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On

DESIGN AND PERFORMANCE ANALYSIS OF THREE-PHASE SOLAR PV INTEGRATED UPQC

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Submitted in partial fulfilment of the requirement

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IN

ELECTRICAL AND ELECTRONICS ENGINEERING

(2023-2024)

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DECLARATION

We hereby declare that the work which is being presented in this Project report entitled **"DESIGN AND PERFORMANCE ANALYSIS OF THREE PHASE SOLAR PV INTEGRATED UPQC"** submitted to Electrical and Electronics Engineering Department of "AAR Mahaveer Engineering College " affiliated to Jawaharlal Nehru Technological University, Hyderabad is an authentic record of our team work carried out under the esteemed guidance of **Mrs**. **SHEELA KUMARI** of EEE Department, AARM in partial fulfilment for the award of Degree of **Bachelor of Technology** in the Department of Electrical and Electronics Engineering. The results embodied in this project work have not been submitted to any other Institute for the award of any degree or diploma. No part of the thesis is copied from books/journals/internet and where the portion is taken the same has been duly referred to in the text. The report work is based on the Mini Project done by Ourself and not copied from other sources.

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ABSTRACT

The growing emphasis on green energy and sustainable energy management has spurred the integration of distributed energy resources and distributed energy storage into distribution networks and micro grids. However, this surge in power electronic-based devices has led to a significant decline in power quality (PQ) within the distribution system. To address this issue, this article introduces a photovoltaic (PV) integrated unified power quality conditioner (UPQC) equipped with an adaptive compensating technique based on a variable leaky least mean square (VLLMS) algorithm. This soft computing- oriented method offers rapid convergence to the desired condition through an iterative approach while maintaining the weight of updating parameters within specified limits. Unlike conventional methods that rely on low pass or moving average filters, the VLLMS- based algorithm directly extracts fundamental components from polluted source voltage and load current to generate reference signals for the switching of shunt and series voltage source converters (VSCs) of the UPQC. By incorporating the feed-forward component of PV in the compensating technique of the shunt VSC, the system efficiently manages power balance between the grid, load, and PV, thereby resolving PQ issues such as current harmonics and poor power factor at the point of common coupling (PCC). Furthermore, it ensures the regulation of dc-link voltage. The series converter maintains a pure sinusoidal voltage at the load terminal regardless of sag/swell and harmonics present in the grid voltage. The effectiveness of the proposed system is validated through simulation implementation under various static and dynamic operating conditions.

CHAPTER 1

INTRODUCTION

1.1. Overview

One of the main responsibilities of a utility system is to supply electric power in the form of sinusoidal and currents with appropriate magnitudes and frequency for the customers at the points of common coupling (PCC). Although the generated voltage of synchronous machines in power plants are almost sinusoidal, some unsighted conditions such as lightning and short circuit faults and non linear loads cause steady state error or transient voltages and current disturbances. For instance, electric arc furnaces cause voltage fluctuations, power electronic converters generate current harmonics and distort voltage waveforms, and short circuits faults result in voltage sags and swells. On the other hand most customer loads such as computers, microcontrollers and hospital equipment are sensitive and unprotected to power quality disturbances and their proper operation depends on the quality of the voltage that is supplied to them.

This is possible only by ensuring an uninterrupted flow of power at proper voltage and frequency levels. As a result of this, FACTS devices and Custom power devices are introduced to electrical system to improve the power quality of the electrical power. With the help of these devices we are capable to reduce the problems related to power quality. There are many types of Custom Power devices. Some of these devices include Active Power Filters (APF), Surge Arresters (SA). Battery Energy Storage Systems (BESS), Super conducting Magnetic Energy Systems (SMES), Static Electronic Tap Changers (SETC), Solid State Fault Current Limiter (SSFCL), Solid-State Transfer Switches (SSTS), Static VAR Compensator (SVC), Distribution Series Capacitors (DSC), Dynamic Voltage Restorer (DVR), Distribution Static synchronous Compensators (DSTATCOM) and Uninterruptible Power Supplies (UPS) , Unified power quality conditioner (UPQC). But in this work, the main focus is kept only on DSTATCOM, DVR

and OPEN UPQC.

A DSTATCOM is a shunt compensator, based on power electronic converter. It is connected in shunt at PCC to protect critical loads from all load side disturbances. The
DSTATCOM is an effective device to reduce current variations and harmonics from the distribution network.

The unified power quality conditioner (UPQC), composed of a power-electronic series main unit installed in the medium-voltage/low-voltage (LV) substation, along with several power-electronic shunt units connected close to the end users. The series and parallel units do not have a common dc link, so their control strategies are independent of each other.

1.2. Introduction

The integration of photovoltaic (PV) systems into distribution networks has emerged as a significant facet of contemporary power generation strategies. PV technology offers a renewable and environmentally sustainable alternative to conventional fossil fuel-based energy sources. However, this integration presents formidable challenges, particularly in maintaining optimal power quality standards.

Power quality embodies a critical aspect of electrical power supply, encompassing parameters such as voltage stability, waveform integrity, and harmonic distortion levels. These factors profoundly influence the operational efficiency and longevity of electrical equipment and appliances. Within the context of PV integration, ensuring high power quality is paramount to prevent adverse effects on grid stability and reliability.

A primary concern associated with PV systems is their inherent intermittency due to solar resource variability. Unlike traditional power plants, which offer consistent output, solar energy generation fluctuates with environmental conditions, time of day, and geographical location. Such variability introduces voltage fluctuations and instability within distribution networks, posing challenges to reliable power delivery.

To address these challenges and bolster power quality in PV-integrated systems, researchers and engineers have turned to advanced power electronic devices like Unified Power Quality Conditioners (UPQC). UPQC represents a versatile solution capable of mitigating a broad spectrum of power quality issues, including voltage sag, swell, flicker, harmonics, and reactive power imbalances. By actively regulating voltage and current waveforms, UPQC devices stabilize grid voltage, suppress harmonic distortion, and compensate for reactive power fluctuations, thereby enhancing overall power supply quality.

This project endeavors to explore the efficacy of UPQC in improving power quality within PV-integrated systems operating within distribution networks. Through a comprehensive approach encompassing simulation studies and practical experimentation, we aim to evaluate the impact of UPQC deployment on critical power quality parameters. Our investigation seeks to assess UPQC's effectiveness in mitigating voltage fluctuations, harmonic distortion, and other disturbances, thus contributing to the optimization of PV system performance and grid stability.

In subsequent sections, we will delve into the theoretical underpinnings of power quality issues in PV-integrated systems, review pertinent literature on UPQC technology and its applications, outline our research methodology, present our findings and analysis, and discuss the implications for the future development of renewable energy infrastructure. By undertaking this interdisciplinary inquiry, we aspire to advance knowledge in sustainable energy systems and facilitate the realization of a more resilient and reliable power grid.

1.3. Problem Statement

The integration of photovoltaic (PV) systems into distribution networks poses challenges to maintaining consistent power quality standards due to the intermittent nature of solar power generation. This intermittency leads to voltage fluctuations, harmonic distortions, and reactive power imbalances, impacting grid stability and reliability. The problem at hand is to investigate and assess the effectiveness of Unified Power Quality Conditioners (UPQC) in mitigating these power quality issues within PV-integrated distribution networks.

1.4. Project Objectives

The primary objective of this study is to evaluate the efficacy of Unified Power Quality Conditioners (UPQC) in enhancing power quality within photovoltaic (PV) integrated systems operating in distribution networks. Specific research objectives include:

1. Investigating the impact of voltage fluctuations, harmonic distortions, and reactive power imbalances on power quality in PV-integrated distribution networks.
2. Understanding the operational principles and characteristics of UPQC technology for mitigating power quality issues.
3. Assessing the performance benefits and limitations of UPQC in terms of voltage stabilization, harmonic suppression, and reactive power compensation within PV- integrated distribution networks.
4. Optimizing UPQC deployment strategies for various grid conditions and PV system configurations to achieve desired power quality improvements.
5. Analyzing the economic feasibility and practical considerations associated with the implementation of UPQC for power quality enhancement in PV-integrated distribution networks.

1.5. Literature Review

[1] Bhende, C.N., et al. (2017) - Voltage regulation in distribution networks with photovoltaic systemusing D-STATCOM.

Provides specific insights into the application of D-STATCOMs for voltage regulation in distribution networks with PV systems. Offers a detailed discussion on control strategies based on proportional-integral (PI) controllers for mitigating voltage fluctuations. Addresses the importance of maintaining system stability under varying load and generation conditions.

Limited discussion on alternative control strategies or comparative analysis with other D-STATCOM applications may restrict the exploration of optimal control methods.
The study may not address potential challenges related to D-STATCOM integration with existing grid infrastructure, such as compatibility issues or retrofitting requirements.

[2] Khan, A.R., et al. (2019) - Fuzzy logic-based control strategy for D-STATCOM to enhance powerquality in distribution systems.

