phase before comparison with a triangle carrier signal, which generates the gating signals for six IGBT switches in D-STATCOM's VSC and compares with the triangle carrier signal.

3.5. System Control Operation of D-STATCOM

The voltage source converter (VSC) with six inductively coupled bipolar transistors (IGBTs), a DC energy storage, and three inductors that are shunt linked, as illustrated in Figure 3.7. It is possible to think of D-STATCOM as a synchronous compensator (or condenser) that can supply variable voltage regulation and reactive power of the bus to which it is connected. D-STATCOM can provide a more rapid energy response than the synchronous compensator. The 3- ϕ voltages generated from D-STATCOM are connected to the utility grid. Correction of the magnitude and phase of the D-STATCOM output voltage enables enhanced regulation of the reactive and real power flow between the D-STATCOM output voltage and the utility grid, resulting in increased grid stability.

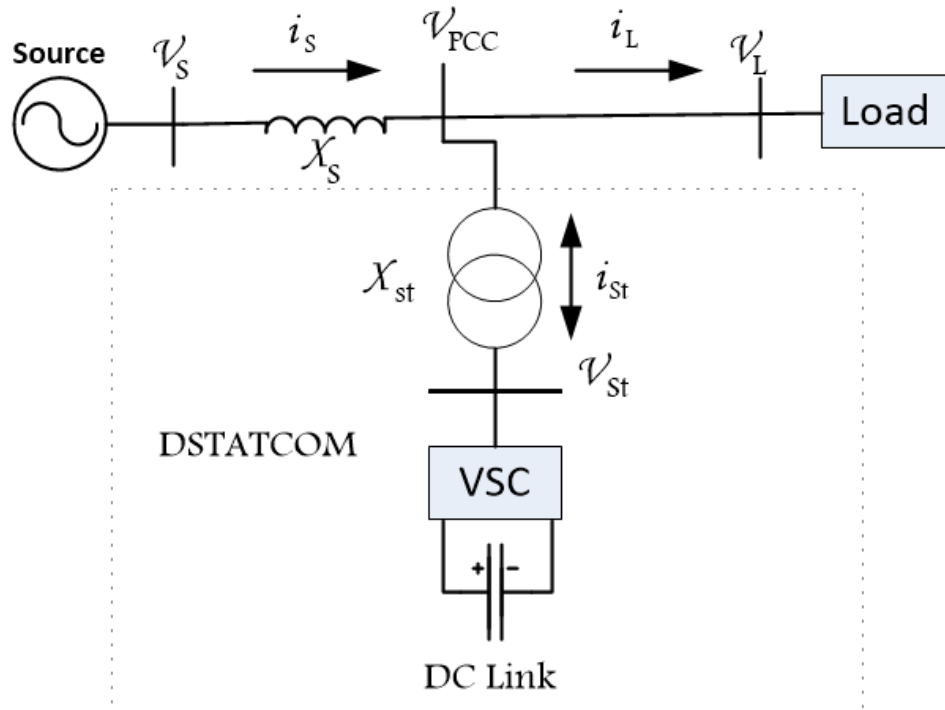


Figure 3.7. D-STATCOM connected to the power system (A. R. Gidd et al. 2019).

No active or reactive power flows among the domestic grid and D-STATCOM if $V_L = V_{st}$. D-STATCOM functions as a capacitive reactance when $V_L < V_{st}$. In this situation, the current and the capacitive reactive power flow from D-STATCOM to the utility grid. D-STATCOM behaves as an inductive reactance linked to its output with a voltage difference $V_L > V_{st}$.

D-STATCOM equations for reactive and real power exchange are as follows: (A. R. Gidd et al. 2019).

$$P = \frac{V_{st} V_{pcc} \sin \delta}{X_{st}} \quad (41)$$

$$Q = \frac{V_{pcc}^2}{X_{st}} - \frac{V_{st} V_{pcc}}{X_{st}} \cos \delta \quad (42)$$

The D-STATCOM's output current is supplied as:

$$I_{st} = \frac{V_{st} - V_{pcc}}{jX_{st}} \quad (43)$$

Where, V_{st} are the voltage of D-STATCOM, V_{pcc} is the point of common coupling voltages and X_{st} total line reactance.

Model parameters for the VSC DC bus voltage model contain the following values: the DC bus voltage, the voltage to run capacitance, and the switch ratings. When utilizing D-STATCOM's VSC, the minimum DC bus voltage required should be greater than twice the maximum peak phase voltage of the distribution system, according to the manufacturer (Kumar, Kumar, and Sreenivasarao 2019). According to this formula, the voltage of the DC bus can be determined as:

$$V_{dc} = \frac{\sqrt{2}}{\sqrt{3}m} 2V_{pcc} \quad (44)$$

where m denotes the modulation index. In most cases, it is presumed to be 0.8 or 1.

The design of the DC bus capacitor employed is determined by the amount of instantaneous energy made accessible to the D-STATCOM during the transient period of operation. As an example of how the energy conversion concept is put into action, consider the following: (A. R. Gidd et al. 2019).

$$3VK\alpha It = \frac{(V_{dc}^2 - V_{dc1}^2) C_{dc}}{2} \quad (45)$$

where the value of the capacitor C_{dc} is in Farad, the overloading factor is denoted by α , phase voltages are described by V , phase current is denoted by I , DC nominal voltages are V_{dc} , minimum level of DC voltages are V_{dc1} , and the amount of time needed to restore the DC bus voltage is denoted by t . L_f is chosen based on I_{cr} ripple current, f_s switching frequency, and V_{dc} bus voltage, which are all factors in determining the inductance of VSC. (A. R. Gidd et al. 2019).

$$L_f = \frac{\sqrt{3}m}{12f_s\alpha I_{cr}} V_{dc} \quad (46)$$

The high-pass filter is set to reduce the switching ripples and noise generated by the PCC.

3.6. D-STATCOM Regulation Controller

3.6.1. DC Link Voltage Regulation

Creating the compensating reference current is critical to D-STATCOM's performance and quality. Where the key factor in the dc-link is the voltage regulation controller. There are two ways to compensate for compensatory current: decreasing or increasing the dc-link voltage (v_{dc}). A particular

reference value on the inverter's dc side is required to ensure proper VSI operation. Maintaining a steady dc-link voltage reduces the VSI switching. As a result of the rotating frame theory, the mean active current factor (i_{D_dc}) must be added to the dc-link voltage to keep it stable. The following controllers will be compared:

- a. Conventional PI control
- b. Artificial Neural Network control (ANN)
- c. Artificial Neural Fuzzy control (ANFIS)

Figure 3.8. depicts a block schematic of the PI controller with its components. This expression refers specifically to the internal design of the control circuit. To supply losses in the D-STATCOM, it is necessary for the source to deliver both the loss reference current component (i_{loss}) and the active reference current component (i_D).

To compute the component of current loss reference at the n^{th} sampling instant, it is required to compare the reference dc bus voltage v_{dc_ref} to the real dc bus voltage v_{dc} at the n th sample moment:

$$v_{d_er}(n) = v_{dc_ref}(n) - v_{dc}(n) \quad (47)$$

To compute the loss component (i_{loss}), the comparing error signal $v_{de}(n)$ is processed through the PI controller.

$$i_{loss}(n) = i_{loss}(n - 1) + K_{pd} \left(v_{d_er}(n) - v_{d_er}(n - 1) \right) + K_{id} v_{d_er}(n) \quad (48)$$

The PI controller output is the D-STATCOM loss reference (i_{loss}). By adding i_{loss} to the average active reference component (i_D) is used to regulate the active reference component of current (I_{Ld}^*) in this manner.

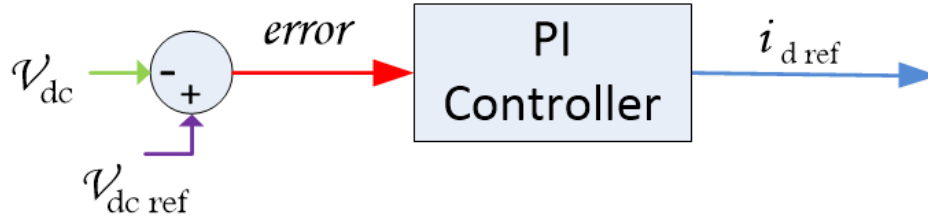


Figure 3.8. PI control diagram

3.6.2. AC Voltage Regulation

D-STATCOM will regulate the voltage of the PCC bus and keep its level of the reference voltage V_{rms_ref} . A PI controller is employed in this scenario (as shown in Figure 3.9), where PCC bus voltage magnitudes is V_{rms} . To determine the error, where the V_{rms_ref} and V_{rms} are compared. The PI controller then uses the erroneous value. The quadrature axis component's reference to the D-STATCOM current i_{q_ref} , which is applied to the inner current loop, is derived from this error signal. When V_{rms_ref} exceeds V_{rms} , D-STATCOM attempts to inject reactive power to boost V_{rms} . Reactive power is absorbed by D-STATCOM when the value of V_{rms_ref} is smaller than V_{rms} to reduce the value of V_{rms} .

In this voltage regulator, the performance of the following controllers will be compared:

- a. Conventional PI control
- b. Artificial Neural Network control (ANN)
- c. Artificial Neural Fuzzy control (ANFIS)

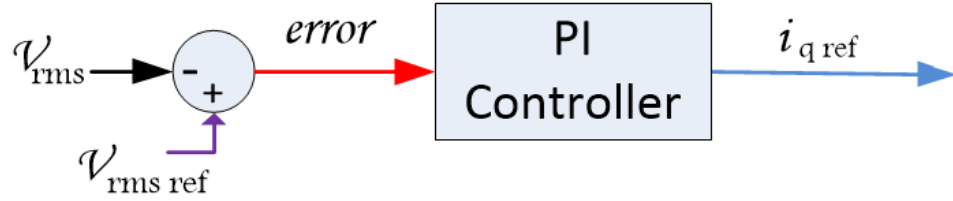


Figure 3.9. AC voltage controller

3.6.3. Phase Locked Loop (PLL) Controller

Three fundamental parts of a conventional SRF PLL: low pass filter, phase detector, and voltage regulated oscillator. V_{abc} is converted to corresponding quadrature and direct voltage components (V_d and V_q) via the phase detector. The direct voltage component V_d equals the phase voltages amplitude V_{abc} when the phase voltages are not distorted. Figure 3.10 shows an example of a PI controller using a zero-voltage reference to implement the filter. The phase angle of a system is found by employing the SRF-PLL (Single-Resonance-Frequency-PLL).

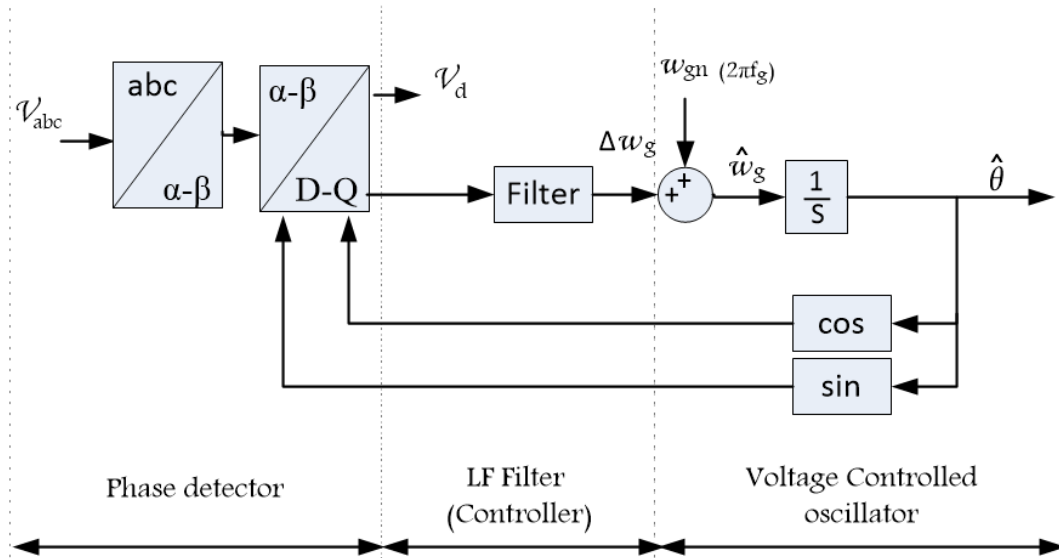
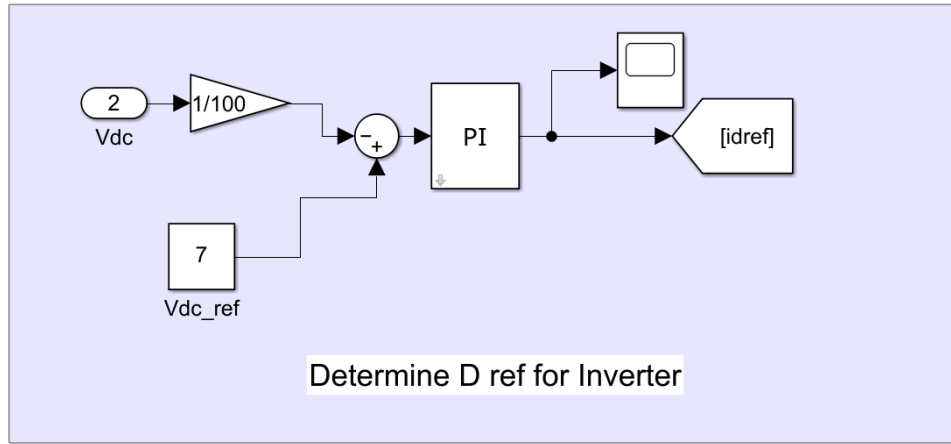


Figure 3.10. An example of a PID or PI controller using a zero-voltage reference to implement the filter.

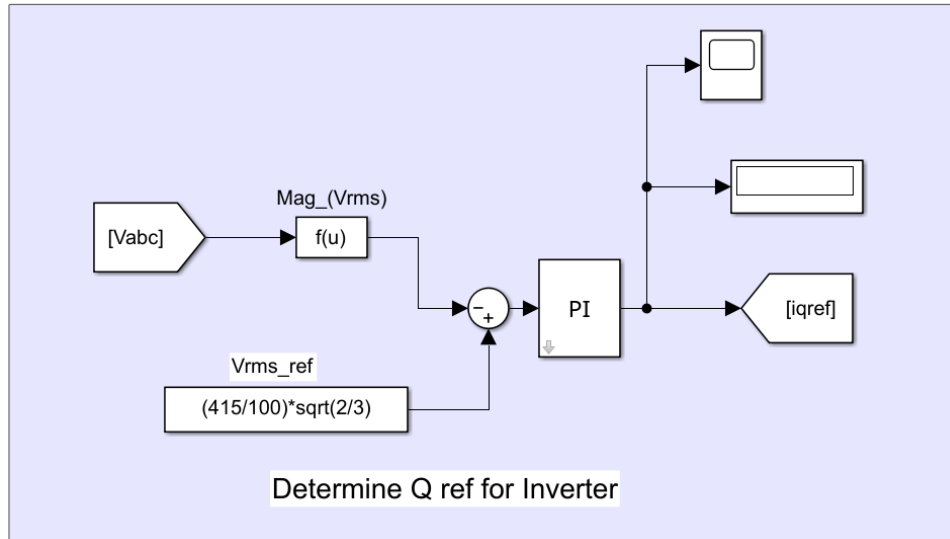
3.7. D-STATCOM Regulation Controller in MATLAB

3.7.1. PI Control

The block diagram of the PI controller is depicted in Figure 3.11 (a). To supply losses in the D-STATCOM and filter, the source must deliver both the active reference current component (i_{d_ref}) and the loss reference current component (i_{Loss}). Current losses (i_{Loss}) are determined by comparing v_{dc} and v_{dc_ref} at the sampling instants (n^{th} sampling instants) to determine which one is greater.



(a)



(b)

Figure 3.11. (a). Block diagram of Id PI control (b). Block diagram of Iq PI control

The PI controller is employed and is shown in Figure 3.11 (b). To determine the error, the V_{rms_ref} and V_{rms} voltages of PCC bus magnitudes are compared. The reference quadrature axis component of the D-STATCOM current (i_{q_ref}) is provided by this error signal, which is applied to the D-STATCOM's inner current loop through the D-STATCOM's error signal.

3.7.2. Artificial Neural Network (ANN)

Artificial Neural Networks (ANNs), which are adaptive techniques with incredible information-processing capabilities, comprise layers of neural nodes that communicate with one another. The layered structure of ANN is demonstrated in Figure 3.12. The ability to integrate nonlinearities that are not readily visible in the inputs allows them to learn and adapt to new conditions as well as learn and adapt to varied surroundings when presented with nonlinearities that are not readily obvious in the inputs (Reyneri 2003). It is desired for artificial neural models to have certain qualities for the following reasons: (a) better data fit is made possible by nonlinearity, (b) in the presence of unclear data and measurement errors, noise insensitivity leads to accurate forecasting, (c) with more parallelism comes increased speed, and greater hardware fault tolerance, (d) learning and adaptability make it possible for the system to respond to changes in its surroundings by changing its internal structure and (e) the model can be applied to previously unrecognized data through generalization (Cheol-Taek Kim and Ju-Jang Lee 2008).