Introduces a novel control strategy based on fuzzy logic for enhancing power quality in distribution systems using D-STATCOMs. Focuses on real-time regulation of voltage and compensation for reactive power, addressing voltage sags and swells effectively. Offers potential for improved performance compared to traditional control methods.

May lack detailed discussion on implementation challenges or comparative analysis with other advanced control techniques. The study may not discuss the robustness of the proposed control strategy in handling uncertainties or variations in network parameters, which could impact its reliability in practical applications.

[3] Gupta, A., et al. (2020) - Comparative analysis of control strategies for D-STATCOM in distribution networks.

Conducts a comparative analysis of different control strategies for D-STATCOMs in distribution networks, including traditional PI controllers, model predictive control (MPC), and adaptive neuro-fuzzy inference system (ANFIS). Provides insights into the performance of various control strategies in terms of voltage regulation, harmonic suppression, and reactive power compensation.

May lack detailed discussion on specific application scenarios or practical considerations for implementing different control strategies. Limited consideration of transient performance metrics or dynamic response characteristics may overlook important aspects of control strategy effectiveness, particularly in scenarios with rapid load or generation fluctuations. The study may not explore the impact of communication delays or data acquisition constraints on the implementation of advanced control strategies, potentially overlooking practical challenges in real-world deployment.

[4] Ahn, et al. (2016) - Voltage regulation and harmonic mitigation techniques in PV-integrated distribution networks:

Ahn conducted a comprehensive analysis of voltage regulation and harmonic mitigation techniques in PV-integrated distribution networks. Their study highlighted the need for advanced control strategies to maintain power quality standards amidst varying solar output.

Advanced control strategies enable effective maintenance of power quality standards despite fluctuations in solar output. Implementation of advanced control strategies may introduce complexity to system design and operation.

[5] Liu, et al. (2018) - Effectiveness of UPQC in mitigating voltage fluctuations and harmonics in PV systems

Liu evaluated the effectiveness of UPQC in mitigating voltage fluctuations and harmonics in PV systems, demonstrating its potential for improving power quality performance. UPQC demonstrates effectiveness in mitigating voltage fluctuations and harmonics, leading to improved power quality.

Complexity of UPQC design and operation may pose challenges in practical implementation.

[6] Zhang, et al. (2019) - Novel control strategy for UPQC to enhance voltage regulation andharmonic compensation in PV systems.

Zhang proposed a novel control strategy for UPQC to enhance voltage regulation and harmonic compensation in PV systems, achieving superior power quality enhancement compared to traditional methods. Novel control strategy results in superior voltage regulation and harmonic compensation compared to traditional methods.

Implementation of novel control strategy may require additional computational resources and expertise.

[7] Gómez & Quintero (2017) - Cost-benefit analysis of UPQC deployment in PV systems.

Gómez & Quintero conducted a cost-benefit analysis of UPQC deployment in PV systems, considering factors such as installation costs, energy savings, and reliability improvements.- UPQC deployment offers long-term economic benefits through energy savings and enhanced system reliability.

Initial investment costs of UPQC deployment may be significant, potentially limiting widespread adoption.

[8] Ghatge, et al. (2019) - Analysis of UPQC performance in PV-integrated distribution networks.

Ghatge conducted an analysis of UPQC performance in PV-integrated distribution networks, focusing on its effectiveness in voltage regulation and harmonic mitigation. UPQC demonstrates robust performance in voltage regulation and harmonic mitigation, enhancing power quality in PV systems.

Implementation complexity and cost may hinder widespread adoption, especially in smaller-scale PV installations

[9] Khadkikar et al. (2018) - Evaluation of UPQC control strategies for PV systems.

Khadkikar evaluated various UPQC control strategies for PV systems, assessing their impact on power quality improvement and system stability. UPQC control strategies offer versatility and adaptability to different PV system configurations, enhancing power quality under varying operating conditions.

Selection and implementation of appropriate control strategies require careful consideration of system dynamics and operational requirements.

1.6. Scope of work

From the literature review, it is observed that power quality is major area of concern for power engineers now days. Reliability of power supply is of utmost importance for the utilities to achieve global benefits. Different types of custom power devices are proposed to improve the power quality and to maintain voltage and current profile. Utility is responsible for maintaining voltage profile supplied to the consumers, while consumers are responsible for maintaining current profile at the PCC. Industrial loads such as induction motor drive, and dynamic loads causes fluctuations and degrade the power quality. In order to improve the quality of power, custom power devices like DSTATCOM and UPQC has been used. The results are obtained by using MATLAB/ SIMULINK.

Therefore, in the presented work, attempts have been made to analyze the functionalities of the PV-UPQC in a distribution system under different conditions for its maximum utilization besides PQ improvement. The main contributions of the proposed work are highlighted in the following.

1) Implementation of VLLMS-based adaptive compensation strategy, which offers accurate and faster tracking of the fundamental component from the highly distorted current and voltage signals, eliminating the need for low-pass or moving average filters in comparison with VSSLMS based technique.

2) Alleviation of current related PQ issues, reactive power compensation, dc-link voltage regulation by shunt VSC; also efficient management of power between load, grid, and PV under varying PV generation and load demand due to the involvement of feed-forward component for PV in the shunt controller.

3) Enhancement of performance of the series controller under highly polluted grid voltage by considering two different components for reference signal generation using voltage unit templates—one component for voltage sag/swell and other component for voltage harmonics

CHAPTER 2

BACKGROUND WORK

CHAPTER 2
BACKGROUND WORK

2.1. DEFINITION OF POWER QUALITY

Power quality has different meanings to different people. The definition of power quality given in the IEEE dictionary originates in IEEE Std. 1100: "*Power quality is the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment*."

However, as is stated by Heydt (1998) and Boolen (1999), there is no single definition of the term "power quality". For example, Heydt (1998) gives the following description: "*Power quality is the provision of voltages and system design so that the user of electric power can utilise electric energy from the distribution system successfully, without interference or interruption.*" The next explanation is provided by Bollen (1999): "*Power quality is the combination of voltage quality and current quality. Thus power quality is concerned with deviations of voltage and/or current from the ideal.*" On the other hand, power quality problems are described by Morán et. al. (1999) in the following way: "*A power quality problem exists if any voltage, current or frequency deviation results in a failure or in bad operation of the customer's equipment. The quality of the power supply consists basically of two elements, the supply reliability and the voltage quality.*" Based on the previous descriptions it can be concluded that the concept "power quality" involves two parties: the supplier of the electricity and the user. The "power quality" can then be regarded as a measure of purity of the energy which is transferred from the supplier to the user.

Current quality is concerned with deviations of the current from the ideal. The ideal current is a single-frequency sine wave of constant frequency and magnitude. An additional requirement is that this sine wave is in phase with the supply voltage. Thus where voltage quality has to do with what the utility delivers to the consumer, current quality is concerned with what the consumer takes from the utility. Voltage and current are strongly related and if either voltage or current deviates from the ideal it is hard for the other to be ideal. Voltage quality is concerned with deviations of the voltage from the ideal. The ideal voltage is a single-frequency sine wave of constant frequency and constant magnitude. The term voltage quality can be interpreted as the quality of the product delivered by the utility to the customers. Power quality problem is defined as any power problem manifested in voltage,

2.2. SOURCES OF POOR POWER QUALITY

- Adjustable –speed drives
- Switching Power supplies
- Arc furnaces
- Electronic Fluorescent lamp ballasts
- Lightning Strike
- L-G fault
- Non- linear load
- Starting of large motors
- Power electronic devices

2.3. NEED OF POWER QUALITY

There is an increased concern of power quality due to the following reasons

- New generation loads that uses microprocessor and microcontroller based controls and power electronic devices, are more sensitive to power quality variations than that equipments used in the past.
- Most of the networks are interconnected these days. Integrated processes mean that the failure of any component has much more important consequences.

- The demand for increased overall power system efficiency resulted in continued growth of devices such as high-efficiency adjustable-speed motor drives and shunt capacitors for power factor correction to reduce losses. This is resulting in increasing harmonic level on power systems and has many people concerned about the future impact on system capabilities.
- End users have an increased awareness of power quality issues. Utility customers are becoming better informed about such issues as interruptions, sags, and switching transients and are challenging the utilities to improve the quality of power delivered.

2.4. CLASSIFICATION OF POWER QUALITY PROBLEMS AND THEIR IMPACTS

The power quality is badly disturbed due to the extensively use of nonlinear and dynamic loads and various faults in power system. Moreover, the controlling equipment and electronic devices based on computer technology demand higher levels of power quality. This type of devices are sensitive to small changes of power quality, a short time change on PQ can cause great economical losses. Because of the two reasons mentioned above, no matter for the power business, equipment manufacturers or for electric power customers, power quality problems had become an issue of increasing interest. Under the situation of the deregulation of power industry and competitive market, as the main character of goods, power quality will affect the price of power directly in near future.

This thesis takes into account the most common power quality problems such as voltage sags/swells and current harmonics as shown in Figure-2.1. Together they account for high percentage of the power quality disturbances affecting most commercial and industrial customers.