When creating a neural network, the essential building pieces are called "neurons," and they are organized in a specific pattern depending on the number of layers in the network. The weights of all of the neurons in a layer are determined by the weights of the neurons in the layer above them. The

formation of a neural network is created by an “input” layer, one or quite one “hidden” layer(s), and also the “output” layer. (Rana et al. 2018b).

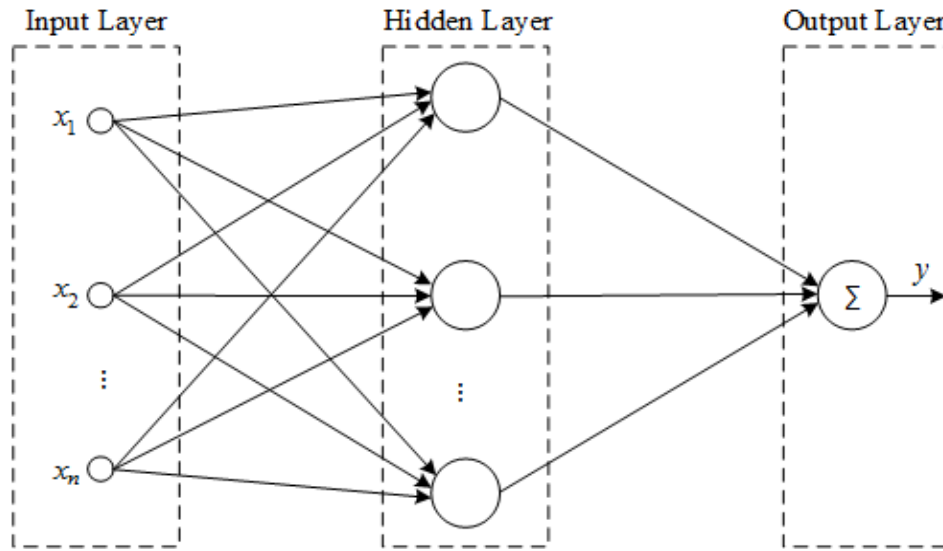


Figure 3.12. Artificial neural network

3.7.3. Adaptive Neuro-Fuzzy Inference System (ANFIS)

ANFIS combines the ability of ANN to learn and its relational structure with the ability of fuzzy logic to make decisions. As with ANN, ANFIS uses samples to learn from a training data set. Therefore, the optimal ANFIS structure for handling the relevant issue is discovered. The resulting structure is put through its paces to assess how it performs with samples that have never been encountered before. The ANFIS model's lower error rates prove its suitability. In an artificial neural network, the weight values cannot be justified, as the inability to explain the value of the weights belonging to an ANN model is a disadvantage. Due to this significant problem, the ANFIS framework has a fuzzy inference technique that eliminates this drawback. Many real-world problems can be solved because of their structure (Karaboga and Kaya 2019a).

There are two types of parameters in the ANFIS framework: consequence and premise. An optimization approach is used in training ANFIS to determine these parameters. These parameters are computed using least squares estimation (LSE) and gradient descent (GD) methods, respectively. To achieve the most significant results using ANFIS, selecting the most appropriate optimization approach for the situation is necessary. In ANFIS training, both derivative-based (GD, LSE, etc.) and non-derivative-based (heuristic algorithms like GA, PSO, ABC, etc.) algorithms are employed. (Karaboga and Kaya 2019b).

The advantages of ANFIS is that it is a hybrid system that combines the advantages of artificial neural networks with those of fuzzy inference methods to provide a complete picture. It is able to capture a process's nonlinear structure, rapid learning capabilities, and adaptability. The ANFIS has been used in various fields, including anticipating passenger demand, economics, the environment, and energy (Şahin and Erol 2017).

Figure 3.13 shows the layered structure of ANFIS. Where the first layer is the fuzzification layer, the crisp numerical values are fuzzified with respect to the firing strength of the membership function. When it comes to practical problems, membership functions are a good method to solve them by experience rather than through knowledge. The membership functions include trapezoidal, Gaussian, and triangular shapes, among others. In the second layer of the controller, rules are applied to the fuzzified values of layer 1. Normalized firing strengths are used to distinguish between this layer's individual rule firing strengths and the total rule firing strengths. In the third layer, an aggregate of all outputs of layer 2 is calculated, and finally, these

fuzzy outputs are again retranslated into crisp numerical values. This process is called defuzzification.

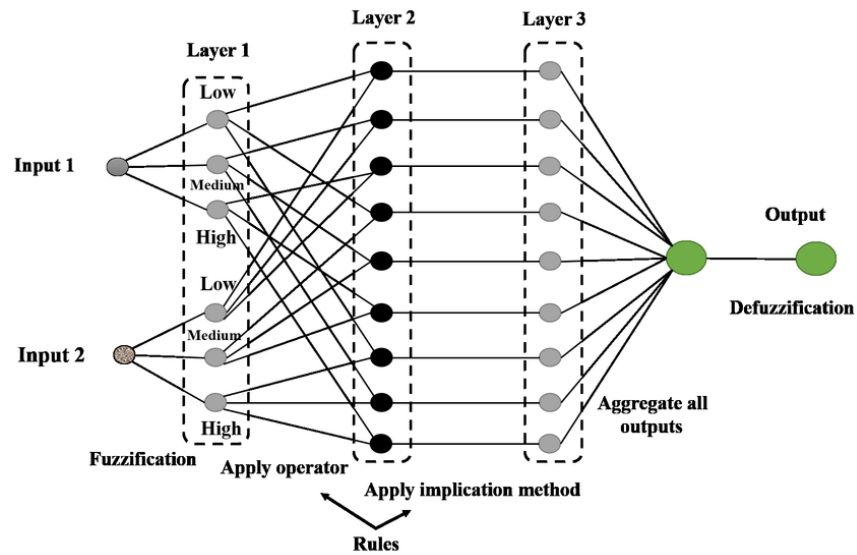


Figure 3.13 Layered structure of ANFIS (Aleem et al. 2017)

Chapter 4: Simulation and Results

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4.1. Introduction

This chapter explains the power system model and the Distribution static synchronous compensator (D-STATCOM). The simulation was carried out on the Lenovo T490, Core-i55, with 16 GB of RAM using MATLAB 2021a software. A comparison of proposed controllers (PI, ANN, and ANFIS) is also presented in this chapter.

4.2. Electric Power System Model

An electric distribution network system with an integrated renewable energy system is modeled and simulated in MATLAB/Simulink. Figure 4.1 illustrates the simulated electrical system, which consists of a voltage source representing the grid with a 90kW solar PV array, a distribution transformer, a D-STATCOM, and six different loads. The key parameters are adapted from a research work published in (Al-Shetwi et al. 2020). The details of the study system are presented in the following subsections.

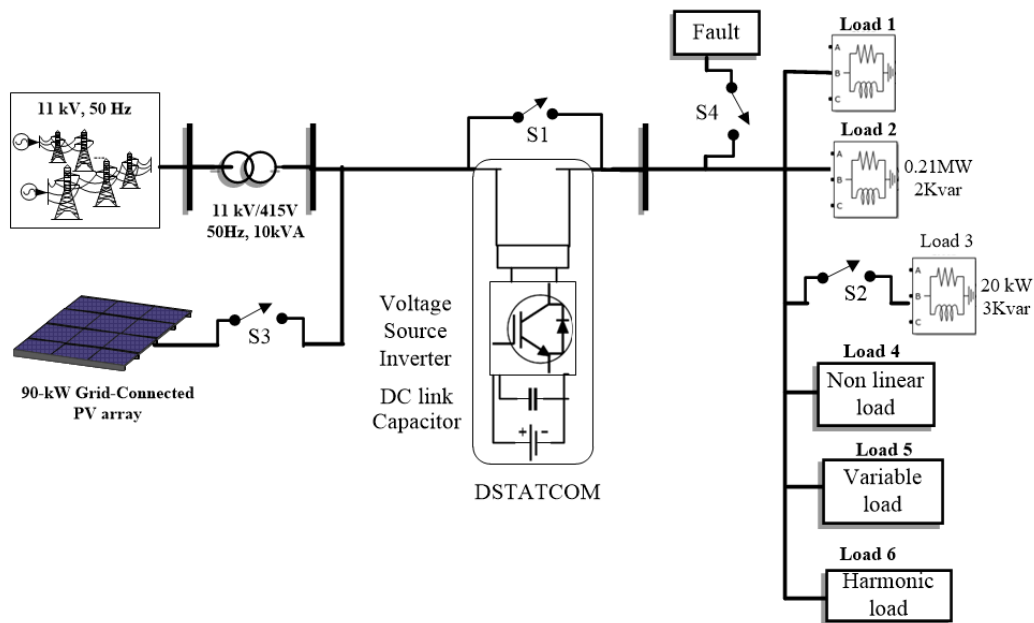


Figure 4.1. Block diagram of the power system model with D-STATCOM integrated with PV System.

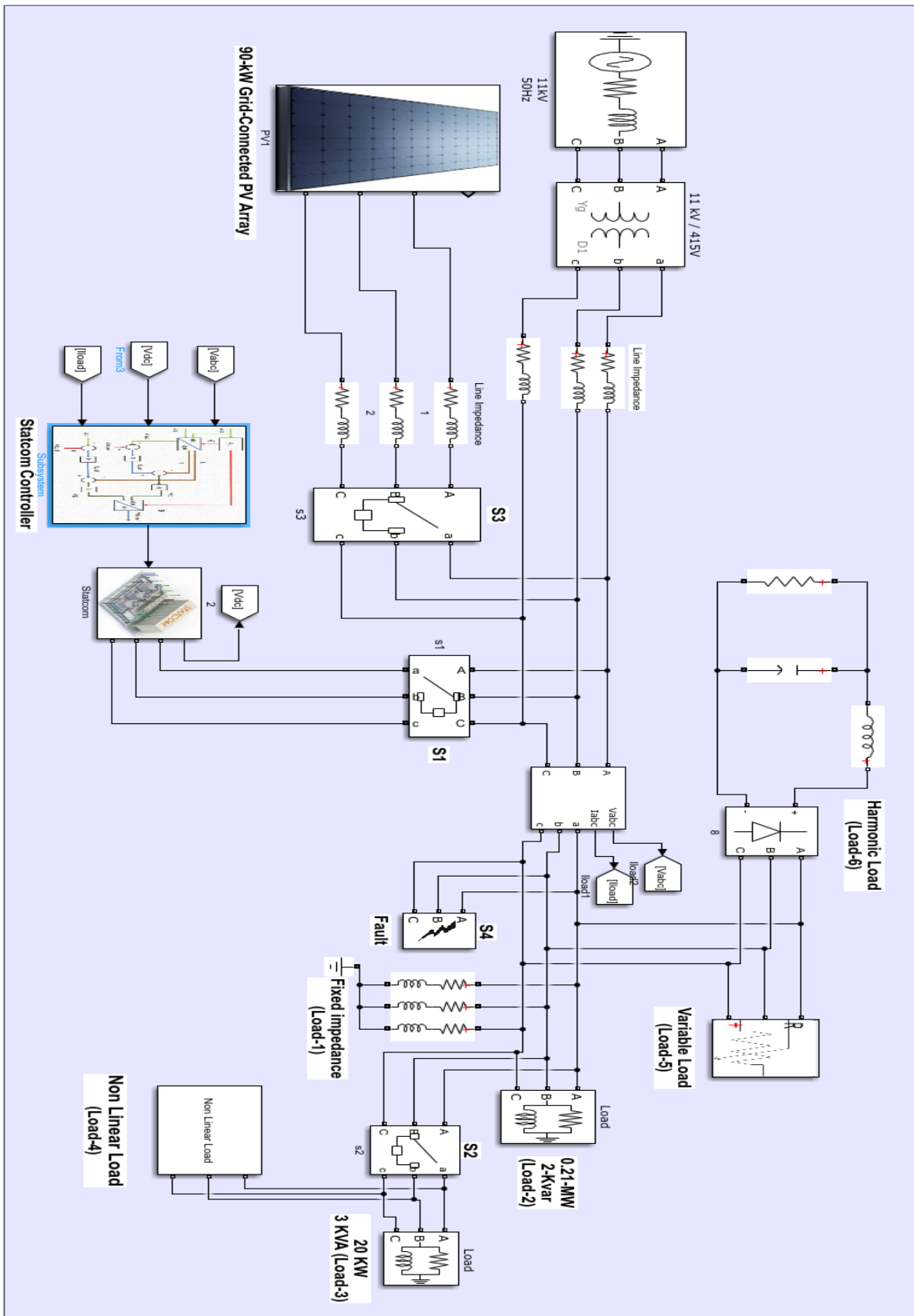


Figure 4.2. Simulated power system model with D-STATCOM integrated with 90 kW Grid-connected PV array.

A control signal is fed to the D-STATCOM through proposed supplementary controllers to smooth the voltage profile, mitigate the power quality concerns, mitigate the effect of different loading conditions, and reduce THD in compliance with the required standards. The D-STATCOM is connected to the power supply for voltage support at a common coupling node, as it is absorbing or generating reactive power. The exact simulated system layout in MATLAB/Simulink is presented in Figure 4.2.

4.2.1. Power Supply

The adopted power supply in the simulation model is a three-phase AC voltage with a short-circuit capacity of 31 MVA, and the actual line voltage value is 415 V / 50Hz (EWA 2021). A transmission line is used to transfer power to the loads; with impedance of $R=0.01 \Omega$, $L=1 \times 10^{-3} \text{ H}$.

4.2.2. System Loads

Six different electrical loads are active in the different time slots, and their details are presented in Table (4.1)

Table (4.1): Different load types and parameters used in the simulation

Load Number	Active Time	Load Type	Parameters
Load 1	0-12s active	Fixed Impedance Load	Phase A: ($15 \Omega + j 11 \Omega$)
			Phase B: ($30 \Omega + j 15 \Omega$)
			Phase C: ($60 \Omega + j 65 \Omega$)
Load 2	0-12s active	Constant Active and Inductive power load	Active power 0.21 MW + inductive reactive power 2k VAR

Load 3	2-8s active	Constant Active and Inductive power load	Active power 20 kW + induction reactive power 3k VAR
Load 4	2-8s active	Non-linear load (using bridge-connected diodes parallel RLC branch link)	200 ohm, 1×10^{-3} H , 600×10^{-6} F
Load 5	0-12s active	Variable load	The mean load value is 7Ω with a standard deviation ± 1
Load 6	0-12s active	Non-linear (harmonic) load	150Ω , 500×10^{-6} F

4.2.3. PV System

The PV system employed in the simulation has 20 parallel PV strings and 22 series PV modules, where the maximum power (peak) for each PV module is 213.15W at STC. Therefore, the approximate total power generated by the PV system is 90kW ($20 \times 22 \times 213.15\text{W}$) at the maximum irradiation at STC (Nkambule, Hasan, and Ali 2019) and that around 30% of total power consumption of the system. The PV system is connected with a DC-DC boost converter to a maximum power point tracker (MPPT) to ensure maximum power generation from the PV system. The DC voltage is converted to AC through an inverter using pulse-width modulation (PWM) of 1k Hz frequency. Figure 4.3 shows the internal structure of the modeled PV system in MATLAB/Simulink.