1. Transients.
2. Interruptions.
3. Sag / under voltage.
4. Swell / Overvoltage.
5. Waveform distortion.
6. Voltage fluctuations.
7. Frequency variations.

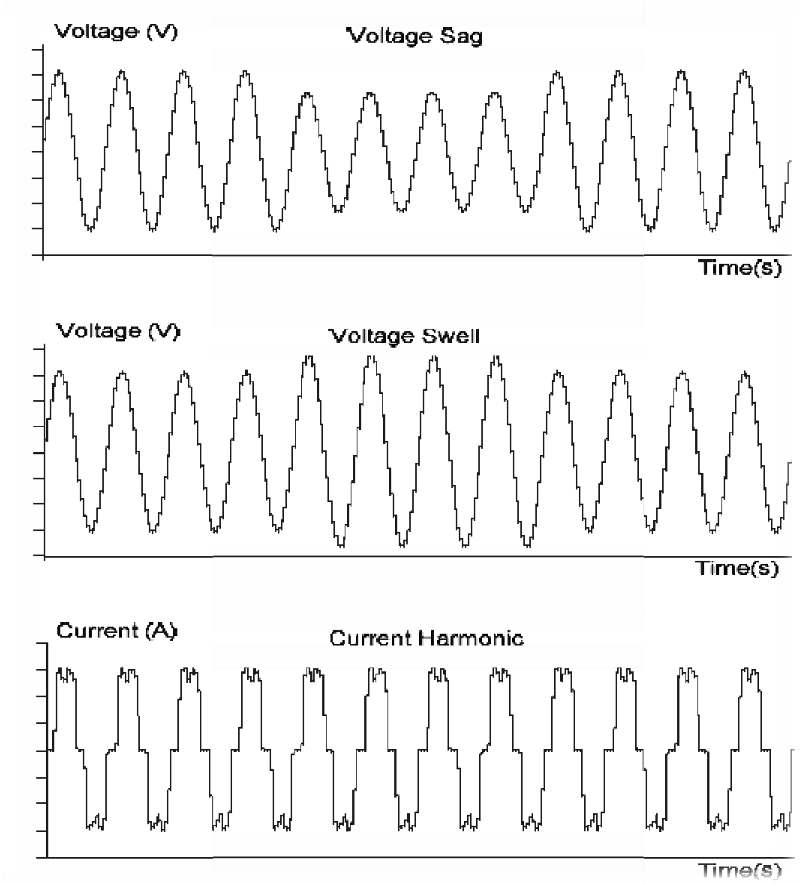


Figure-2.1: Most Common Types of Power Quality Problems

2.4.1. Voltage Swells

A voltage swell can be defined as an increase to between 1.1 and 1.8 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to 1 min. The voltage swells are usually associated with system fault conditions, but they are not as common as voltage sags. One way that a swell can occur is from the temporary voltage rise on the unfaulted phases during a single line to ground fault (Dugan et al., 2003). Swells can also be caused by switching off a large load or energizing a large capacitor bank, insulation breakdown, sudden load reduction and open neutral connection. Voltage swells can negatively affect the performance of sensitive electronic equipment, cause data errors, produce equipment shutdowns, may cause equipment damage and reduce equipment life. It causes nuisance tripping and degradation of electrical contacts.

2.4.2. Voltage Sag

Voltage sag is defined as a decrease to between 0.1 and 0.9 per unit (pu) in rms voltage at the power frequency for durations from 0.5 cycle to 1 min. Voltage sags are generally related with system faults but can also be caused by energization of heavy loads or starting of large motors and overloaded wiring. The term sag describes a short- duration voltage decrease. Voltage sag problems in industrial equipment include (Eberhard et al., 2007) relays opening due to the dip affecting the relay's coil voltage, undervoltage sensors on the AC mains operating unnecessarily, incorrect reports from sensors, such as air flow sensors or water pressure sensors, circuit breakers or fuses operating, either due to the increase in current on non-dipped phases or (more often) due to a large increase in current immediately after the dip or a small section of highly-sensitive electronics that responds incorrectly to the sag.

A study of voltage sag effect has been done analytically in the time domain, by using dynamic load models mainly designed for stability analysis. The proposed system is analysed to compensate for voltage sag of 0.2 sec. occurred due to three phase fault at consumer end.

2.4.3. Current Harmonic Distortion

The harmonic voltage and current distortion are strongly linked with each other because harmonic voltage distortion is mainly due to non-sinusoidal load currents. Current harmonic distortion requires over-rating of series components like transformers and cables. As the series resistance increases with frequency, a distorted current will cause more losses than a sinusoidal current of the same rms value (Bollen, 2001). Types of equipment that generate current harmonics are single-phase loads, switched mode power supplies, electronic fluorescent lighting ballasts, small Uninterruptible Power Supply (UPS) units and variable speed drives (Meral, 2009).

$$V_{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V1}$$

where $V1$ is the rms magnitude of the fundamental component, and Vn is the rms magnitude of component n where n = 2,3,……..
.... ,∞

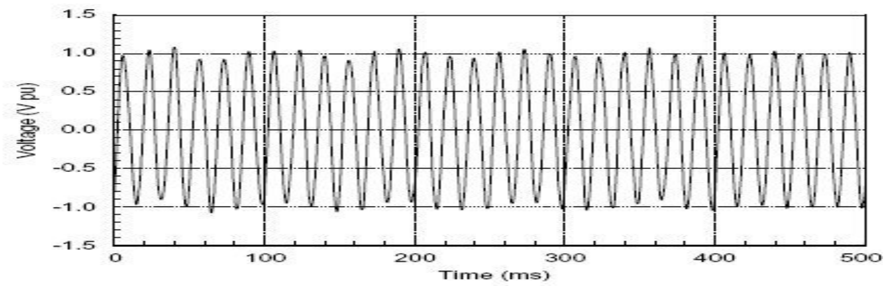
Table 2.1: IEEE-519 current harmonic distortion limits

Maximum current harmonic distortion in percent of I_{LH}						
Individual harmonic order (Odd harmonics)						
I_{SC}/I_{LH}	**<11**	**11≤h<17**	**17≤h<23**	**23≤h<35**	**35≤h**	**TDD**
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<100	12.0	5.5	5.0	2.0	1.0	15.0
0>1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonics are limited to 25% of the odd harmonic limits above						
Current distortions that results in a DC offset, e.g., half-wave converters, are not allowed						
* All power generation equipment is limited to these values of current distortions, regardless of actual I_{SC}/I_{LH}.						

These limits are proportional to the short circuit current ratio and each consumer must limit the current that they draw accordingly as shown in Table 2.1. The aim of the standard is to ensure that voltage harmonic distortion is kept low by limiting the current harmonics drawn by end users.

2.4.4. Voltage Flickers/Fluctuations

Voltage fluctuations are relatively small (less than 5 percent) variations in the rms line voltage. Cyclo converters, arc furnaces, and other systems that draw current not in synchronization with the line frequency are the main contributors of these variations. Most common effect of voltage flicker is an unwanted pulsating torque due to the fluctuation of the speed in electric drives.



2.2.Voltage Fluctuations

2.5. SOLUTIONS TO POWER QUALITY PROBLEMS

The mitigation of power quality problems can be achieved in two ways. The solution to the power quality can be done from customer side or from utility side. First method is called load conditioning and the other method is line conditioning. Load conditioning ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion while the installation of line conditioning systems suppresses or counteracts the power system disturbances. They are depend on PWM converters and connected in shunt or in series to low and medium voltage distribution system. Series active power filters must operate in conjunction with shunt passive filters in order to compensate the load current harmonics. Series active power filters operates as a controllable voltage source whereas shunt active power filters operate as a controllable current source.

(i) Lightening and Surge Arresters: Arresters are designed for lightening the protection of transformers, but these are not sufficient for limiting voltage to protect sensitive electronic control circuits from voltage surges.

(ii) Thyristor Based Static Switches: The static switch is a device for switching a new element into the circuit when the voltage support is needed. It has dynamic response time of about one cycle. It may be used in the alternate power line applications. To correct quickly for voltage spikes, sags or interruptions, the static switch may used to switch one or more of devices such as filter, capacitor, alternate power line, energy storage systems etc.

(iii) Energy Storage Systems: Storage systems may be used to protect sensitive production equipments from shutdowns due to voltage sags or momentary interruptions. The energy is fed to system for compensate for the energy that will lost by the voltage sag or interruption. These are usually DC storage systems such as batteries, UPS, superconducting magnet energy storage (SMES), storage capacitors or even fly wheels driving DC generators. The output of these devices can be supplied to the system through an inverter on a momentary basis.

(iv) Electronic Tap Changing Transformer

(v) Harmonic Filters: Filters are used to reduce or eliminate harmonics. It is always advantage able to use a 12-pluse or higher transformer connection, rather than a filter.