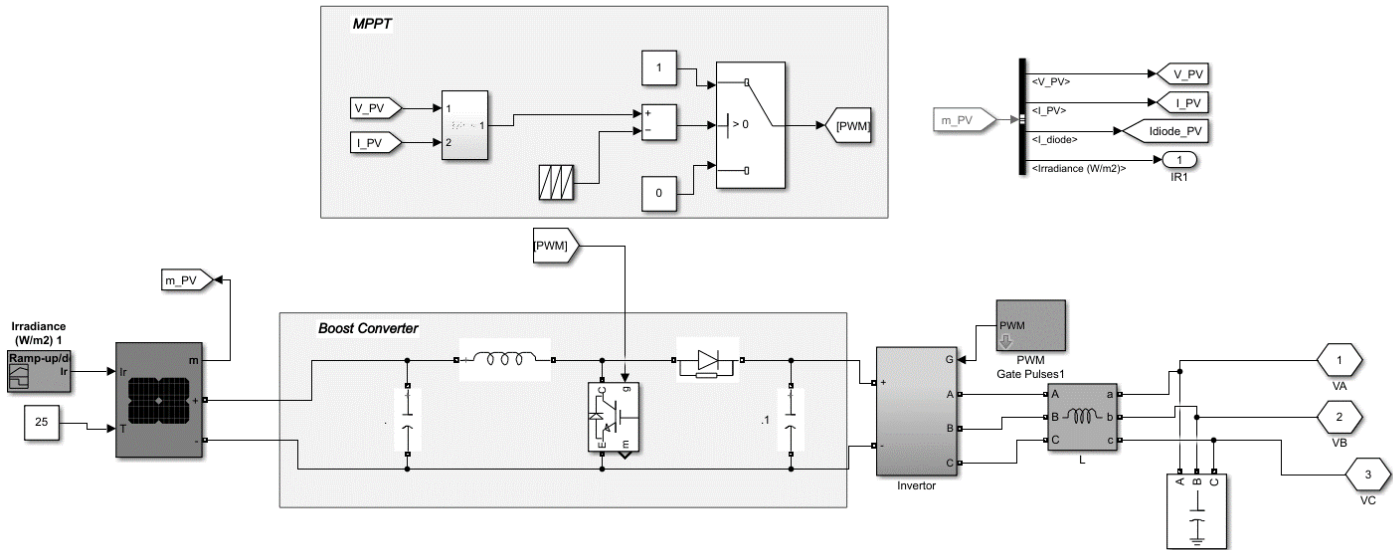


Figure 4.3. The internal structure of the PV system model in MATLAB

The PV system is activated at time 2.5s and deactivated at time 11s for simulation purposes. The PV irradiation is changed with different irradiation values in order to simulate changes in irradiation and their effect on the grid network, as shown in Figure 4.4. The solar irradiance of 1000 W/m^2 is used from time 0 - 6 s, and then reduced to 500 W/m^2 for $t = 6 - 10 \text{ s}$ and then

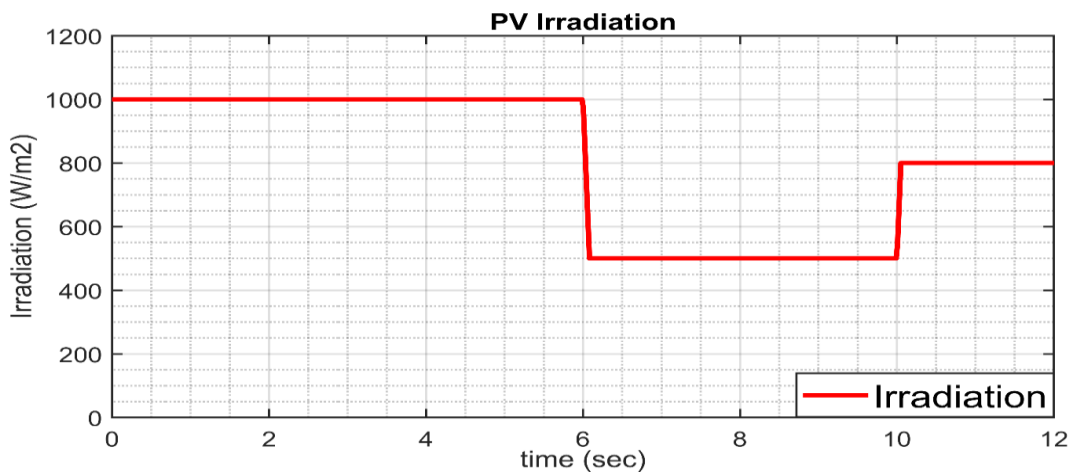


Figure 4.4. Solar PV irradiance Graph

increased again to 800 W/m^2 . The change in solar irradiance is necessary to incorporate the intermittency of sunlight due to the diverse weather like sunny and overcast conditions.

4.2.4. Simulation Fault

A two-phase to ground fault is applied to simulate the effectiveness of the different controllers under contingency conditions. For this purpose, a simulation fault is active between phases A & B and ground (ABG fault) at time 5s for 6.8 ms with fault resistance $R_{on} = 8 \Omega$ and ground resistance 0.01Ω .

4.3. D-STATCOM

D-STATCOM is used to regulate the voltage of the electric power system, and it contains a DC/AC inverter and a D-STATCOM D-Q controller, as shown in Figure 4.5. D-STATCOM DC/AC inverter is connected on one side to the coupling through the filter and on the other side to the capacitors.

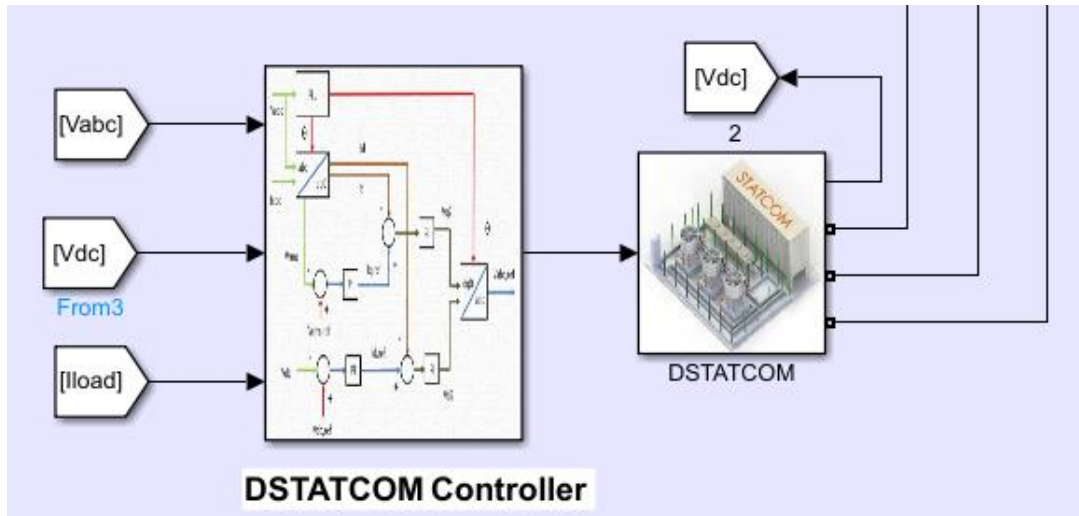


Figure 4.5. D-STATCOM Controller modeled in MATLAB/Simulink

The DC voltage source remains constant by controlling the capacitor voltage, as the capacitors ($10000 \times 10^{-6} \text{ F}$) store reactive power and play the role of a

constant voltage source (700 V), which it forms a three-phase alternating voltage as shown in equation (4-1).

$$\text{The RMS Voltage} = \left(\frac{700}{2}\right) \sqrt{\left(\frac{3}{2}\right)} = \sim 415V \quad (4-1)$$

4.4. D-STATCOM Controller

The D-SATCOM has main three modules: AC controller, DC Regulator, and Voltage Source Converter (VSC) (Ali, Khan, and Raja 2014).

4.4.1. DC Voltage Regulator

The DC voltage regulator is shown in Figure 4.6 where the DC voltage (Vdc) is compared with the reference voltage ($V_{dc-Ref} = 700$) so that the error signal entering the PI controller can be obtained, and the Id-ref can be extracted from the PI controller.

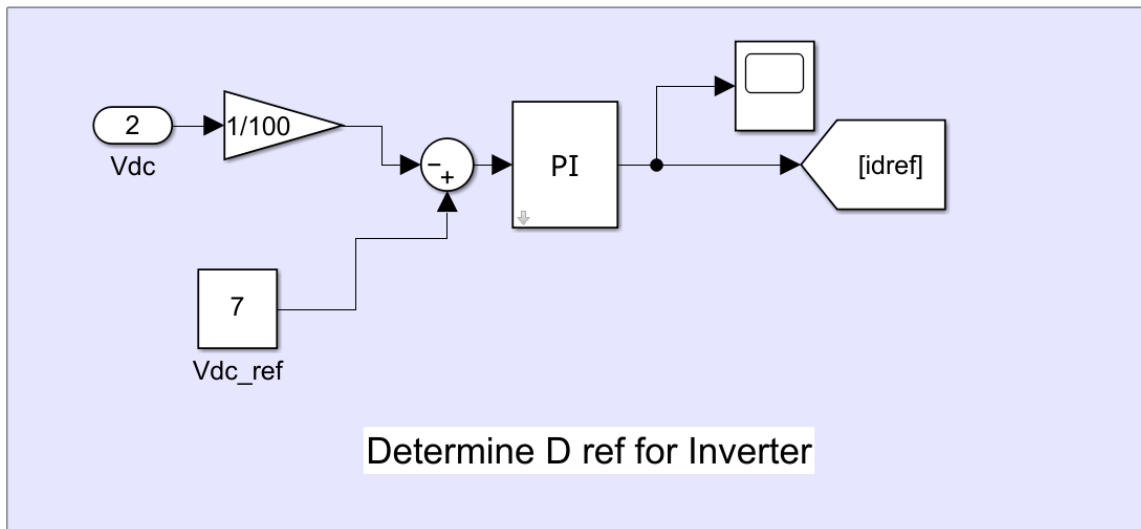


Figure 4.6. DC voltage regulator

4.4.2. AC Voltage Regulator

The AC voltage regulator is shown in Figure 4.7, where V_{rms} the magnitude of the AC voltage (V_{abc}) is compared with the reference voltage of $V_{rms_ref} = (415 * \sqrt{2/3})$ so that the error signal entering the PI controller can be obtained, and the I_q -ref can be extracted from the PI controller.

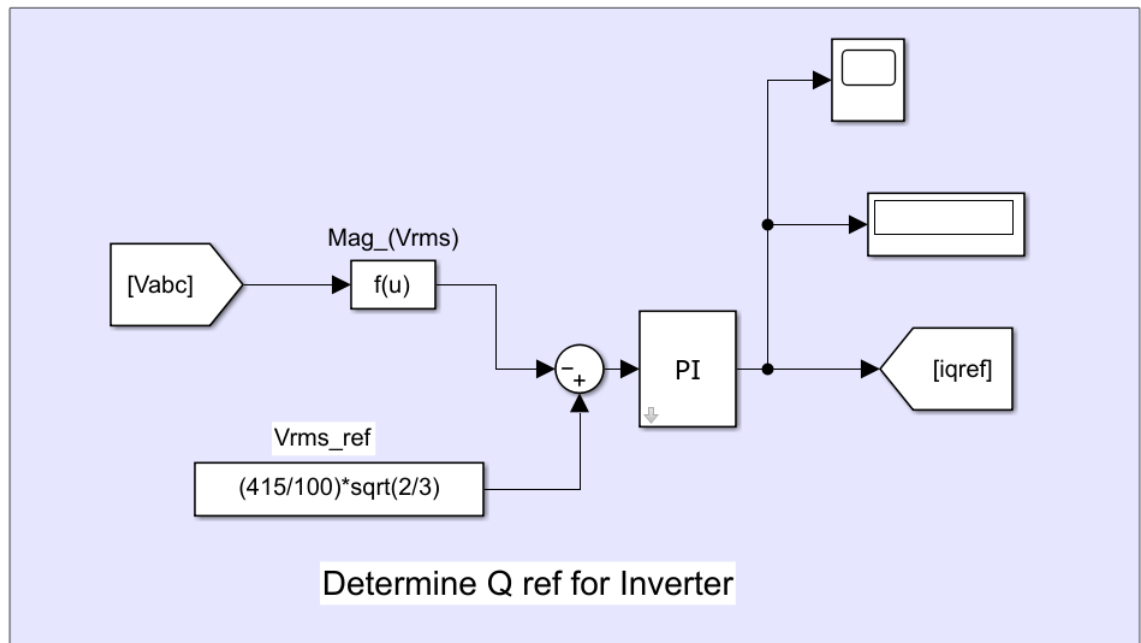
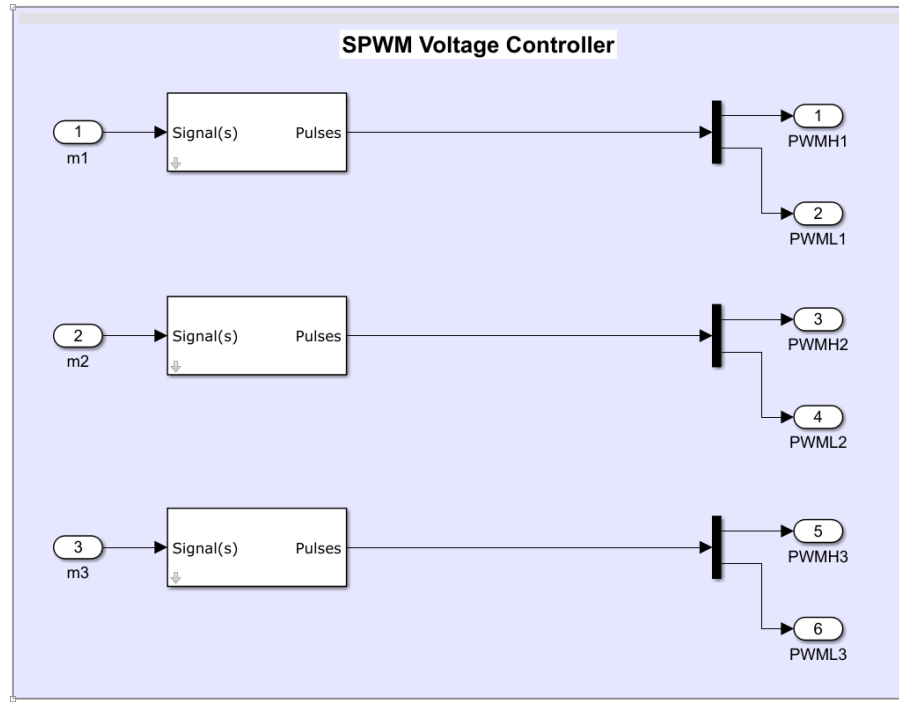


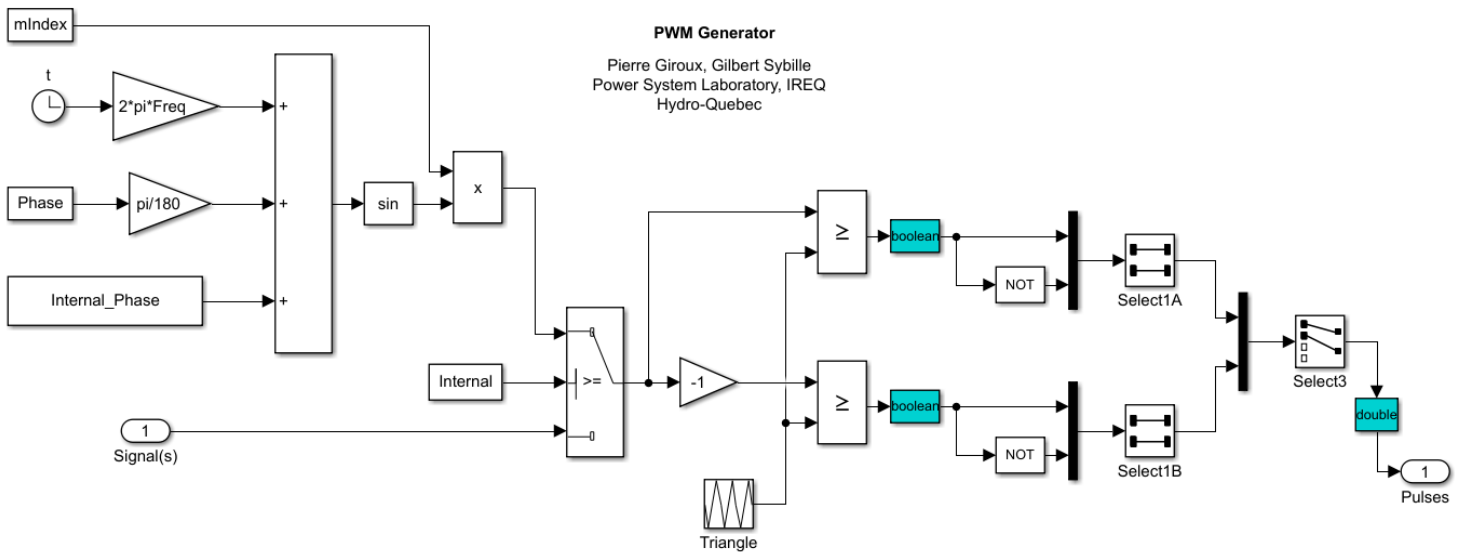
Figure 4.7. AC voltage regulator

4.4.3. Voltage Source Converter

The VSC works on the firing pulses on transistors. The generation of the trigger pulses of the transistors is controlled using the sinusoidal pulse wave modulation technique (SPWM) or a hysteresis current controller. A detailed explanation of both of these methods is given in Chapter 3. The MATLAB Models of the SPWM and PWM generator are given in Figure 4.8.



(a)

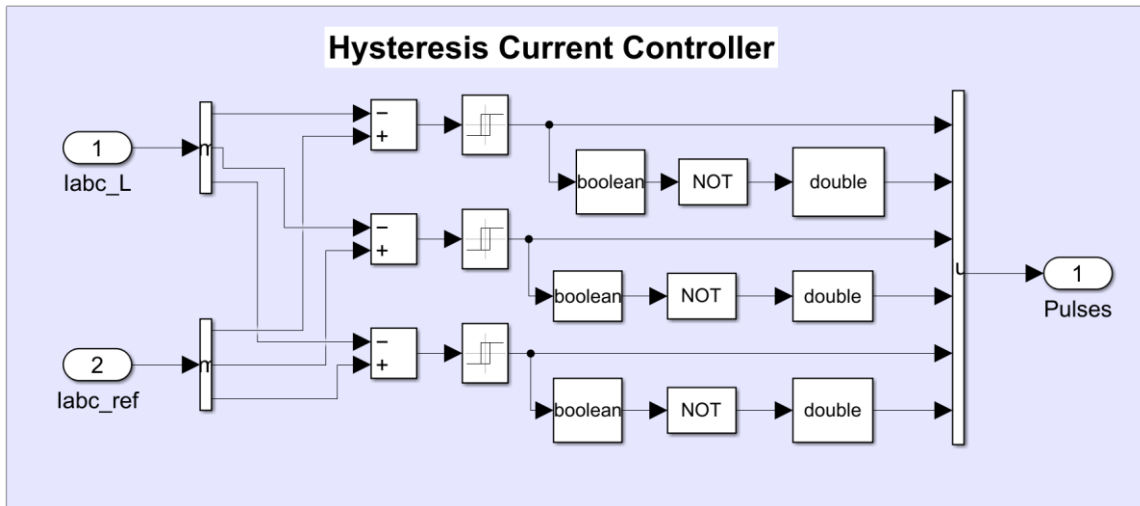


(b)

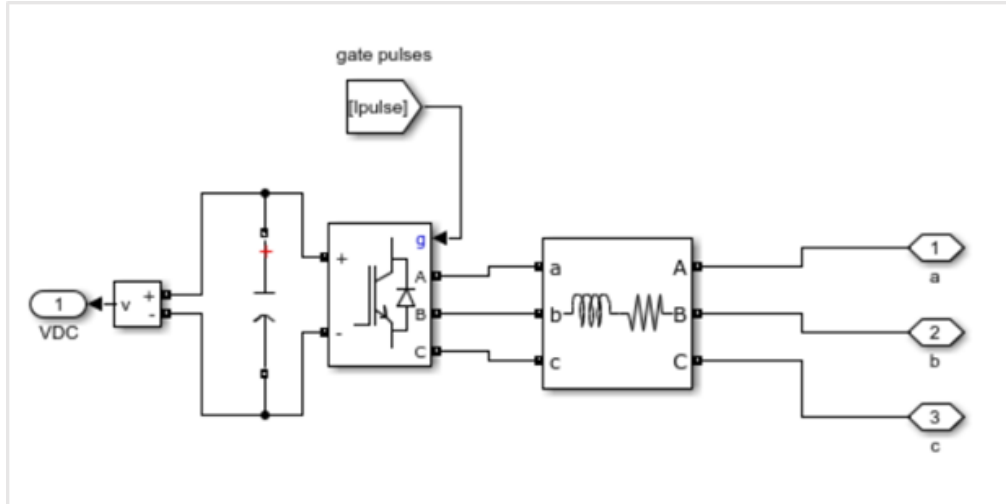
Figure 4.8. (a) Model of SPWM controller, and (b) PWM generator in MATLAB

In other hand, the internal control of the hysteresis current controller is shown in Figure 4.9. The waveform of the desired current is given as input, then the difference between the desired current (input) and actual current (output) is

calculated and IGBT is turned on or off according to the difference value, and a capacitor is connected to the IGBT. As a result, the three-phase AC voltage is generated and connected to the PCC power system.



(a)



(b)

Figure 4.9. (a) The internal control of Hysteresis current controller (b) AC/DC Inverter by transistors pulsing.

4.4.4. Phase-Locked Loop (PLL)

A PLL is a frequency synthesizer system that produces an output signal whose phase depends on the phase of its input signal (V_{abc} three-phase voltage). As shown in Figure 4.10 PLL is used to get the angle ($\theta = \omega t$) and measure $\sin\theta$ & $\cos\theta$ which the D-STATCOM controller uses to calculate the component of the dq-axis.

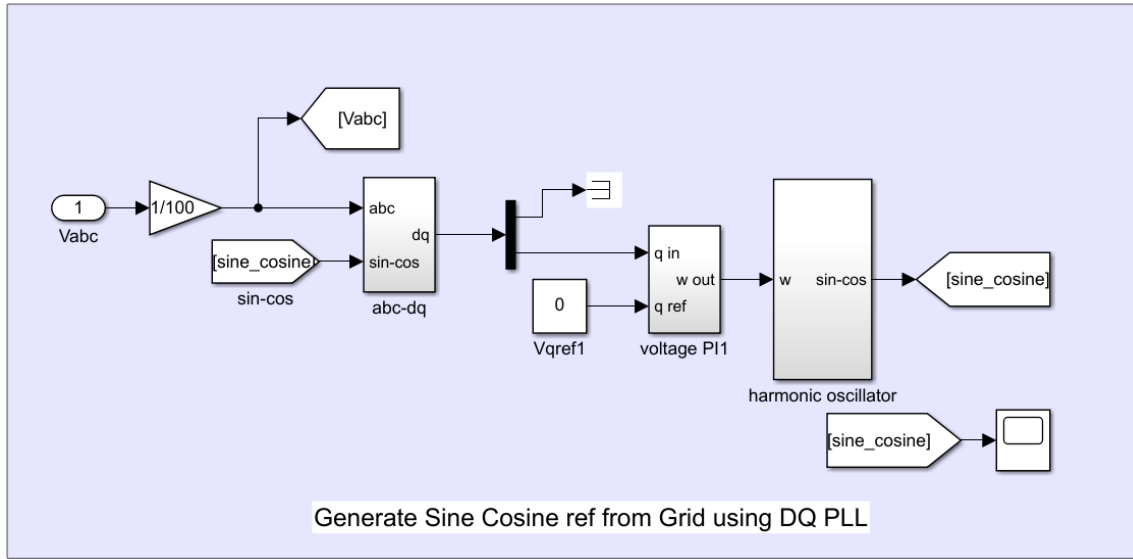


Figure 4.10. The Current Regulator

4.4.5. SRF D-Q Controller

To simplify the calculations, the current in the ABC form is converted to the d-q form by applying Park's transformation method. This is done using the configuration presented in Figure 4.11 in MATLAB. The first thing is to transform the load current from ABC to a d-q form by using Park's transformation and then applying a low-pass filter to smooth the signal. That is achieved by measuring the three-phase load current and converting it to a (dq) form to find I_d and I_q .

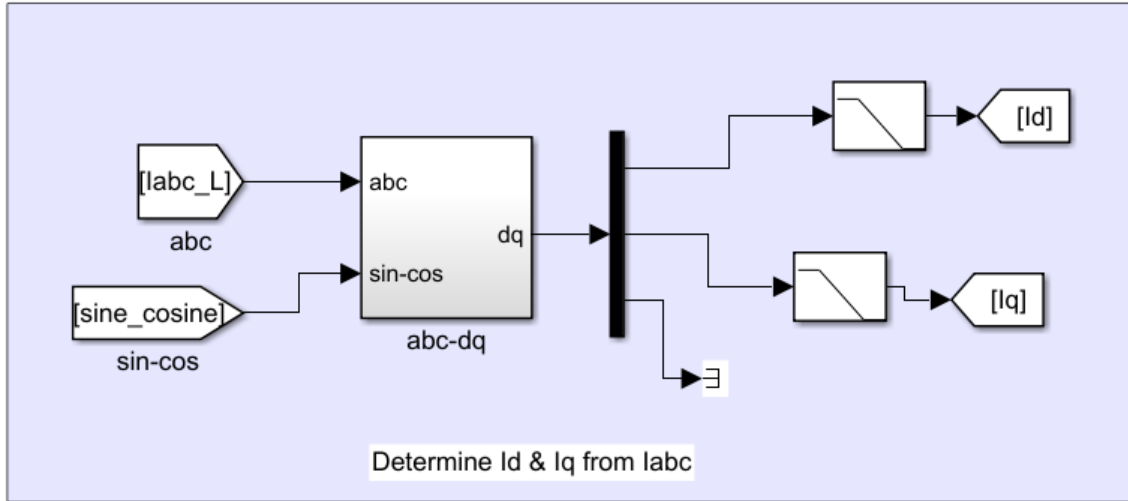


Figure 4.11. SRF D-Q conversion

4.4.6. SRF D-Q Controller – SPWM Controller

The current regulator consists of two regulating loops, each containing a PI controller. In the first regulating loop, the current (I_d) is compared with the reference current (I_{d-ref}) from the DC regulator to get the error signal entering the PI controller. The actual power flow between the D-STATCOM and the electric power grid system is controlled through this loop. In the second regulating loop, the current (I_q) is compared with the reference current (I_{q-ref}) from the AC voltage regulator to obtain the error signal entering the PI controller. Through this loop, the reactive power flow between the D-STATCOM and the electric power grid system is controlled, as shown in Figure 4.12.

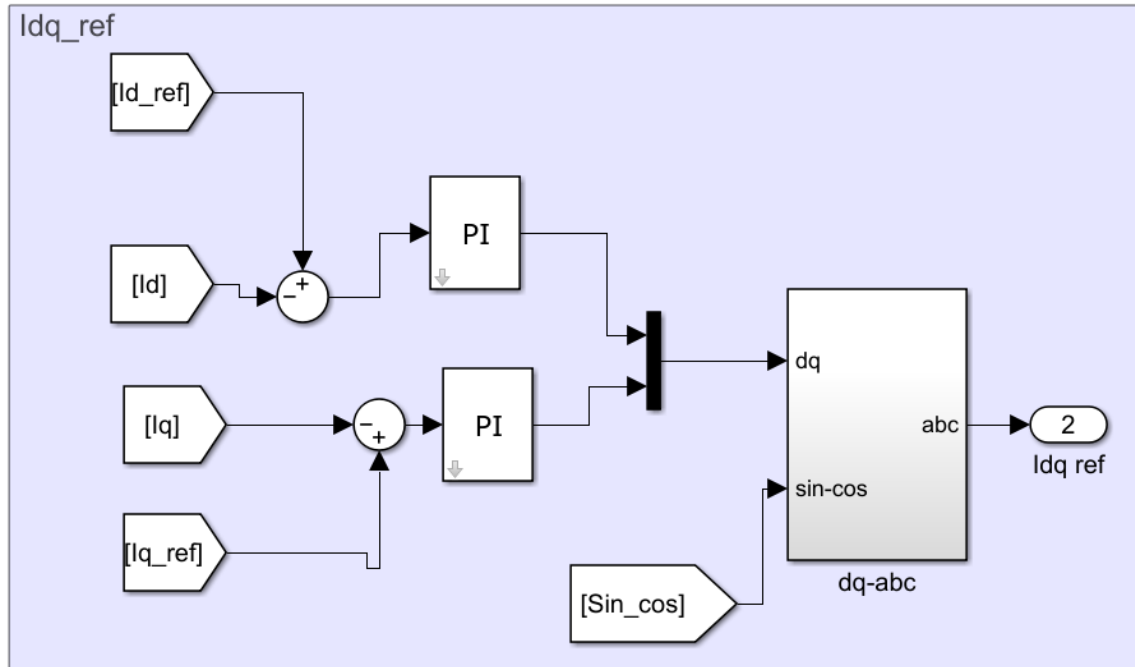


Figure 4.12. SRF D-Q controller – SPWM controller.

By applying reverse Park's transformation using d-axis, q-axis and θ the I_{dq_ref} signal is obtained. The I_{dq_ref} signal is used in the SPWM inverter to generate the Pulsing as described in the previous section.

4.4.7. SRF D-Q Controller - Hysteresis Current Controller

As shown in Figure 4.13, the current regulator consists of two summation loops. In the first loop, the current (I_d) is added with the reference current (I_{d_ref}) that is coming from the DC regulator to get the d-axis component. The actual power flow between the D-STATCOM and the electric power grid system is controlled through this loop. In the second loop, the current (I_q) is added with the reference current (I_{q_ref}) that is coming from the AC regulator to get the q-axis component. Through this loop, the reactive power flow between the D-STATCOM and the electric power grid system is controlled.

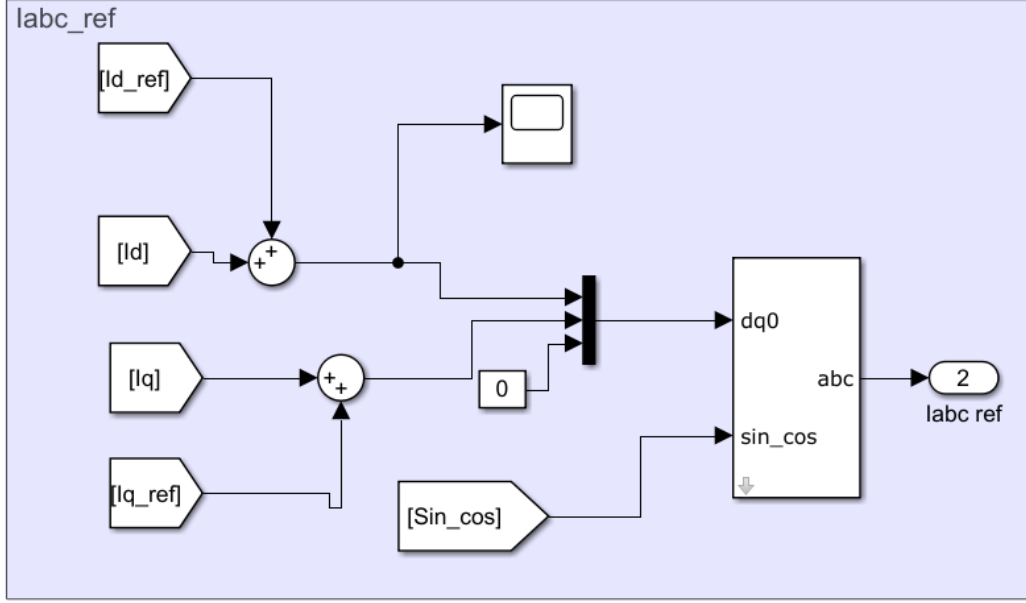


Figure 4.13. SRF D-Q controller - Hysteresis Current controller

Then by applying reverse Park's transformation using d , q axis and θ the current I_{abc_ref} can be obtained. The current I_{abc_ref} is used as a reference for the hysteresis inverter to generate the pulsing described in the previous section in the HCC.

4.5. Control Schemes Installed with D-STATCOM

4.5.1. Training Data Collection

The necessary training data set has been prepared from the system and consists of two input (error and integration of error) and one output of each PI controller. Training data was collected by simulation the system describe in Figure 4.2 but with using only load-1 and load-2 and by connecting D-SATCOM from 1s to 12s. the PI controller parameter is calculated from equation (23), (24), (33) and (34) described in chapter 3 and result is $K_{pd} = 0.014$, $K_{id} = 2$, $K_{pq} = 0.0041$ and $K_{iq} = 200$ where $R_{st} = 0.004$, $L_{st} = 0.003$ and by considering $\delta = 0.707$ (Kerrouche et al. 2020), (Application Note 2009).

4.5.2. Control of D-STATCOM using Neural Network Controller

To improve the effectiveness of the D-STATCOM under normal operating conditions and during contingencies, an ANN controller was applied instead of the existing PI controller in the D-STATCOM controller. The ANN module in MATLAB is shown in Figure 4.14.

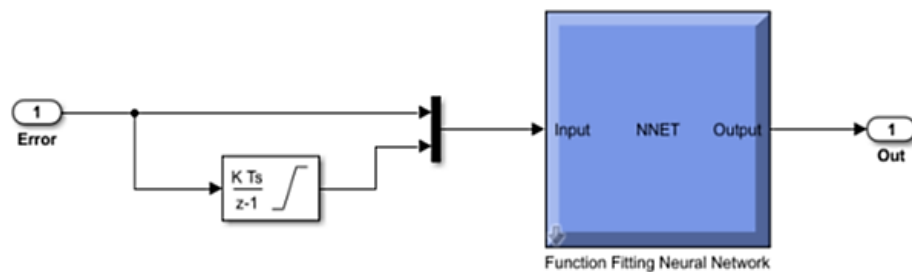


Figure 4.14. ANN MATLAB Module

The training data set was divided into three parts (training - verification - testing) according to the proportions illustrated in Figure 4.15.

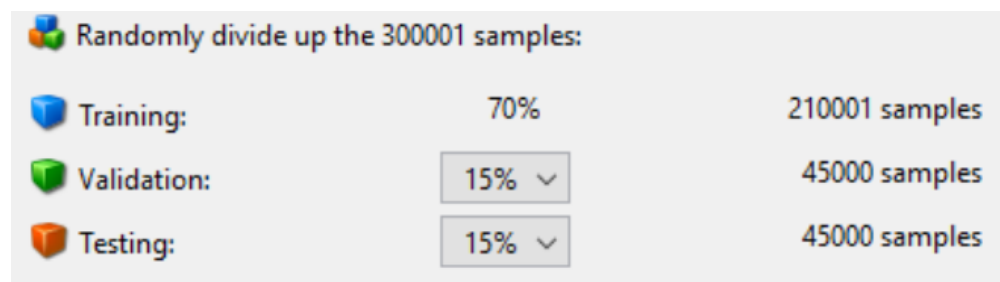


Figure 4.15. ANN sample training data summary

The layout configuration of ANN is presented in Figure 4.16.

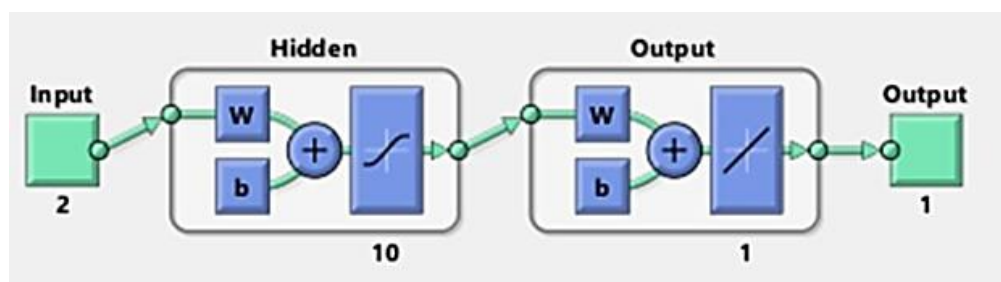


Figure 4.16. ANN internal layer configuration

The Levenberg-Marquardt (LM) algorithm is used to train the neural network, using the training dataset tested with a pause condition of 1,000 training cycles, as shown in Figure 4.17. LM has the fastest convergence in terms of iteration number, and it can obtain lower mean square errors than any of the other algorithms (Zayani, Bouallegue, and Roviras 2008).