2.6. SOLAR PHOTOVOLTAICS

2.6.1. Introduction

The conversion of solar radiation occurs by the photovoltaic effect which was first observed by Becquerel. It is quite generally defined as the emergence of an electric voltage between two electrodes attached to a solid or liquid system upon shining light onto this system. Energy conversion devices which are used to convert sunlight to electricity by the use of the photo-voltaic effect are called solar cells. Single converter cell is called a solar cell or more generally photovoltaic cell and combination of such cells designed to increase the electric power output is called a solar module or solar array and hence the name 'Photovoltaic Arrays'. Solar cells can be arranged into large groupings called arrays. These arrays, composed of many thousands of individual cells, can function as central electric power stations, converting sunlight into electrical energy for distribution to industrial, commercial and residential users. Solar cells in much smaller configurations are commonly referred to as solar cell panels or simply panels. Practically, all photovoltaic devices incorporate a P-N junction in a semiconductor across which the photo voltage is developed. The solar panels consist mainly of semiconductor material, with Silicon being most commonly used.

2.6.2. Basics of Solar Cell

The overwhelming majority of solar cells are fabricated from silicon with increasing efficiency and lowering cost as the materials range from amorphous (non- crystalline) to polycrystalline to crystalline (single crystal) silicon forms. Unlike batteries or fuel cells, solar cells do not utilize chemical reactions or require fuel to produce electric power and unlike electric generators, they do not have any moving parts.

Light enters the device through an optical coating, or antireflection layer that minimizes the loss of light by reflection; it effectively traps the light falling on the solar cell by promoting its transmission to the energy-conversion layers below. The antireflection layer is typically an oxide of silicon, tantalum or titanium that is formed on the cell surface by spin coating or a vacuum deposition technique.

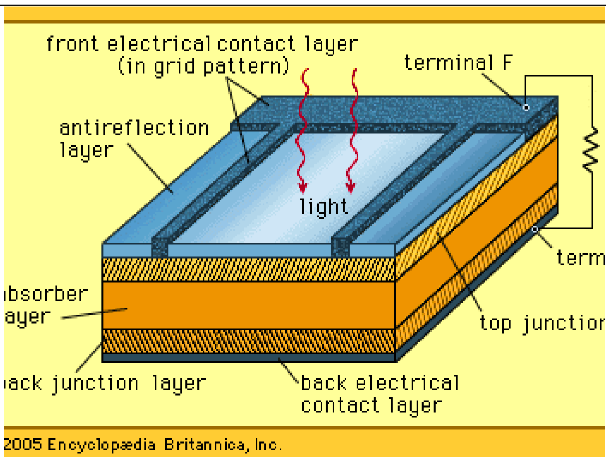


Fig.2.3.Solar Cell

The three energy-conversion layers below the antireflection layer are the top junction layer, the absorber layer, which constitutes the core of the device, and the back junction layer. Two additional electrical contact layers are needed to carry the electric current out to an external load and back into the cell, thus completing an electric circuit. The electrical contact layer on the face of the cell where light enters is generally present in some grid pattern and is composed of a good conductor such as a metal. Since metal blocks light, the grid lines are as thin and widely spaced as is possible without impairing collection of the current produced by the cell. The back electrical contact layer has no such diametrically opposed restrictions. It needs to simply function as an electrical contact and thus cover the entire back surface of the cell structure. Because the back layer also must be a very good electrical conductor, it is always made of metal. Since most of the energy in sunlight and artificial light is in the visible range of electromagnetic radiation, a solar cell absorber should be efficient in absorbing radiation at those wavelengths. Materials that strongly absorb visible radiation belong to a class of substances known as semiconductors. Semiconductors in thicknesses of about one-hundredth of a centimeter or less can absorb all incidents visible light; since the junction-forming and contact layers are much thinner, the thickness of a solar cell is essentially that of the absorber. Examples of semiconductor materials employed in solar cells include Silicon, Gallium Arsenide, Indium Phosphide and Copper Indium Selenide.

2.6.3 Solar Cell Characteristics

The current-to-voltage characteristic, power-to-voltage characteristics of a solar cell are non-linear, which make it difficult to determine the maximum power point. It is straightforward to determine the maximum power point on a linear curve as maximum power is transferred at the midpoint of the current-voltage characteristic. A typical V-I characteristic of solar cell is shown in Fig.2.4

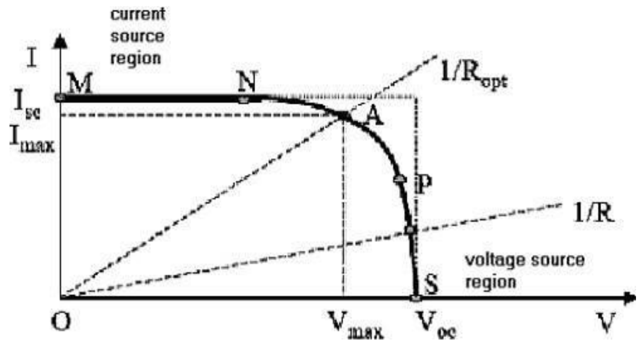


Fig.2.4.V-I Characteristics of Solar Cell

For a solar cell, the non-linear relationship means the maximum power point has to be determined by calculating the product of the voltage and output current. In order to extract maximum power from the solar cell, the solar cell must always be operated at or very close to where the product of the voltage and output current is the highest. This point is referred to as the maximum power point (MPP) and it is located around the 'bend' or 'knee' of the I-V characteristic.

The operating characteristic of a solar cell consists of two regions: the current source region and the voltage source region. In the current source region, the internal impedance of the solar cell is high and this region is located on the left side of the current- voltage curve. The voltage source region, where the internal impedance is low, is located on the right side of the current-voltage curve. As can be observed from the characteristic curve, in the current source region, the output current remains almost constant as the terminal voltage changes and in the voltage source region, the terminal voltage varies only minimally over a wide range of output current.

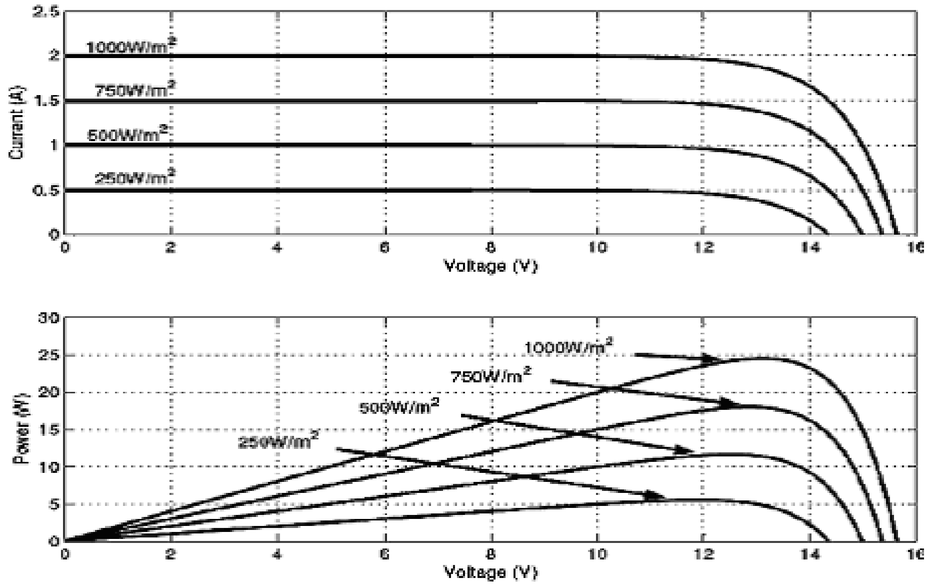


Fig.2.5. I-V and P-V Characteristics of a Solar cell including Irradiance effect

The change in voltage is minimal with varying irradiance and for most practical applications, the change is considered negligible.

Although irradiance is an important factor in determining the I-V characteristic of a solar panel, it is not the only factor. Temperature also plays an important role in predicting the I-V characteristic, and the effects of both factors have to be considered when designing a PV system. Whereas the irradiance mainly affects the output current, the temperature mainly affects the terminal voltage. A plot of I-V and P-V characteristic with varying temperature is shown in Fig 2.6. It is observed from Fig 2.6 that the terminal voltage increases with decreasing temperature. One of the reasons the solar panel operates more efficiently with decreasing temperature is due to the electron and hole mobility of the semiconductor material. As temperature increases, the electron and hole mobility in the semiconductor material decreases significantly. The electron mobility for Silicon at 25º C is about 1700cm2/volt-sec and will decrease to about a fourth of this value as temperature increases to 225º C and likewise the hole mobility decreases from about 600cm2/volt-sec at 25ºC to 200cm2/volt-sec as temperature increases to 225ºC. While the higher reference temperatures are not realistic operating conditions for a solar panel, it does show that electron and hole mobility decrease with increasing temperature.