The final stage is to test the performance of ANN by determining the system errors for the test samples, where the following result was reached: $MSE = 6.18 \times 10^{-5}$.

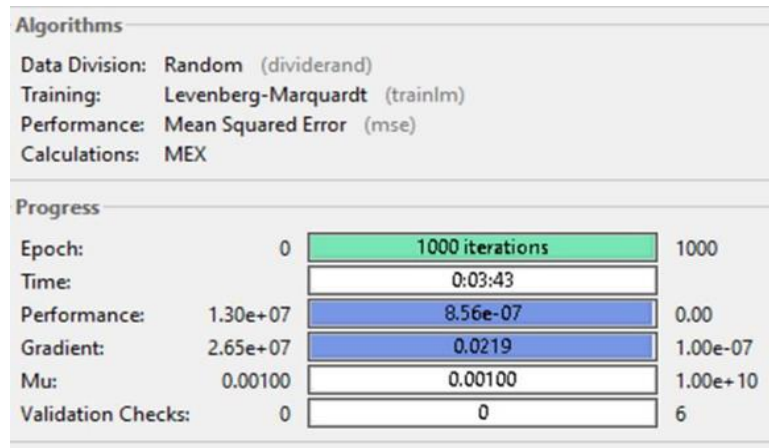


Figure 4.17. ANN training result

4.5.3. Control of D-STATCOM using ANFIS

The Adaptive Neuro-Fuzzy Inference System (ANFIS) controller was designed to compare the system's performance under various scenarios. Therefore, The ANFIS controllers replaced the PI controllers in the system, as shown in Figure 4.18.

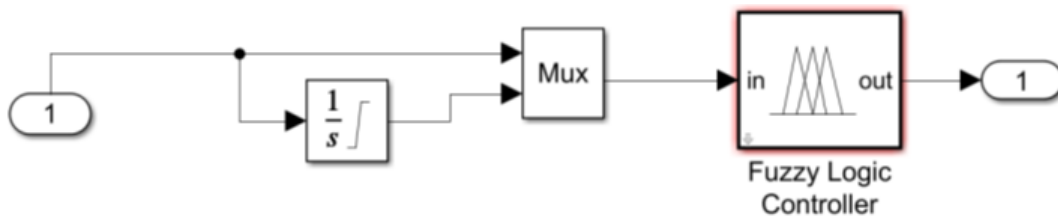


Figure 4.18. ANFIS MATLAB Module

ANFIS is a hybrid controller that combines the benefits of artificial neural networks and fuzzy inference methods to integrate the advantages of both techniques. The necessary training data set was prepared from the system, which consists of 50,000 samples (inputs, output).

The inference system was built by defining the number and pattern of the controller's input and output membership functions, with the definition of a set of logical rules governing these functions. Six layers of membership functions were adopted for each of the two controller inputs and followed a single linear membership to the system's output, as shown in Figure 4.19.

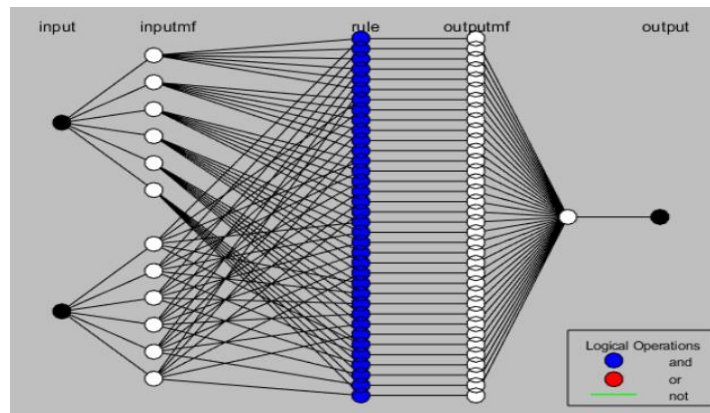


Figure 4.19. ANFIS internal layer configuration

The ANFIS inference system uses a hybrid training algorithm to adjust the Sugeno-Type Fuzzy Inference System (FIS) parameters using the training dataset. Here, the pause condition of ten training cycles was used to train the ANFIS controller. More information can be find in Appendix-1.

The performance of the ANFIS system is further evaluated by determining the system errors, that give a Root Mean Square Error (RMSE)=0.001.

4.6. Results

The power system integrated with the PV system and D-STATCOM experiences a one-fault scenario with different loading conditions. Simulations were carried out for 12 s. The eight simulation scenarios are presented briefly in Table (4.2). The six type of loads have been already presented in Table (4.1).

Table (4.2): The eight different scenarios of simulation

Sr.	Scenarios	Seconds
1	D-STATCOM system connected	1
2	Load-3 and Load-4 active	2
3	PV connected to the grid with 100% capacity	2.5
4	ABG Fault active	5
5	PV drop to 50% capacity	6
6	Load-3 and Load-4 dis-active	8
7	PV increase to 80% capacity	10
8	PV dis-connected from the grid	11

Figure 4.20 shows the performance of the six control schemes (SPWM-PI, SPWM-ANN, SPW-ANFIS, HYSTRESIS-PI, HYSTRESIS-ANN AND HYSTRESIS-ANFIS) in the controlling load voltage profile under eight operating scenarios if the power system.

Figure 4.20 (a) presents the pattern of the solar irradiation level on the PV system and shows a pattern of 1000 W/m^2 from 0 to 6 s, 500 W/m^2 for 6 -10 s, and 800 W/m^2 from 10-12 s.

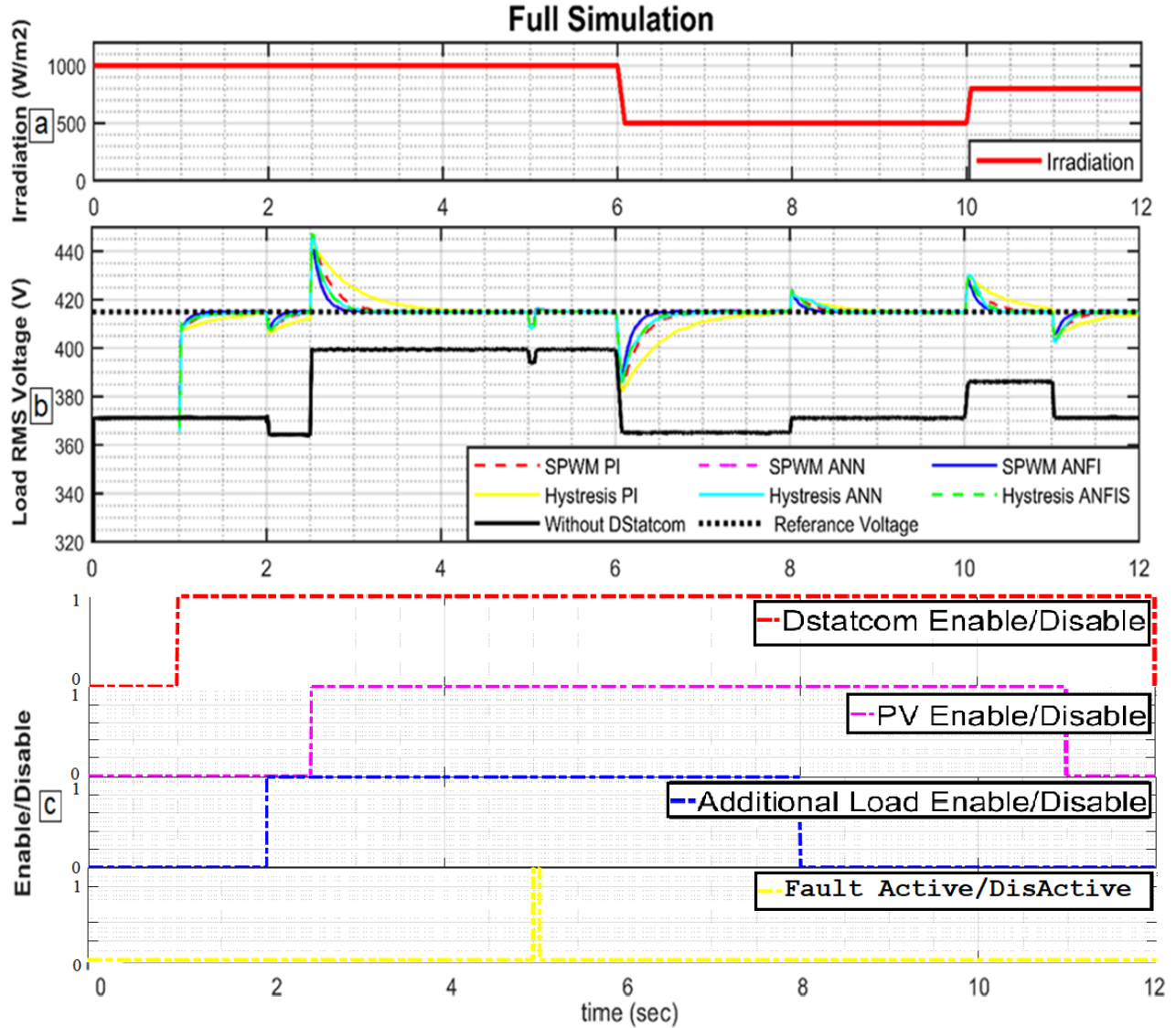


Figure 4.20. Simulation result for 12s of simulation describes PV, RMS voltage, and the eight different operating scenarios

The overall RMS voltage profile of the load is illustrated in Figure 4.20 (b). Each change of voltage will be described in detail in the following sections.

Figure 4.20 (c) shows the timing and the sequence of the operating conditions for the fault, loading condition, D-STATCOM operation, and PV system integration. The red line shows the D-STATCOM status, as it shows that it was OFF from 0 s to 1 s, and ON from 1 s to 12 s. The purple line shows that

the PV system was disconnected from 0 s to 2.5 s and only connected from 2.5 s to for 11 s. The blue line shows that the addition loads (load-3 and load-4) was active at 2 s and dis-active from the system at 8 s. Finally, the yellow line shows that the short circuit fault of two-phase to ground occurs at 5 s for a duration of 6.8 ms.

Table 4.3 to Table 4.10 present the performance of the six control schemes in controlling the load RMS voltage for the system with the D-STATCOM scenario. The performance of the controllers is compared in terms of the Root Mean Square Error (RMSE), Steady State Error (SS Error), settling time, settling average value, rise time, and peak value for all the six control schemes.

Figure 4.20 (a) and Figure 4.21 shows the graph for load RMS voltages under all scenarios. The profile of load voltages without D-STATCOM is even less than the reference voltage of 415V. Also, the graph shows the smoothness in voltage profile with minimum error with respect to reference grid voltage (415V) is attained in the cases of SPWM D-STATCOM with ANFIS and then in SPWM D-STATCOM with ANN case. This result is further evaluated quantitatively by calculating the control characteristics of the voltage profile (Root Mean Square Error (RMSE), Steady State Error (SS Error), settling time, settling average value, rise time, and peak value).

Where the RMSE is the root of the mean of the squared errors between the load RMS voltage reference value and actual values RMS voltage as bellow equation.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (V_{rms} - V_{rms_ref})^2}$$

RMSE will justify how fast the D-STATCOM controller regulate the load voltage to the reference voltage of 415v in each scenario.

However, SS Error is error that occurs between the reference value and actual value of a control system, and that only when it's settled down. SS error will justify how D-STATCOM maintain the load voltage after reaching the reference value.

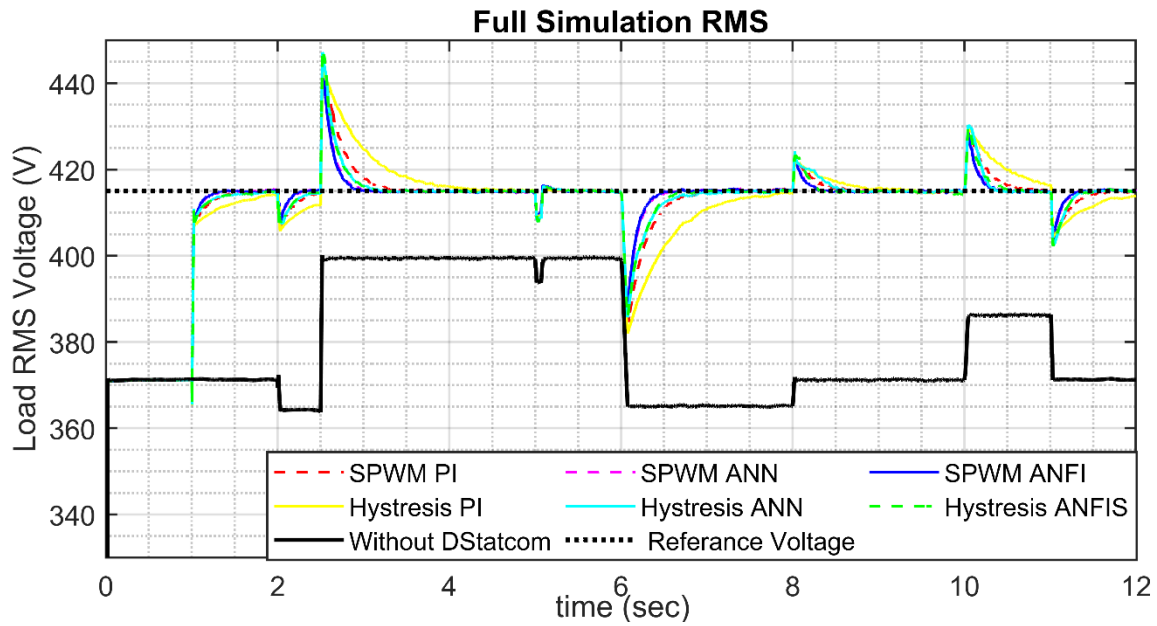


Figure 4.21. Simulation result for 12s of simulation, RMS load voltage for the eight different scenarios active/ di-active step

In the following subsections, each of the eight scenarios presented in Figure 4.21 will be separately explained along with its operational time.

4.6.1. Scenario 1: D-STATCOM ON

In scenario 1, the D-STATCOM is connected with the power system at 1 s and remain connected to the power system till the end of the simulation time of 12 s. The changes in voltage profile for all the scenarios SPWM D-STATCOM with ANN, PI, and ANFIS, Hysteresis D-STATCOM with ANN,

PI, and ANFIS, as well as load voltage profile without D-STATCOM are monitored as shown in Figure 4.22. For the time (1 to 2) s, the voltage profile of the SPWM D-STATCOM ANFIS and ANN smoothly reach the desired reference point as compared with other control schemes. It can be seen from Figure 4.22 that the load RMS voltage is corrected to the reference voltage (415V) as soon as the D-STATCOM is enabled.

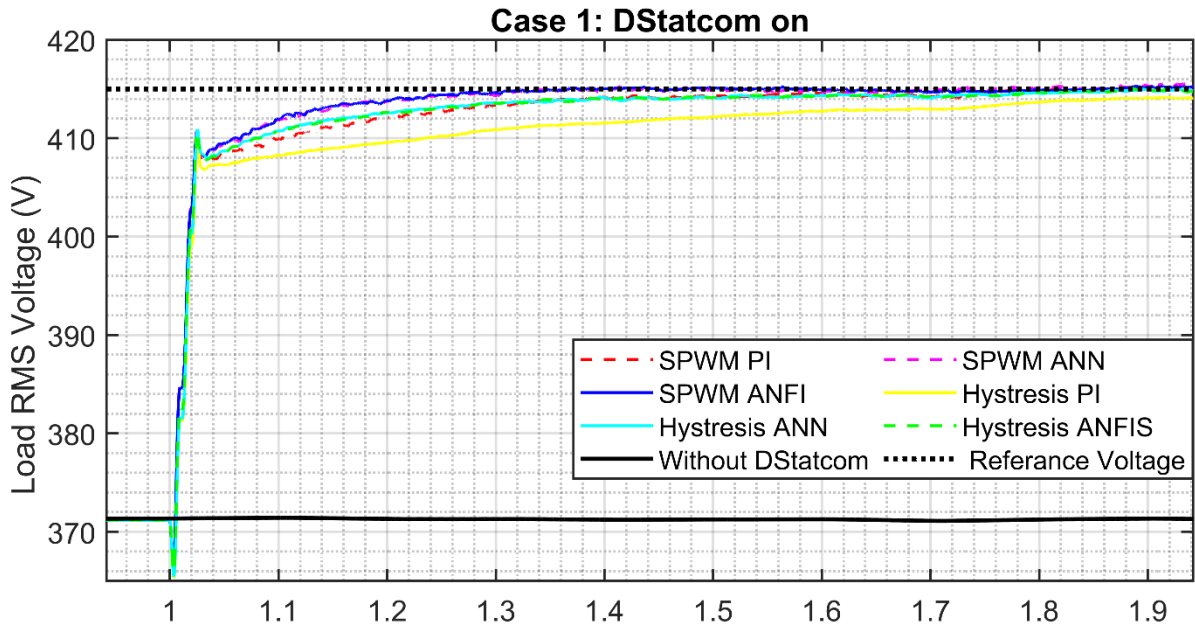


Figure 4.22. Simulation results in 1-2s describe RMS voltage of load while D-STATCOM active

Table (4.3) reveals that the ANFIS controller employing SPWM has the lowest RMSE, settling time, and rise time. However, ANN controller with SPWM has the best Settling Average Value and SSError. Moreover, the ANFIS/ANN controller has the lowest RMSE, settling time, and rise time. This demonstrates that the performance of the SPWM inverter is better than the hysteresis inverter.

Table (4.3): Performance evaluation of the results during 1-2s when D-STATCOM is active

D-STATCOM ON						
	Hisit_PI	Hisit_ANN	Hisit_ANFIS	SPWM_PI	SPWM_ANN	SPWM_ANFIS
RMSE	6.356%	5.483%	5.399%	5.299%	5.023%	5.003%
SSError	0.9099	0.5403	0.4228	0.603	0.1020	0.2173
Settling Time (ms)	167.388	66.563	73.868	114.377	66.664	65.312
Settling Avg. value	413.047	413.649	413.698	414.009	414.332	414.010
Rise Time (ms)	448.736	176.536	182.014	242.715	142.554	120.294
Peak	414.154	414.981	415.007	415.397	415.765	415.367

4.6.2. Scenario 2: Active, Reactive, and Non-Linear Load

ON

The additional load (load-3) and (load-4), are connected to the power system from time 2 to 8 s of the simulation time. Figure 4.23 shows the load voltage during the simulation time period (2 to 2.5) s. It can be seen from Figure 4.23 that the load RMS voltage is regulated by the D-STATCOM to the reference voltage (415V) when the additional load is connected to the system. In addition, it can be seen that the fastest response is achieved by using the controller of ANFIS and ANN modulated by SPWM.

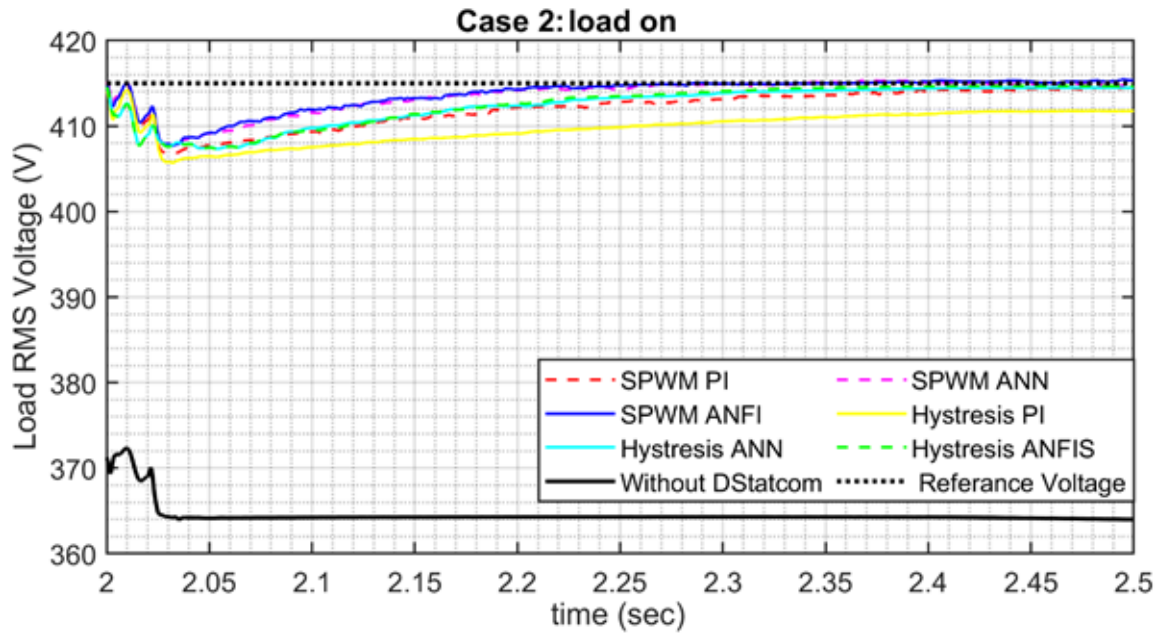


Figure 4.23. Performance evaluation of results during 2-2.5s describe RMS voltage of additional load active

Similarly, it can be seen from Table 4.4 that controller ANFIS with SPWM has the lowest RMSE, settling time, and rise time and the best Settling Average Value. On the other hand, the controller of ANN using SPWM has a lower SSError value than the other controllers. The SPWM ANFIS and Hysteresis ANFIS controllers have the lowest settling time, and the SPWM ANFIS and ANN controllers have the lowest rise time. It also demonstrates that the performance of the SPWM inverter and hysteresis inverter varies under this scenario.

Table (4.4): Simulation results for 2-2.5s when additional load is active

Additional load On (20 kW and 3 kVar and a non-linear load of 200 ohms, 1×10^{-3} H, 600×10^{-6} F)						
	Hisit_PI	Hisit_ANN	Hisit_ANFIS	SPWM_PI	SPWM_ANN	SPWM_ANFIS
RMSE	5.517%	3.467%	3.455%	3.610%	2.413%	2.299%
SSError	3.2424	0.5379	0.3190	0.5676	0.2761	0.3761
Settling Time (ms)	363.485	295.507	287.745	358.228	393.773	244.769
Settling Avg. value	409.956	410.908	414.697	410.798	411.625	415.210
Rise Time (ms)	1514.347	544.447	623.955	704.784	607.911	395.906
Peak	414.210	414.478	414.721	415.056	415.472	415.470

4.6.3. Scenario 3: PV ON with 1000 W/m² Irradiation

The PV system is connected to the power system during the interval from 2.5 s to 11 s of the simulation time. The load voltage is illustrated in Figure 4.24 for time 2.5 s to 4.5 s. It can be seen that the load RMS voltage has been improved by activating the PV to the system. It can be also seen that the fastest response reached to the reference point is achieved by using the controller of ANFIS and ANN modulated by SPWM.

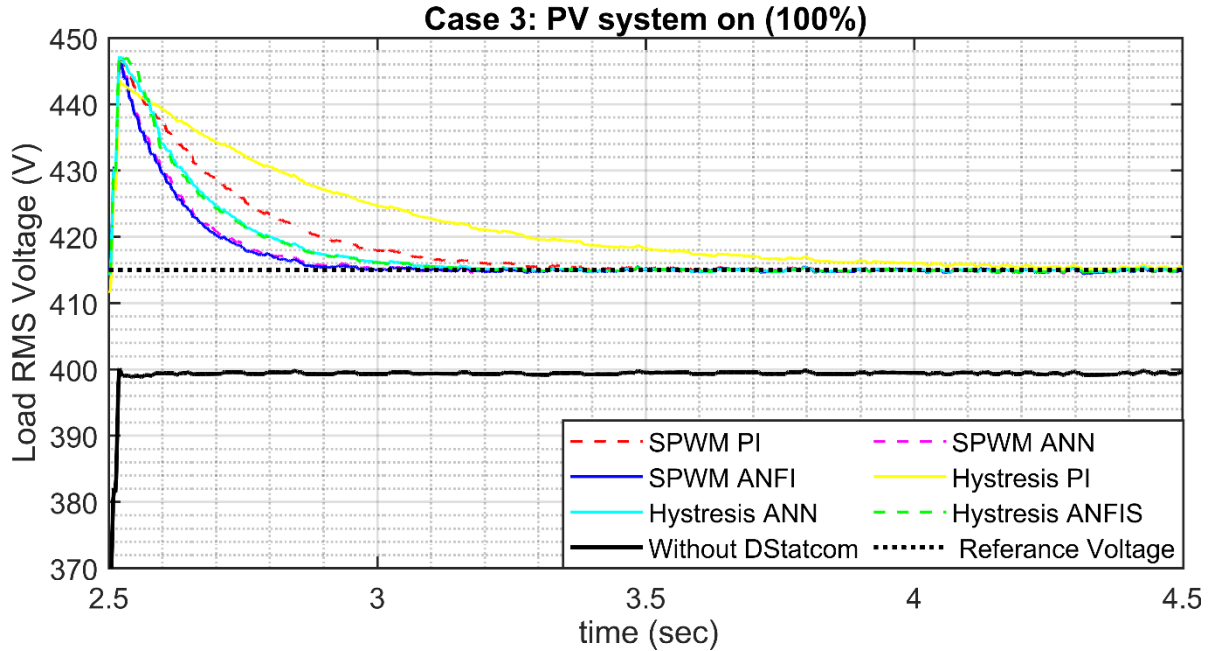


Figure 4.24. Simulation results in 2.5-4.5s describe RMS voltage of load while PV active

Table (4.5) shows that the ANFIS controller using SPWM has the lowest RMSE, settling time, and rise time. It has the best Settling Average Value. Meanwhile, the ANN controller using Hysteresis has a lower SSError value than the other controllers. The SPWM ANFIS and ANN have the lowest settling time and rise time. The results demonstrate that the performance of the SPWM inverter is better than the hysteresis inverter, even with a similar controller type used in this scenario.

Table (4.5): Performance evaluation of results during 2.5-4.5s when PV is active

PV on 100%						
	Hisit_PI	Hisit_ANN	Hisit_ANFIS	SPWM_PI	SPWM_ANN	SPWM_ANFIS
RMSE	11.213%	7.803%	7.797%	8.641%	6.338%	6.167%
SSError	1.0292	0.0418	0.0756	0.0951	0.0832	0.0770
SettlingTime (ms)	893.602	361.889	354.850	475.931	257.025	252.001
Settling Avg value	429.718	430.947	431.055	430.744	430.466	429.057
RiseTime (ms)	947.992	812.672	579.379	858.923	565.054	472.563
Peak	443.608	447.177	447.423	446.758	446.400	446.233

4.6.4. Scenario 4: Two-Phase to Ground Fault on the System

Fig 4.25 shows the performance of the controllers during the ABG fault condition. The load RMS voltage graph has been corrected to reference voltage (415V) when the ABG fault is applied in the power system. Furthermore, it can be seen that the fastest response reached to the reference point is by using the controller of PI modulated by Hysteresis current source inverter.

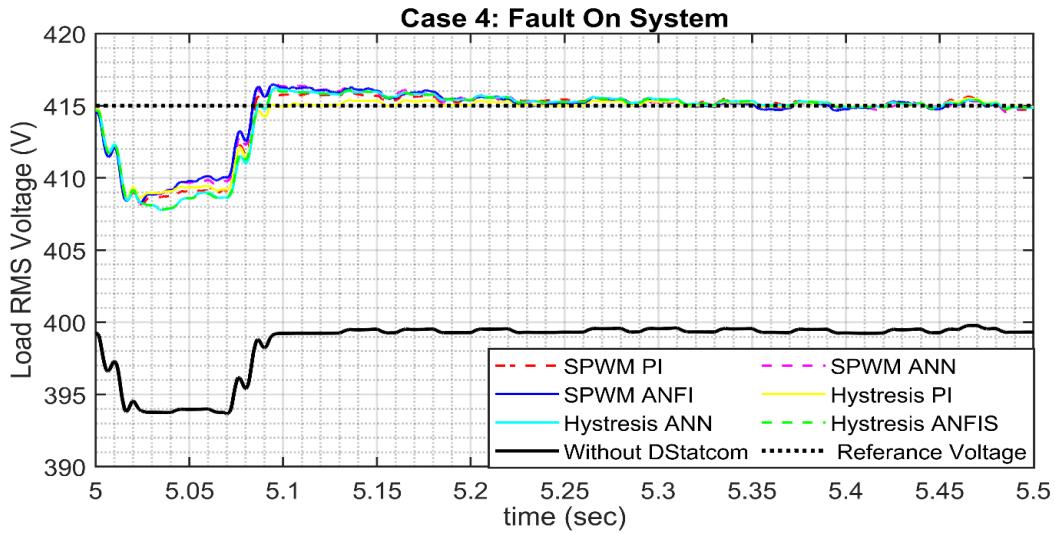


Figure 4.25. Simulation result for the RMS voltage profile for different controllers during an ABG fault condition

Table (4.6) shows the performance comparison of the controller in terms of the RMSE, SSError, settling time, settling average value, rise time, and peak value. The ANFIS controller using SPWM and the PI controller using Hysteresis achieved the lowest RMSE and SSError. On the other hand, the controller of the PI with Hysteresis has the lowest settling time and rise time. Also, it achieved the best Settling Average Value compared to other controllers. However, other controllers' performance was not effective in case of ABG fault active, and only the SPWM ANFIS has shown better RSME and

SSError. In this case, the performance of the Hysteresis PI controller was better in settling time, settling average value, and rise time.

Table (4.6): Performance evaluation of results during 5-5.5s while fault is active

Two-phase to ground fault						
	Hisit_PI	Hisit_ANN	Hisit_ANFIS	SPWM_PI	SPWM_ANN	SPWM_ANFIS
RMSE	2.130%	2.403%	2.392%	2.248%	2.128%	2.091%
SSError	0.0962	0.1565	0.1263	0.2212	0.2168	0.0904
SettlingTime (ms)	90.834	267.457	216.604	471.603	273.025	266.055
Settling Avg value	415.175	415.493	415.474	412.031	415.572	415.551
RiseTime (ms)	0.363	0.445	0.372	0.372	0.386	0.390
Peak	415.513	416.248	416.172	415.906	416.612	416.479

4.6.5. Scenario 5: PV Drops to 50%

In this scenario, the PV system power is reduced to 50 % due the drop in the irradiation to 500 (W/m²) over the time (6 to10) s of the simulation time. The load voltage is illustrated in Figure 4.26 for the time from 6 to 8 s. It can be noticed from Figure 4.26 that the controllers have corrected the load RMS voltage to the reference voltage (415V) once the PV power drops due to the irradiation effects. In addition, it can be seen that the fastest response reached to the reference point is achieved by using the ANFIS and ANN controller with SPWM.

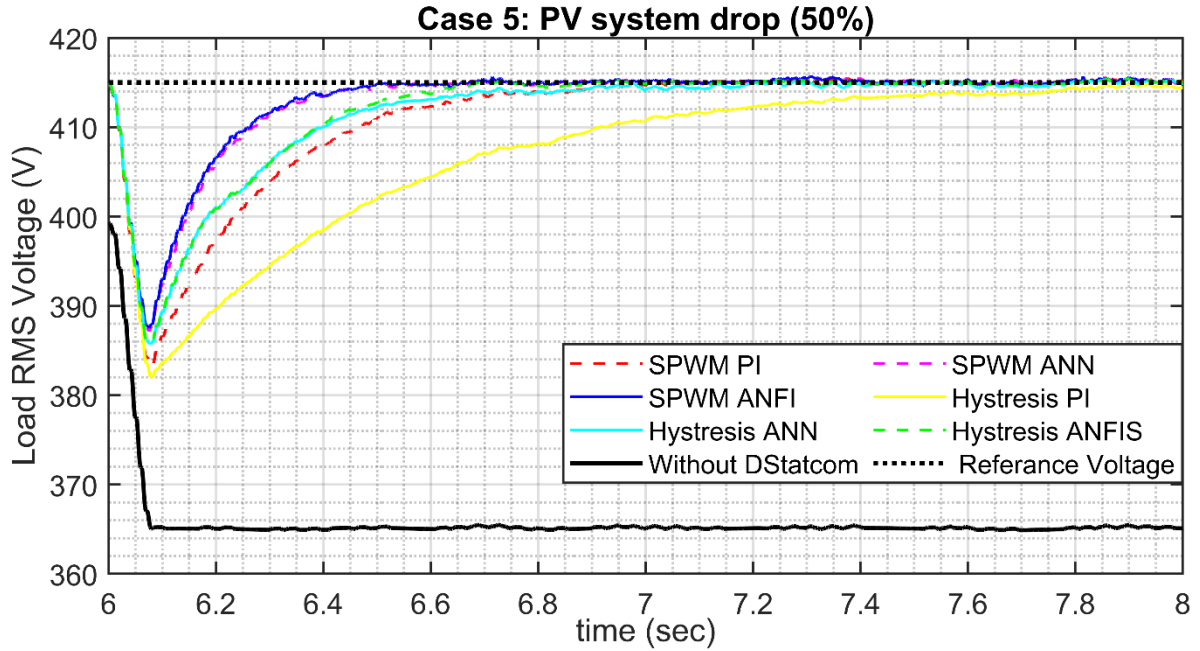


Figure 4.26. Simulation results of 6-8s describe RMS voltage of load when PV power drops to 50%

It can be also seen from Table 4.7 that the ANFIS controller using SPWM has the lowest RMSE, settling time, and rise time. However, the ANN controller using SPWM has a lower SSError value and the best Settling Average value than the other controllers. The ANFIS/ANN controllers with SPWM is leading in all performance parameters in this case.

Table (4.7): Performance evaluation of results during 6-8s when PV power drops to 50%

PV on 40%						
	Hisit_PI	Hisit_ANN	Hisit_ANFIS	SPWM_PI	SPWM_ANN	SPWM_ANFIS
RMSE	16.532%	9.985%	9.928%	11.568%	8.101%	7.870%
SSError	4.3148	0.8114	0.1177	0.2677	0.0509	0.1040
SettlingTime (ms)	776.749	445.170	457.214	525.932	330.660	327.821
Settling Avg value	396.451	400.313	414.841	414.671	415.050	415.155
RiseTime (ms)	719.182	664.967	682.463	706.406	626.384	179.882
Peak	414.745	414.882	415.287	414.867	415.506	415.632

4.6.6. Scenario 6: The Additional Load Disconnected

In this scenario, the additional load (load-3) and (load-4) that connected in scenario 2 are disconnected from the power system at time 8s of the simulation time. The load voltage profile is illustrated in Figure 4.27 for time 8 s to 10 s. It is evident from the load RMS voltage that the voltage has been adjusted to the reference voltage (415V) after the load is disconnected from the power system. It can also be seen that the fastest response is achieved when employing the ANFIS and ANN controller with SPWM.