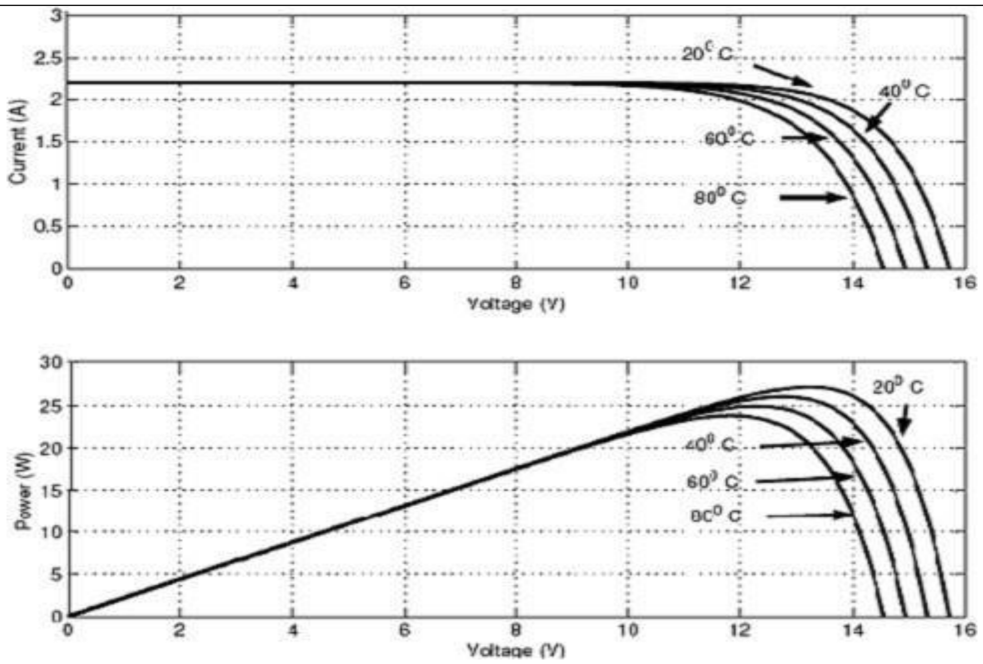


Fig.2.6. I-V and P-V Characteristics of solar cell with varying temperature

The cell's short circuit current intersects the Y-axis at point B and the open circuit voltage intersects the X-axis at point C. To achieve maximum energy transfer, systems powered by solar cells should be designed to transfer energy to the load at point A on the I-V curve. No energy should be delivered at points B and C, and most of the energy should be delivered as the operating point approaches point A. In a solar panel array, it is even more important that load impedance and source impedance are well matched. Once the cells are matched by their I-V characteristics, they can be grouped into individual arrays and each array is then made to operate at its maximum energy transfer point.

Majority of solar cells have high capacitance associated with their forward biased p-n junctions because the charged carriers are much closer together. The unwanted capacitance increases as the size of the solar cell and junction area increases. The I-V curve of the solar cell can be determined by taking fast I-V measurements, which is done by applying a constant voltage and measuring the resulting current for the device being tested. However the high capacitance makes it difficult to get fast I-V measurements.

The shape of the I-V curve of the solar cell is governed by the cell's high Thevenin's equivalent impedance. The short circuit current is determined by the incident light intensity and it is inversely proportional to the applied voltage. The total circuit voltage and incident light determine the external circuit current

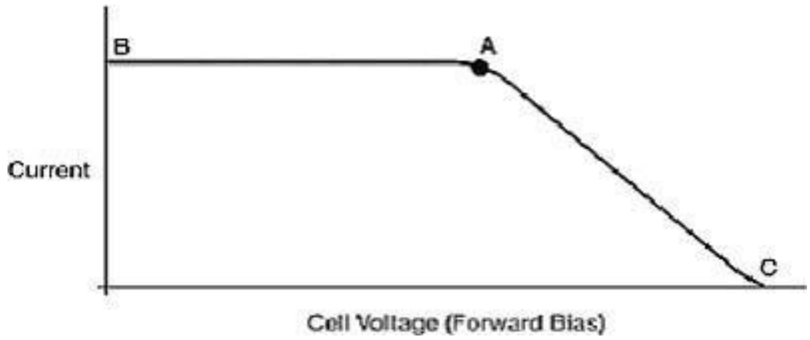


Fig.2.7. Illustration of Maximum power point

2.6.4. Solar cell Modeling

To properly model a solar cell, it is important to understand how solar cells operate. Solar cells are primarily made of semiconductor material that when exposed to light induces a process of photon reflection and absorption, generation of free carriers and lastly charge separation, which creates an electric field. The semiconductor properties determine how effectively this process occurs. Some of the most important properties include the absorption coefficient, the reflectance of the semiconductor surface, drift-diffusion parameters and surface recombination velocities.

For practical power applications, the voltage produced by one solar cell is usually not sufficient to power most equipment. An array of 20 to 80 solar cells connected in series to form a “Solar Module” is usually necessary to provide the required voltage. Solar cell manufacturers provide some key parameters of a solar module in their Data Sheet. The output power is given in Wp (Watt peak), which means the module is rated at Standard Test Conditions (STC). The STC are illumination levels of 1000 W/m2 (bright sunshine), a spectrum equivalent to Air Mass 1.5 and 25°C module temperature at the test. The manufacturer’s data sheet also provides the short circuit current, the current produced when the output voltage is zero and the open circuit voltage, the voltage across the output terminals when there is no current flowing in the cell.

The simplified equivalent circuit of a solar cell consists of a diode and a current source which are switched in parallel. The current source generates the photo current I_{Ph}, which is directly proportional to the solar irradiance G. The p-n transition area of the solar cell is equivalent to a diode.

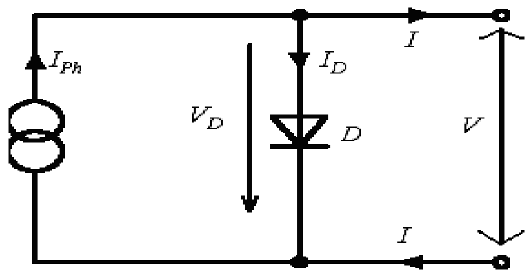


Fig.2.8. Equivalent circuit of a solar cell

The *V-I* equation of the simplified equivalent circuit could be derived from Kirchhoff's current law

$$I = I_{Ph} - I_D = I_{Ph} - I_S \cdot (\exp(\frac{V}{m \cdot V_T}) - 1)$$ **…(2.1)**

Where

I_{Ph} --- Photo current

I_D --- Diode current

I_S --- Diode reverse saturation current

m --- Diode ideal factor

V_T = (k*T)/q is Thermal voltage (25.7 mV at 25°C)

k = Boltzmann Constant=1.3824*e-23

T = Absolute Temperature

q = charge of an electron=1.60*e-19 couloumbs

V = output voltage of the solar cell

I = output current through the solar cells

The simplified equivalent circuit doesn't give an optimal representation of the electrical process at the solar cell. In real solar cells a voltage loss on the way to the external contacts could be observed. This voltage loss could be expressed by a series resistor R_S. Furthermore leakage currents could be observed, which could be described by a parallel resistor R_P. (Fig. 2.9)

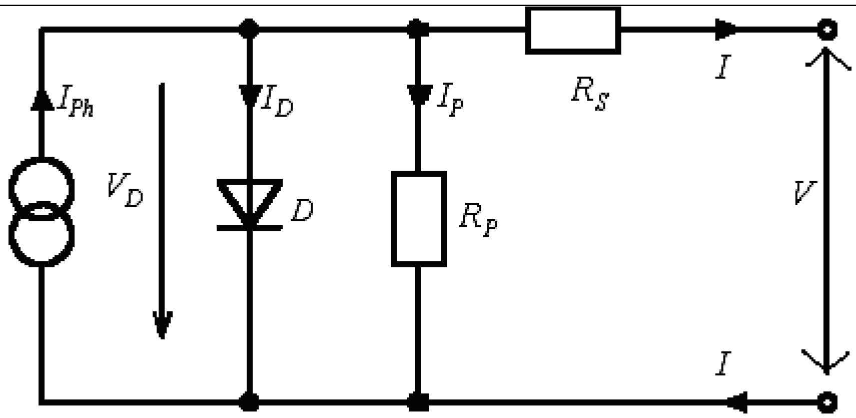


Fig.2.9**:** Equivalent Circuit for One Diode Model Of A Solar Cell

Derived from Kirchhoff's first law the equation for the extended I-V curve could be achieved.

$$I = I_{Ph} - I_D - I_P \qquad \textbf{... (2.2)}$$

$$I_P = {V_D}/{R_P} = \left\{ \frac{(V + IR_S)}{R_P} \right\} \qquad \textbf{... (2.3)}$$

$$I = I_{Ph} - \left\{ I_S \left(\exp\left(\frac{q(V + IR_S)}{mkTN_S} \right) - 1 \right) \right\} - \left(\frac{V + IR_S}{R_P} \right) \qquad \textbf{... (2.4)}$$

Where

I_{Ph} is the photo current

I_D is the Diode current

R_S is the cell's series resistance, R_P is the shunt resistance

The specifications of the solar module supplied by the manufacturer's data sheet are as shown in Table.2.2.

Table 2.2: The key specifications of the solar MSX – 60 PV panel

At Temperature T = 25ºC, Insulation G=1000W/m²		
Open circuit voltage	V_{oc}	21.0 V
Short circuit current	I_{sc}	3.74A
Voltage at max.power	V_m	17.1V
Current at max power	I_m	3.5A
Maximum power	P_m	60.0W

2.7. FACTS

Flexible AC Transmission Systems, called FACTS, got in the recent years a well known term for higher controllability in power systems by means of power electronic devices. Several FACTS-devices have been introduced for various applications worldwide. A number of new types of devices are in the stage of being introduced in practice.

In most of the applications the controllability is used to avoid cost intensive or landscape requiring extensions of power systems, for instance like upgrades or additions of substations and power lines. FACTS-devices provide a better adaptation to varying operational conditions and improve the usage of existing installations. The basic applications of FACTS-devices are:

1. Power flow control,
2. Increase of transmission capability,
3. Voltage control,
4. Reactive power compensation,
5. Stability improvement,
6. Power quality improvement,
7. Power conditioning,
8. Flicker mitigation,
9. Interconnection of renewable and distributed generation and storages.

Figure 2.10 shows the basic idea of FACTS for transmission systems. The usage of lines for active power transmission should be ideally up to the thermal limits. Voltage and stability limits shall be shifted with the means of the several different FACTS devices. It can be seen that with growing line length, the opportunity for FACTS devices gets more and more important.

The influence of FACTS-devices is achieved through switched or controlled shunt compensation, series compensation or phase shift control. The devices work electrically as fast as current, voltage or impedance controllers. The power electronic component allows very short reaction times down to far below one second.

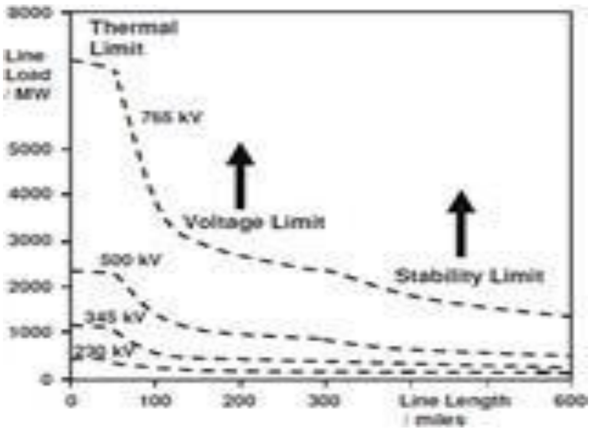


Fig.2.10. Operational limits of transmission lines for different voltage levels

For the FACTS side the taxonomy in terms of 'dynamic' and 'static' needs some explanation. The term 'dynamic' is used to express the fast controllability of FACTS- devices provided by the power electronics. This is one of the main differentiation factors from the conventional devices. The term 'static' means that the devices have no moving parts like mechanical switches to perform the dynamic controllability. Therefore most of the FACTS-devices can equally be static and dynamic.

The development of FACTS-devices has started with the growing capabilities of power electronic components. Devices for high power levels have been made available in converters for high and even highest voltage levels. The overall starting points are network elements influencing the reactive power or the impedance of a part of the power system. Fig.2.11. shows a number of basic devices separated into the conventional ones and the FACTS-device.

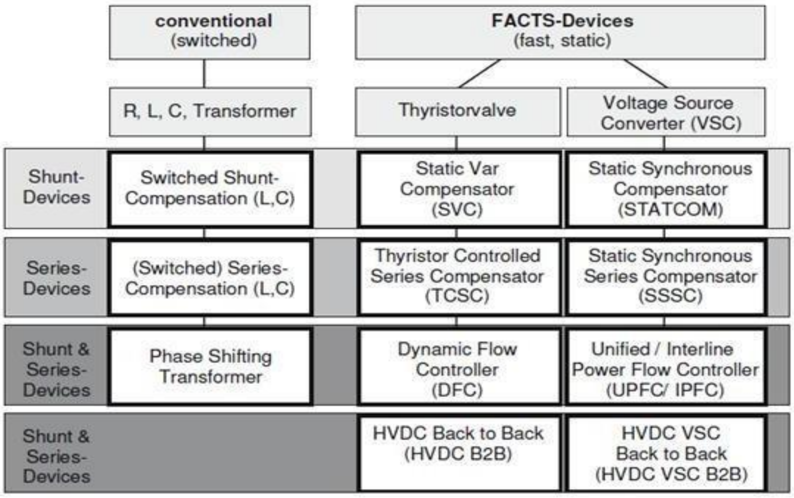


Fig.2.11. Overview of major FACTS-Devices

The left column in Figure 2.11 contains the conventional devices build out of fixed or mechanically switch able components like resistance, inductance or capacitance together with transformers. The FACTS-devices contain these elements as well but use additional power electronic valves or converters to switch the elements in smaller steps or with switching patterns within a cycle of the alternating current. The left column of FACTS-devices uses Thyristor valves or converters. These valves or converters are well known since several years. They have low losses because of their low switching frequency of once a cycle in the converters or the usage of the Thyristors to simply bridge impedances in the valves.

The right column of FACTS-devices contains more advanced technology of voltage source converters based today mainly on Insulated Gate Bipolar Transistors (IGBT) or Insulated Gate Commutated Thyristors (IGCT). Voltage Source Converters provide a free controllable voltage in magnitude and phase due to a pulse width modulation of the IGBTs or IGCTs. High modulation frequencies allow to get low harmonics in the output signal and even to compensate disturbances coming from the network. The disadvantage is that with an increasing switching frequency, the losses are increasing as well. Therefore special designs of the converters are required to compensate this.

2.8. CONFIGURATIONS OF FACTS-DEVICES

2.8.1. Shunt Devices:

The most used FACTS-device is the SVC or the version with Voltage Source Converter called STATCOM. These shunt devices are operating as reactive power compensators. The main applications in transmission, distribution and industrial networks are:

1. Reduction of unwanted reactive power flows and therefore reduced network losses.
2. Keeping of contractual power exchanges with balanced reactive power.
3. Compensation of consumers and improvement of power quality especially with huge demand fluctuations like industrial machines, metal melting plants, railway or underground train systems.
4. Compensation of Thyristor converters e.g. in conventional HVDC lines.
5. Improvement of static or transient stability.

Almost half of the SVC and more than half of the STATCOMs are used for industrial applications. Industry as well as commercial and domestic groups of users require power quality. Flickering lamps are no longer accepted, nor are interruptions of industrial processes due to insufficient power quality. Railway or underground systems with huge load variations require SVCs or STATCOMs.

2.8.1(a) SVC:

Electrical loads both generate and absorb reactive power. Since the transmitted load varies considerably from one hour to another, the reactive power balance in a grid varies as well. The result can be unacceptable voltage amplitude variations or even a voltage depression, at the extreme a voltage collapse.

A rapidly operating Static Var Compensator (SVC) can continuously provide the reactive power required to control dynamic voltage oscillations under various system conditions and thereby improve the power system transmission and distribution stability.

Applications of the SVC systems in transmission systems:

a. To increase active power transfer capacity and transient stability margin.

b. To damp power oscillations.

c. To achieve effective voltage control.

In addition, SVCs are also used:

1. In transmission systems:

a. To reduce temporary over voltages.

b. To damp sub synchronous resonances.

c. To damp power oscillations in interconnected power systems.

2. In traction systems:

a. To balance loads.

b. To improve power factor.

c. To improve voltage regulation.

3. In HVDC systems

a. To provide reactive power to ac–dc converters.

4. In arc furnaces

a. To reduce voltage variations and associated light flicker.

Installing an SVC at one or more suitable points in the network can increase transfer capability and reduce losses while maintaining a smooth voltage profile under different network conditions. In addition an SVC can mitigate active power oscillations through voltage amplitude modulation.

SVC installations consist of a number of building blocks. The most important is the Thyristor valve, i.e. stack assemblies of series connected anti-parallel Thyristors to provide controllability. Air core reactors and high voltage AC capacitors are the reactive power elements used together with the Thyristor valves. The step up connection of this equipment to the transmission voltage is achieved through a power transformer.