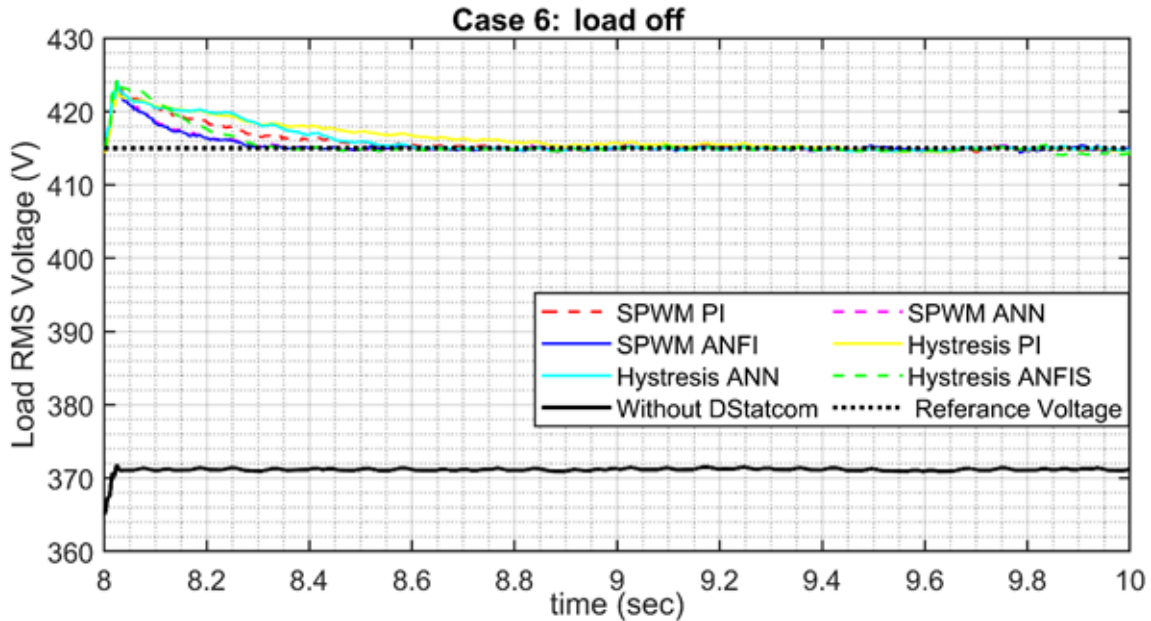


Figure 4.27. Simulation result of the load RMS voltage profile when disconnecting the additional load

Table (4.8) elaborates on the other parameters of the voltage profile like RMSE, SSError, settling time, settling average value, rise time and peak value. It can be noted that ANFIS controller with SPWM achieved the lowest RMSE, settling time, and rise time. In addition, the controller of ANFIS employing Hystressis has a lower SSError value than other controllers.

Table (4.8): Performance evaluation of results during 8-10s with disconnection of additional load

Additional load Off (20 kW and 3 kVar and a non-linear load of 200 ohms, 1×10^{-3} H, 600×10^{-6} F)						
	Hisit_PI	Hisit_ANN	Hisit_ANFIS	SPWM_PI	SPWM_ANN	SPWM_ANFIS
RMSE	3.284%	3.124%	2.721%	2.694%	1.980%	1.912%
SSError	0.7337	0.1751	0.0651	0.2467	0.1751	0.0656
SettlingTime (ms)	626.083	452.464	272.129	436.496	255.502	254.916
Settling Avg value	419.353	419.464	414.921	419.342	419.093	419.174
RiseTime (ms)	1514.347	544.447	623.955	704.784	607.911	395.906
Peak	423.534	424.238	424.361	424.167	423.808	423.768

4.6.7. Scenario 7: PV Increases to 80%

In this scenario, the PV system power is increased to 80 % owing to the irradiation to 800 (W/m^2) over time (10 to 11) s of the simulation time. The controllers' response in regulating the load voltage profile is illustrated in Figure 4.28. It can be noticed from Figure 4.28 that the D-STATCOM corrects the load RMS voltage to the reference voltage (415V) despite the PV power is increased to 80%. Moreover, it can be seen that the fastest response reached to the reference point is by using the ANFIS and ANN controller with by SPWM.

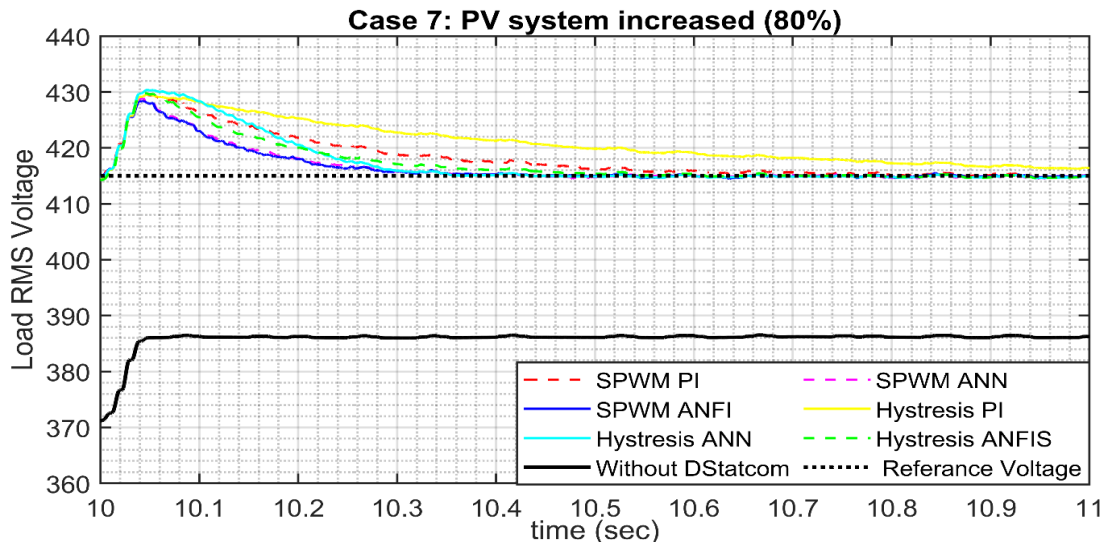


Figure 4.28. Simulation result of the load RMS voltage when PV power is increase to 80%

Table (4.9) reveals that the ANFIS using SPWM has the lowest RMSE, SSError, settling time, and rise time and has the best Settling Average value compared to other controllers.

Table (4.9): Performance evaluation of results during 10-11s while PV power increased to 80%.

PV On to 80%						
	Hisit_PI	Hisit_ANN	Hisit_ANFIS	SPWM_PI	SPWM_ANN	SPWM_ANFIS
RMSE	6.964%	5.061%	4.438%	5.079%	3.596%	3.485%
SSError	1.4215	0.0824	0.0730	0.0818	0.0618	0.0492
SettlingTime (ms)	774.759	282.371	352.724	531.192	271.763	271.757
Settling Avg value	422.886	422.464	422.190	422.050	421.614	421.437
RiseTime (ms)	1097.086	826.993	775.717	836.779	850.257	704.364
Peak	429.515	430.355	429.795	429.479	428.922	428.424

4.6.8. Scenario 8: PV OFF

The PV system is disconnected from the main power system at 11 s, the simulation time in this scenario. The load voltage profile is illustrated in Figure 4.29 for the time duration from 11 s to 12 s. The load RMS voltage is corrected by the D-STATCOM action to the reference voltage (415V) despite disconnecting the PV from the system. It can also be seen that the fastest response reached to the reference point is achieved by using the ANFIS and ANN controller modulated by SPWM.

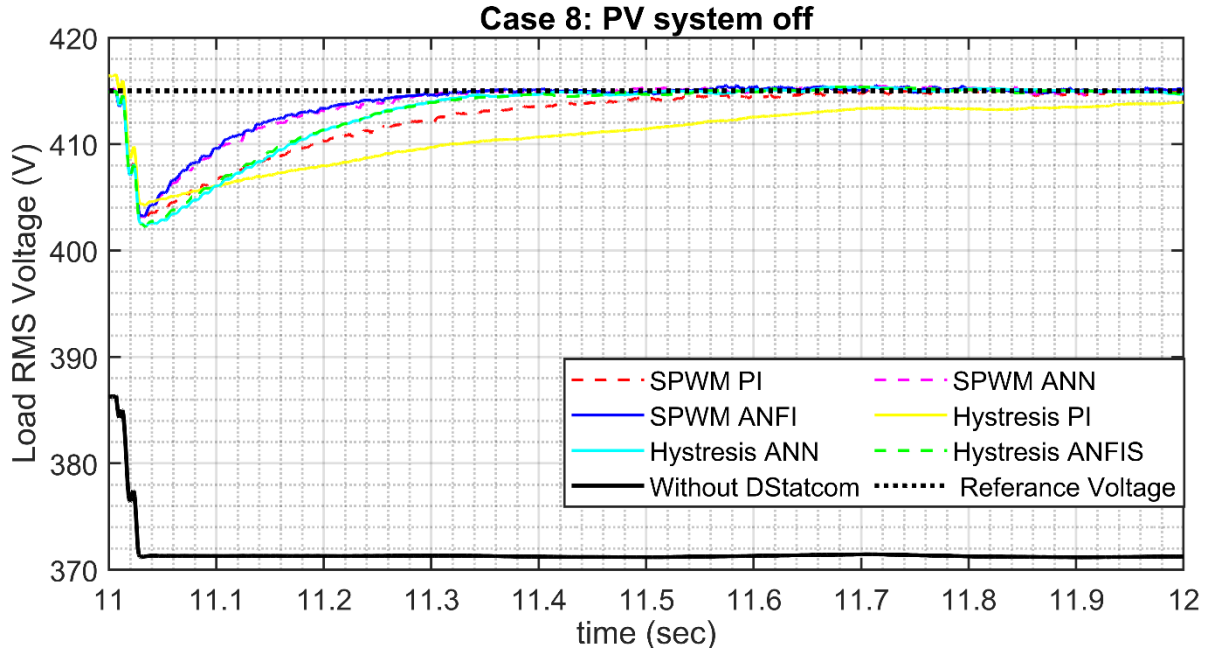


Figure 4.29. Simulation result of load RMS voltage when the PV system is disconnected

Furthermore, Table (4.10) illustrates that the ANFIS controller using SPWM has the lowest RMSE, settling time, and rise time and has the best Settling Average value. On the other hand, the ANN controller using SPWM has a lower SSError value than other controllers.

Table (4.10): Performance evaluation of results during 11-12s while PV system is disconnected

PV System disconnected						
	Hisit_PI	Hisit_ANN	Hisit_ANFIS	SPWM_PI	SPWM_ANN	SPWM_ANFIS
RMSE	4.849%	3.813%	3.708%	3.818%	2.783%	2.696%
SSError	1.0885	0.3099	0.2773	0.1060	0.0643	0.1835
Settling Time (ms)	654.519	274.732	277.430	441.472	263.822	245.899
Settling Avg value	409.130	408.804	408.799	414.889	409.322	415.113
RiseTime (ms)	1124.434	897.449	773.265	701.865	534.085	402.271
Peak	416.554	415.341	415.369	415.263	415.533	415.554

4.6.9. Total Harmonic Distortion (THD)

According to the IEEE standard 519-1992, the voltage THD must be less than 5% of the fundamental frequency, and each individual harmonic distortion

should not be more than 3%. The voltage distortion limits are shown in Table (4.11). If the THD exceeds this limit, it would be considered as poor quality issue that need to rectified, (IEEE 1993).

Table (4.11): IEEE Std 519–1992 Harmonic Voltage Distortion Limits (Blooming and Carnovale 1992)

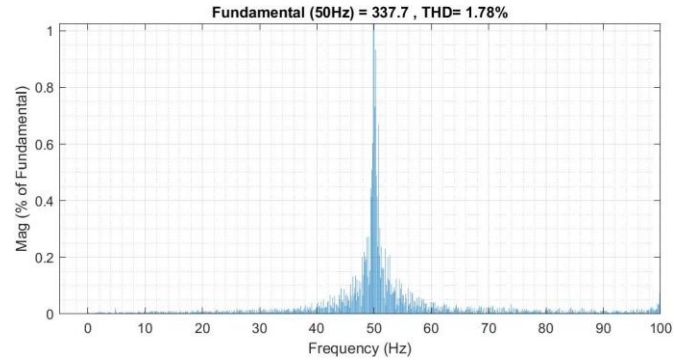
Voltage Distortion Limits		
Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5
NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.		

The Total Harmonic Distortion in the voltage for the SPWM- (PI, ANN, and ANFIS) and Hysteresis- (PI, ANN, and ANFIS) are shown in Figure 4.30 and Figure 4.31 for the total time of the simulation with max frequency of 100 Hz. Where the "mag (% fundamental)" value is the magnitude of the fundamental frequency component of load RMS voltage signal, expressed as a percentage of the total signal magnitude. Therefore, if the frequency is 50 Hz and by using an appropriate sampling frequency, then the "mag (% fundamental)" value should be close to 100% or 1.

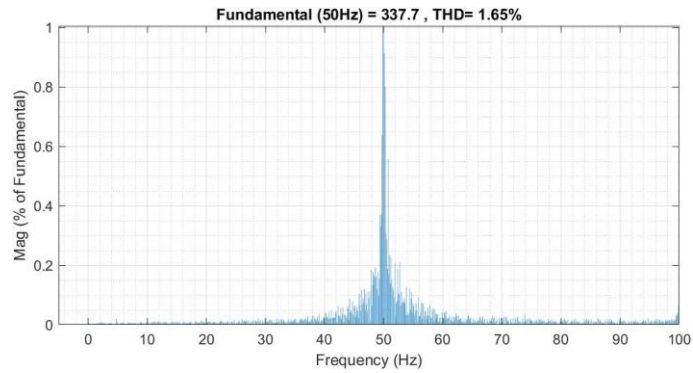
The detailed results of the THD for the full time of the simulation (0-12 s) to all the three controllers adapted with Hysteresis and SPWM inverter are listed in Table (4.12). The lowest THD percentage was observed with SPWM with ANFIS control strategy, with only 1.64% THD. The highest THD for the D-STATCOM-based system with a PI controller was 1.95% in the Hysteresis PI scheme. The THD was around 3.38% when no external controller was employed in the system.

Table (4.12): Comparison of THD for different controllers

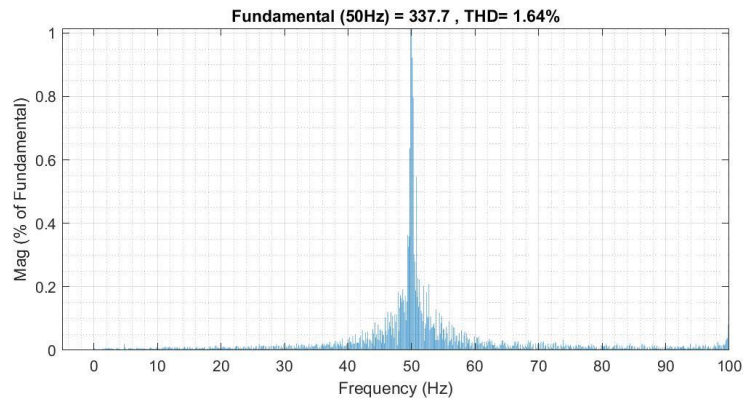
Hysteresis	PI	ANN	ANFIS	Without D-STATCOM
	1.95%	1.75%	1.76%	3.38%
SPWM	PI	ANN	ANFIS	Without D-STATCOM
	1.78%	1.65%	1.64%	3.38%