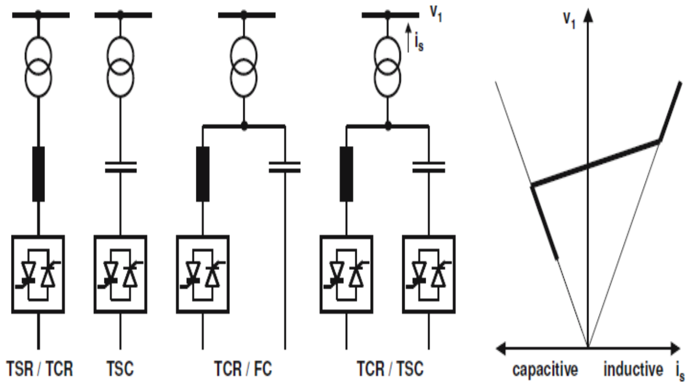


Fig.2.12. SVC building blocks and voltage / current characteristic

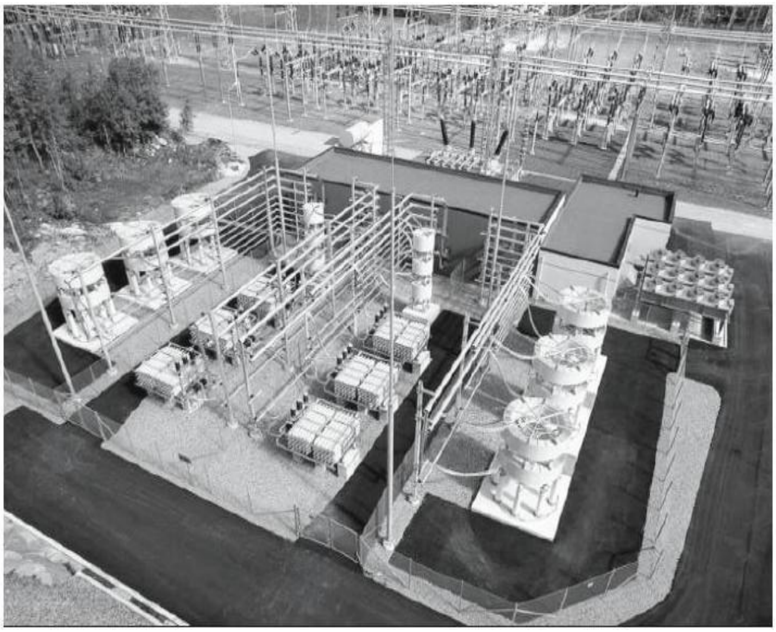


Fig.2.13. Svc using a tcr and an fc

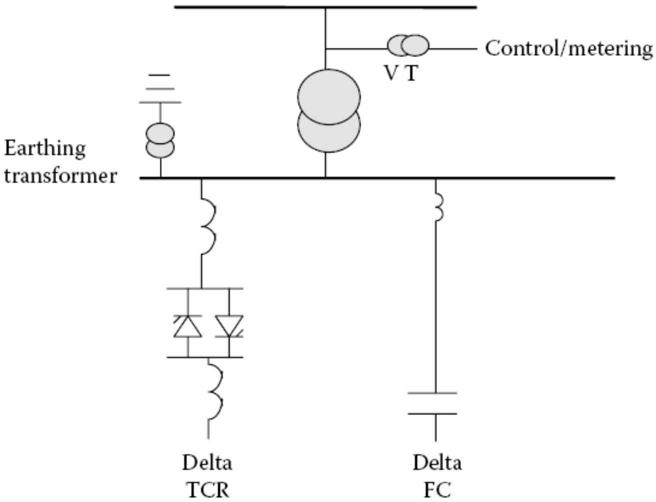


Fig.2.14.Svc of the fc/tcr type

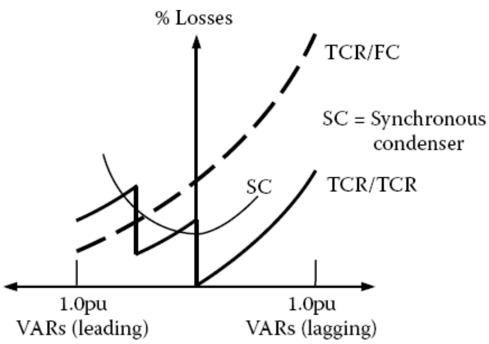


Fig.2.15.The loss characteristics of TSC–TCR, TCR–FC compensators.

2.8.1(b) STATCOM:

In 1999 the first SVC with Voltage Source Converter called STATCOM (Static Compensator) went into operation. The STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs. A STATCOM is build with Thyristors with turn-off capability like GTO or today IGCT or with more and more IGBTs. The static line between the current limitations has a certain steepness determining the control characteristic for the voltage.

The advantage of a STATCOM is that the reactive power provision is independent from the actual voltage on the connection point. This can be seen in the diagram for the maximum currents being independent of the voltage in comparison to the SVC. This means, that even during most severe contingencies, the STATCOM keeps its full capability.

In the distributed energy sector the usage of Voltage Source Converters for grid interconnection is common practice today. The next step in STATCOM development is the combination with energy storages on the DC-side. The performance for power quality and balanced network operation can be improved much more with the combination of active and reactive power.

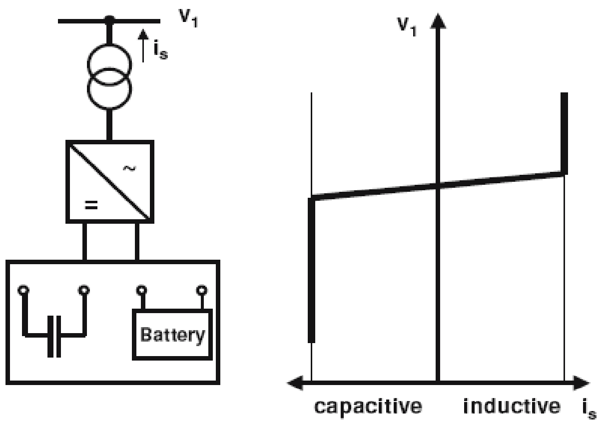


Fig.2.16. Statcom structure and voltage / current characteristic

STATCOMs are based on Voltage Sourced Converter (VSC) topology and utilize either Gate-Turn-off Thyristors (GTO) or Isolated Gate Bipolar Transistors (IGBT) devices. The STATCOM is a very fast acting, electronic equivalent of a synchronous condenser.

If the STATCOM voltage, Vs, (which is proportional to the dc bus voltage Vc) is larger than bus voltage, Es, then leading or capacitive VARS are produced. If Vs is smaller then Es then lagging or inductive VARS are produced.

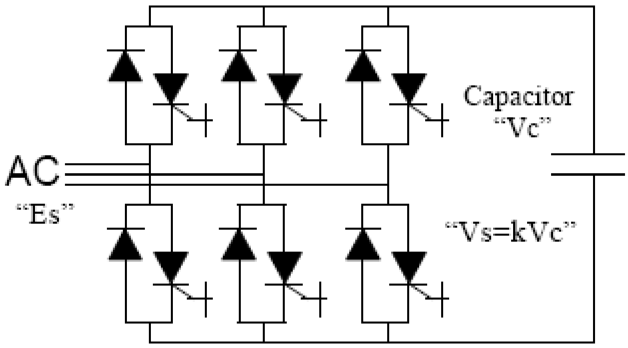


Fig.2.17. 6-pulses statcom.

The three phases STATCOM makes use of the fact that on a three phase, fundamental frequency, steady state basis, and the instantaneous power entering a purely reactive device must be zero. The reactive power in each phase is supplied by circulating the instantaneous real power between the phases. This is achieved by firing the GTO/diode switches in a manner that maintains the phase difference between the ac bus voltage ES and the STATCOM generated voltage VS. Ideally it is possible to construct a device based on circulating instantaneous power which has no energy storage device (ie no dc capacitor).

A practical STATCOM requires some amount of energy storage to accommodate harmonic power and ac system unbalances, when the instantaneous real power is non-zero. The maximum energy storage required for the STATCOM is much less than for a TCR/TSC type of SVC compensator of comparable rating.

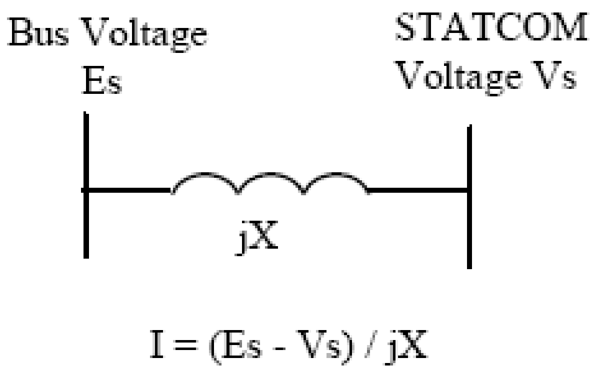


Fig.2.18.Statcom equivalent circuit.

Several different control techniques can be used for the firing control of the STATCOM. Fundamental switching of the GTO/diode once per cycle can be used. This approach will minimize switching losses, but will generally utilize more complex transformer topologies. As an alternative, Pulse Width Modulated (PWM) techniques, which turn on and off the GTO or IGBT switch more than once per cycle, can be used. This approach allows for simpler transformer topologies at the expense of higher switching losses.