(a) SPWM -PI

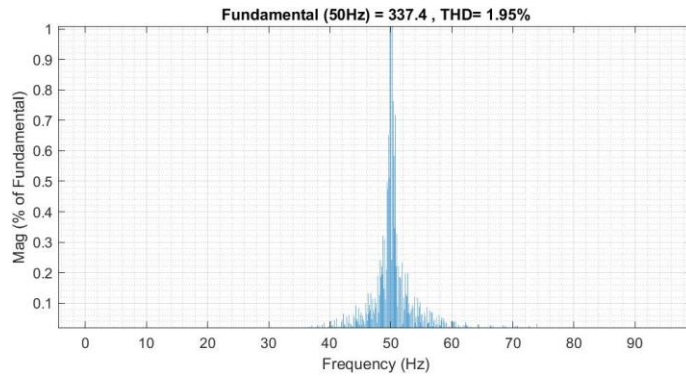


(b) SPWM – ANN

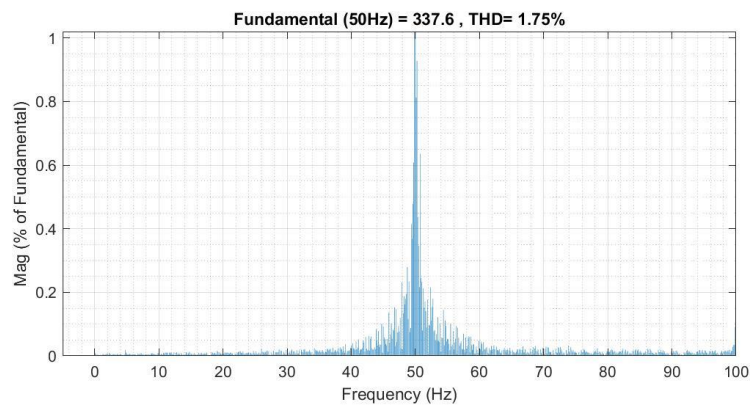


(c) SPWM ANFIS

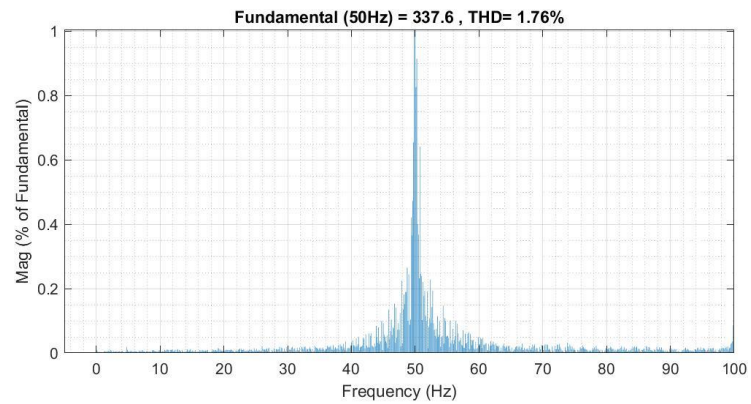
Figure 4.30. Total Harmonic Distortion in voltage for SPWM- (PI, ANN, and ANFIS)



(a) Hysteresis -PI



(b) Hysteresis – ANN



(c) Hysteresis - ANFIS

Figure 4.31. Total Harmonic Distortion in voltage for Hysteresis- (PI, ANN, and ANFIS)

Chapter 5: Conclusion and Future Recommendations

<u>5.1.</u>	<u>Conclusion</u>	98
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5.1. Conclusion

Solar energy is the cleanest, most abundant, and renewable energy source on Earth. The PV systems are considered as one of the best renewable energy resources for highly solar isolated areas worldwide. Hence, as PV system installation capacity increases, it triggers new power quality concerns to the grid system, such as unbalanced or fluctuating voltages. Integration of PV power into the grid presents severe power quality challenges such as voltage and frequency variations, voltage sag, voltage surge, harmonics, reverse power flow, islands, synchronization issues, and intermittent power flow. Another significant issue resulting from the increased penetration of PV energy sources is the harmonic distortion of current and voltage. It occurs in a PV energy system due to power electronic components such as inverters that transform the dc output of photovoltaic panels to an alternating current signal. Harmonics in the system can be reduced with the help of passive filters, active filters, and FACT devices such as the static synchronous compensator (STATCOM). Voltage sag and swell are caused by the system's non-controllable volatility of PV energy sources.

The simulation was carried out by comparing the performance of three controllers (PI, ANN, and ANFIS) to control of D-STATCOM.

The controller of ANFIS and ANN-based D-STATCOM can mitigate power quality problems related to PV integration to reduce the adverse impact of the PV integration on voltage regulation and harmonic distortion.

The PV system and D-STATCOM are integrated into the power system, and simulations were conducted for 12 seconds. Simulations encounter eight different simulation scenarios briefly described in Table (4.2).

The key outcomes of the analysis of the simulation are highlighted below:

- It demonstrates that the smoothness of the load voltage profile, the minimum RMSE, and the fastest control response are achieved by ANFIS SPWM D-STATCOM, followed by ANN. This indicates the powerful control of ANFIS, which has an intelligent Neuro-Fuzzy technique used to model and control ill-defined and uncertain systems.
- However, the performance of the SPWM ANN control scheme for D-STATCOM produces better results in a few scenarios, as it has minimum steady-state error (SSError) in scenarios 2 (connect new load) and 8 (disconnected PV system).
- The Hysteresis PI control scheme shows the lowest settling time and rise time in scenario 4 (fault condition), and this is the most critical scenario in all cases as an external disturbance is applied to the system. That could be attributed to the low response of the controller following a fault in the system, so it sustains the system's voltage profile without having a high reaction response that could cause distortion in the system.
- The Hysterriss ANN control scheme obtains minimum SSError in scenario 2 (connect new load).
- The THD was calculated for the voltage profile, and it reveals that the THD in voltage for SPWM- (PI, ANN, and ANFIS) and Hysteresis- (PI, ANN, and ANFIS) indicates that the controller ANFIS employing SPWM has the lowest value of THD in the system as shown in Table 4.12.

The performance of SPWM with ANFIS was better than other control schemes in most scenarios. Hence, it was found that the SPWM inverter strategy adapts the control input faster than the Hysteresis scheme. The above conclusion signifies that the performance of advanced controllers, especially ANFIS, which has an intelligent Neuro-Fuzzy technique used for modeling and controlling ill-defined and uncertain systems, was better controller among other controllers. It can effectively enhance the power quality of the power system using D-STATCOM devices.

5.2. Future Recommendation

This research motivates further investigation of new and modern algorithms such as Adaptive Neuro-Fuzzy Takagi-Sugeno-Kang (ANFTSK), Adaptive Neuro-Fuzzy Wavelet (ANFW), and Typ-2 ANF controllers. Further research will focus on the performance of these advanced control techniques when integrated with FACTS devices to enhance voltage profile, improve power quality and reduce THD in voltage and current profiles. Similarly, finding the optimal parameters of a control technique at which D-FACTS devices perform at their best is a crucial aspect of future research. Furthermore, the integration of Wind power systems can also bring its limitations into the power system, and the research can be extended by incorporating wind and PV integrated power systems.

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APPENDIX

Appendix (1)- ANFIS internal control configuration

```
[System]
Name='ANFIS_P1'
Type='sugenō'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=36
AndMethod='prod'
OrMethod='probor'
ImpMethod='prod'
AggMethod='sum'
DefuzzMethod='wtaver'

[Input1]
Name='input1'
Range=[-0.335943160026704 1.75237299998955]
NumMFs=6
MF1='in1mf1': 'trimf', [-0.753606392029954 -0.335943160026704
0.0817200719765457]
MF2='in1mf2': 'trimf', [-0.335943160026704 0.0817200719765457
0.499383303979796]
MF3='in1mf3': 'trimf', [0.0817200719765457 0.499383303979796
0.917046535983046]
MF4='in1mf4': 'trimf', [0.499383303979795 0.917046535983045
1.3347097679863]
MF5='in1mf5': 'trimf', [0.917046535983046 1.3347097679863
1.75237299998955]
MF6='in1mf6': 'trimf', [1.3347097679863 1.75237299998955 2.1700362319928]

[Input2]
Name='input2'
Range=[-0.0151845006965984 0.0173810769718102]
NumMFs=6
MF1='in2mf1': 'trimf', [-0.0216976162302802 -0.0151845006965984 -
0.00867138516291673]
MF2='in2mf2': 'trimf', [-0.0151845006965984 -0.00867138516291673 -
0.002158269629235]
MF3='in2mf3': 'trimf', [-0.00867138516291673 -0.002158269629235
0.00435484590444672]
MF4='in2mf4': 'trimf', [-0.002158269629235 0.00435484590444672
0.0108679614381284]
MF5='in2mf5': 'trimf', [0.00435484590444672 0.0108679614381284
0.0173810769718102]
MF6='in2mf6': 'trimf', [0.0108679614381284 0.0173810769718102
0.0238941925054919]

[Output1]
Name='output'
Range=[-6.07408146625185 6.95273738227347]
NumMFs=36
MF1='out1mf1': 'constant', [-6.09227373964349]
```

```

MF2='out1mf2': 'constant', [-3.48707518573823]
MF3='out1mf3': 'constant', [-0.881742076796485]
MF4='out1mf4': 'constant', [1.72347121601184]
MF5='out1mf5': 'constant', [4.32870509499006]
MF6='out1mf6': 'constant', [6.93395454275442]
MF7='out1mf7': 'constant', [-6.06930729188287]
MF8='out1mf8': 'constant', [-3.46403642259808]
MF9='out1mf9': 'constant', [-0.858829709966277]
MF10='out1mf10': 'constant', [1.74642982404394]
MF11='out1mf11': 'constant', [4.35168009259527]
MF12='out1mf12': 'constant', [6.95692520832273]
MF13='out1mf13': 'constant', [-6.04625881561901]
MF14='out1mf14': 'constant', [-3.4412272693052]
MF15='out1mf15': 'constant', [-0.835542244716368]
MF16='out1mf16': 'constant', [1.76977112524913]
MF17='out1mf17': 'constant', [4.37445291679233]
MF18='out1mf18': 'constant', [6.97834811896839]
MF19='out1mf19': 'constant', [0]
MF20='out1mf20': 'constant', [0]
MF21='out1mf21': 'constant', [-0.845582519282086]
MF22='out1mf22': 'constant', [1.79701898961062]
MF23='out1mf23': 'constant', [4.39095706176352]
MF24='out1mf24': 'constant', [0]
MF25='out1mf25': 'constant', [0]
MF26='out1mf26': 'constant', [0]
MF27='out1mf27': 'constant', [0]
MF28='out1mf28': 'constant', [1.81848516348907]
MF29='out1mf29': 'constant', [4.41323303448387]
MF30='out1mf30': 'constant', [0]
MF31='out1mf31': 'constant', [0]
MF32='out1mf32': 'constant', [0]
MF33='out1mf33': 'constant', [0]
MF34='out1mf34': 'constant', [1.8357619590036]
MF35='out1mf35': 'constant', [4.44950931882611]
MF36='out1mf36': 'constant', [0]

```

[Rules]

```

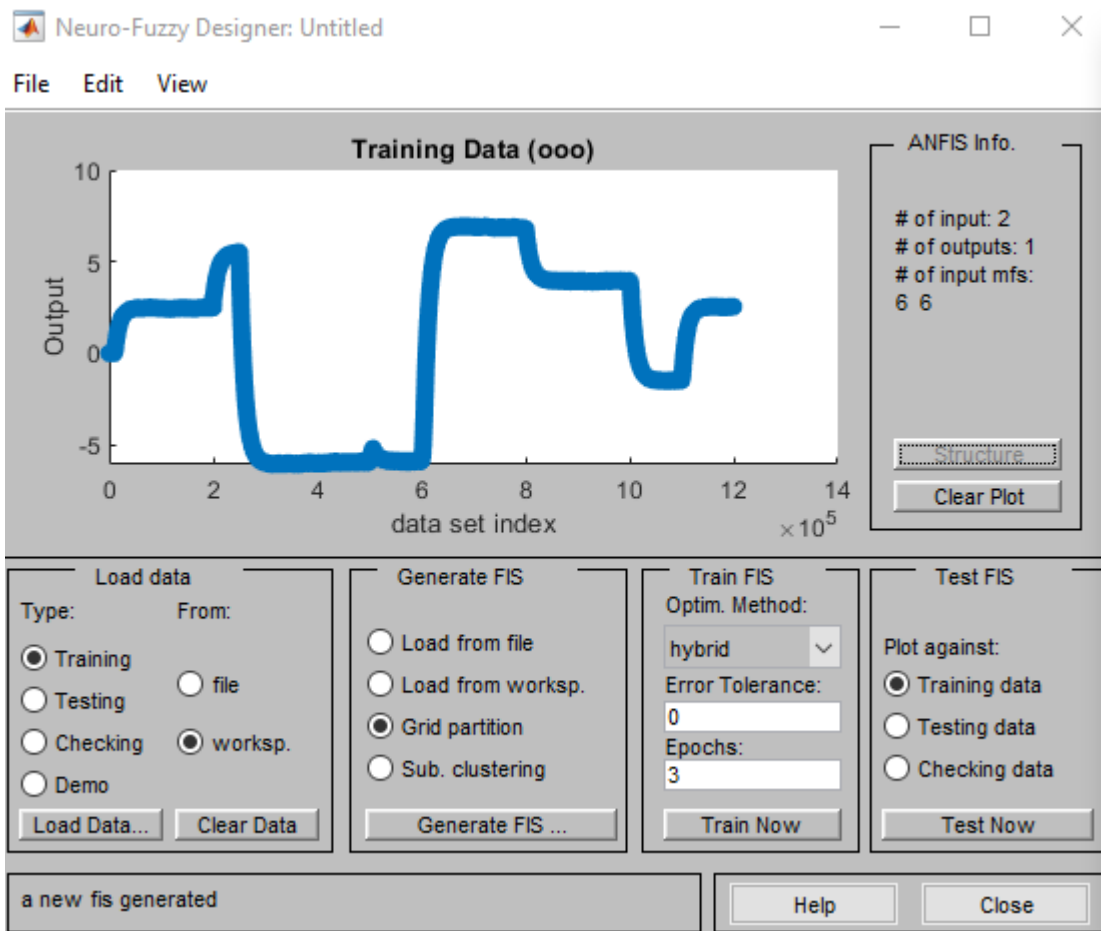
1 1, 1 (1) : 1
1 2, 2 (1) : 1
1 3, 3 (1) : 1
1 4, 4 (1) : 1
1 5, 5 (1) : 1
1 6, 6 (1) : 1
2 1, 7 (1) : 1
2 2, 8 (1) : 1
2 3, 9 (1) : 1
2 4, 10 (1) : 1
2 5, 11 (1) : 1
2 6, 12 (1) : 1
3 1, 13 (1) : 1
3 2, 14 (1) : 1
3 3, 15 (1) : 1
3 4, 16 (1) : 1
3 5, 17 (1) : 1
3 6, 18 (1) : 1
4 1, 19 (1) : 1
4 2, 20 (1) : 1

```

```

4 3, 21 (1) : 1
4 4, 22 (1) : 1
4 5, 23 (1) : 1
4 6, 24 (1) : 1
5 1, 25 (1) : 1
5 2, 26 (1) : 1
5 3, 27 (1) : 1
5 4, 28 (1) : 1
5 5, 29 (1) : 1
5 6, 30 (1) : 1
6 1, 31 (1) : 1
6 2, 32 (1) : 1
6 3, 33 (1) : 1
6 4, 34 (1) : 1
6 5, 35 (1) : 1
6 6, 36 (1) : 1

```



الخلاصة

تعتبر الطاقة الشمسية الكهروضوئية (PV) واحدة من أعلى موارد الطاقة المتجددة في جميع أنحاء العالم. وقد أدى تزايد كمية تركيب النظم الكهروضوئية إلى نشوء مشاكل جديدة في جودة الطاقة لأنظمة الشبكة الكهربائية. وبعض الأمثلة على هذه المشكلات هي اختلاف الجهد الكهربائي وتقلب مستويات الطاقة وتزايد مستوى التشوهات التوافقية. وللتخفيف من هذه المشاكل، يعتبر نظام نقل التيار المتناوب المرن للتوزيع (D-FACTS) حلاً قابلاً للتطبيق يمكن دمجها في نظام التوزيع الكهربائي.

علاوة على ذلك، يعتبر التعويض المتزامن للتوزيع الثابت (D-STATCOM) حلاً آخر لهذه المشاكل لتقليل الآثار السلبية الناشئة من الطاقة الشمسية الكهروضوئية على تنظيم الجهد الكهربائي والتشويه التوافقي في أنظمة التوزيع الكهربائية.

تهدف الأطروحة إلى التخفيف من مشاكل جودة الطاقة المتعلقة بالطاقة الشمسية الكهروضوئية من خلال تصميم نظام تحكم متقدم لجهاز D-STATCOM. وقد تم إجراء دراسة محاكاة عن طريق تصميم نموذج لنظام الطاقة الكهربائية يشتمل على نظام PV وجهاز (D-STATCOM). وقد تم تطبيق ثلاثة أنظمة تحكم وهي التكامل النسبي (PI) و شبكة اعصاب صناعية (ANN)، و نظام تكيفي مبهم عصبي (ANFIS)، ضمن التحكم الداخلي لجهاز D-STATCOM وذلك لتحسين جودة الطاقة لنظام الطاقة الكهربائية. كما تم تطبيق نموذجين مختلفين للتحكم في محول الكهرباء الثابت، الأول هو تضمين عرض النبضة الجيبي (SPWM) والثاني هو وحدة التحكم للتيار التخلفي (HCC).

وتم الحصول على النتائج لمستوى الجهد الكهربائي لمختلف نماذج أنظمة التحكم المدروسة للأنواع المختلفة من محول الكهرباء الثابت في ظل ظروف وسيناريوهات مختلفة. كما تم تقييم الأداء من خلال تقييم خصائص التحكم لوحدة التحكم المختلفة. وتم تحليل السيناريوهات المختلفة من خلال الطرق الرسومية وقياس مستوى التشويه التوافقي الكلي (THD) والخطأ التربيعي لمتوسط الجذر (RMSE).

جامعة البحرين

كلية الهندسة

قسم الهندسة الكهربائية والإلكترونية



تصميم نظام تحكم متقدم لجهاز D-FATCS في الشبكة الكهربائية المتصلة بالنظام الكهربائي الضوئي (PV)

أطروحة مقدمة كجزء من متطلبات الحصول على درجة الماجستير للعلوم الهندسية في الطاقة
المتجددة

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أبريل 2023