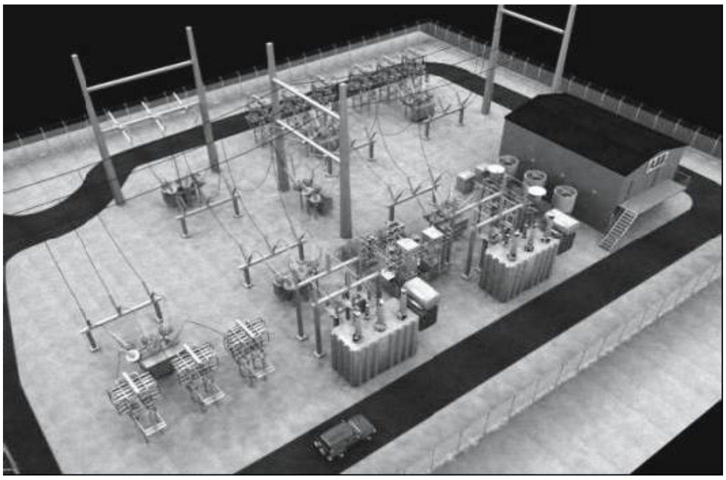


Fig.2.19. Substation with a STATCOM.

2.8.1(C) Unified Power Flow Controller:

The UPFC is a combination of a static compensator and static series compensation. It acts as a shunt compensating and a phase shifting device simultaneously.

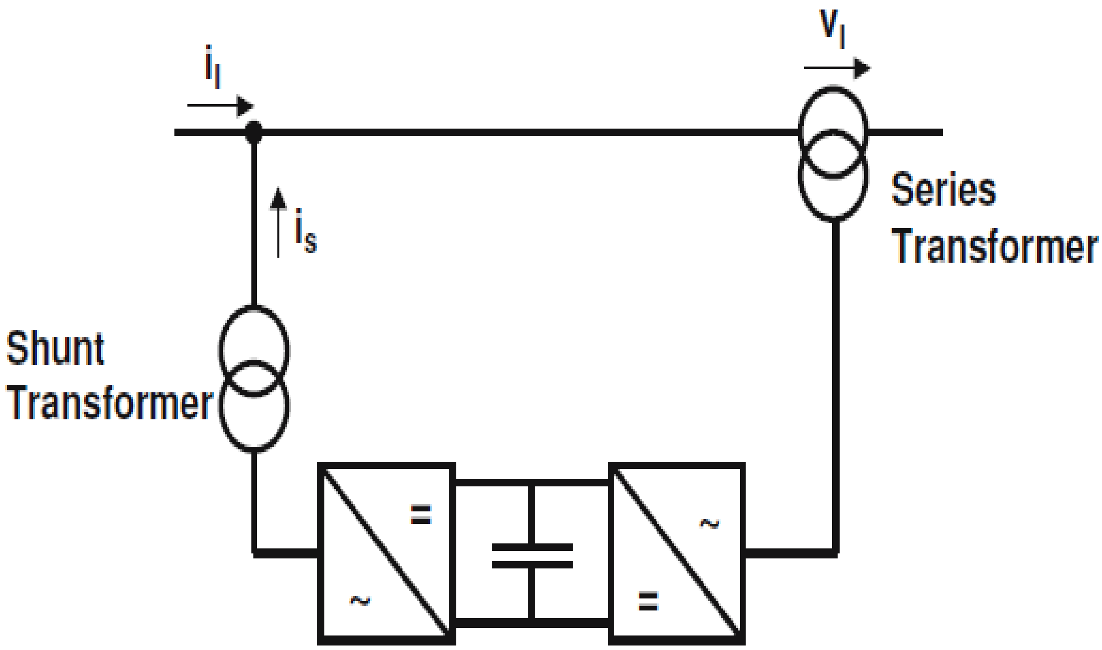
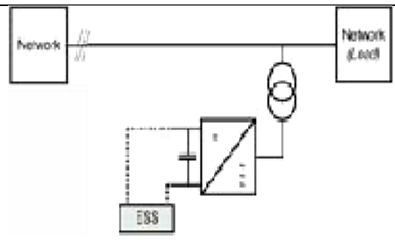
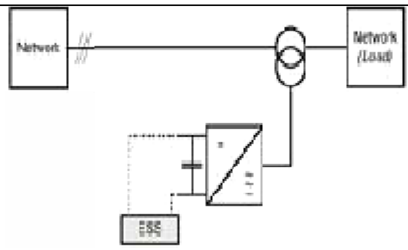
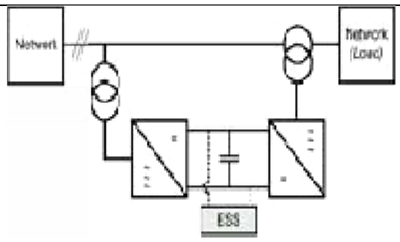


Fig.2.20. Principle configuration of an UPFC

The UPFC consists of a shunt and a series transformer, which are connected via two voltage source converters with a common DC-capacitor. The DC-circuit allows the active power exchange between shunt and series transformer to control the phase shift of the series voltage. This setup, as shown in Figure 1.21, provides the full controllability for voltage and power flow. The series converter needs to be protected with a Thyristor bridge. Due to the high efforts for the Voltage Source Converters and the protection, an UPFC is getting quite expensive, which limits the practical applications where the voltage and power flow control is required simultaneously.

Table-2.3.: FACTS Equipments in Distribution System

Name	**Topology**	**Preferred Tasks**
DSTATCOM (Distribution STSTCOM)		✓ Flicker compensation ✓ Reactive power compensation ✓ Harmonic filter
DVR (dynamic voltage restorer)		✓ Sag/swell compensation
UPQC (unified power quality conditioner)		✓ Under voltage/overvoltage compensation ✓ DSTATCOM and DVR advantages

There are three principle elements to the custom power concept; these are:

✓ The Dynamic Voltage Restorer (DVR), it provides series compensation by voltage injection for power system sag and swell.

✓ The Distribution Static Compensator (D-STATCOM), it provides continuously variable shunt compensation by current injection for eliminating voltage fluctuations and obtaining correct power factor in three-phase systems. An ideal application of it is to prevent disturbing loads from polluting the rest of the distribution system.

✓ Unified Power Quality Conditioner (UPQC), it provide series and shunt compensation i.e. inject voltage in sag and swell condition and inject current for elimination of voltage fluctuations ,correct power factor, avoid pollution to rest of the distribution system.

CHAPTER 3

PROPOSED SYSTEM

CHAPTER 3
PROPOSED SYSTEM
UNIFIED POWER QUALITY CONDITIONER

The provision of both DSTATCOM and DVR can control the power quality of the source current and the load bus voltage. In addition, if the DVR and STATCOM are connected on the DC side, the DC bus voltage can be regulated by the shunt connected DSTATCOM while the DVR supplies the required energy to the load in case of the transient disturbances in source voltage. The configuration of such a device (termed as Unified Power Quality Conditioner (UPQC)) is shown in Fig. 14.15. This is a versatile device similar to a UPFC. However, the control objectives of a UPQC are quite different from that of a UPFC.

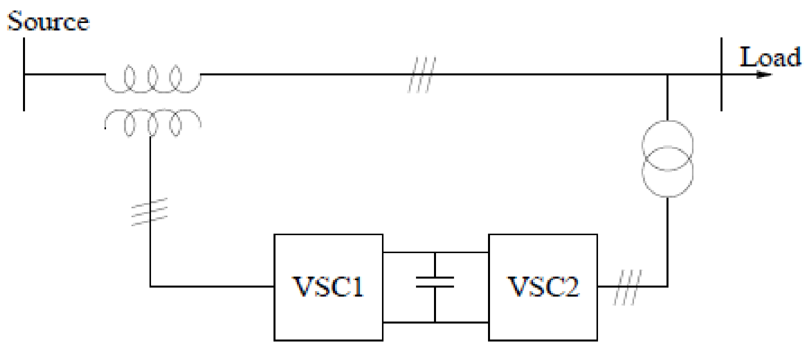


Fig.3.1.Unified power quality conditioner

3.1. CONTROL OBJECTIVES OF UPQC

The shunt connected converter has the following control objectives

1. To balance the source currents by injecting negative and zero sequence components required by the load
2. The compensate for the harmonics in the load current by injecting the required harmonic currents
3. To control the power factor by injecting the required reactive current (at fundamental frequency)
4. To regulate the DC bus voltage.

The series connected converter has the following control objectives

1. To balance the voltages at the load bus by injecting negative and zero sequence voltages to compensate for those present in the source.
2. To isolate the load bus from harmonics present in the source voltages, by injecting the harmonic voltages
3. To regulate the magnitude of the load bus voltage by injecting the required active and reactive components (at fundamental frequency) depending on the power factor on the source side
4. To control the power factor at the input port of the UPQC (where the source is connected. Note that the power factor at the output port of the UPQC (connected to the load) is controlled by the shunt converter.

3.2. Operation of UPQC

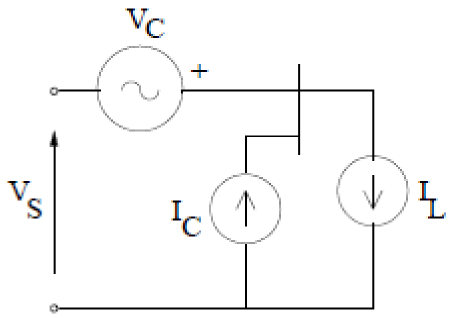


Fig.3.2.Operation of UPQC

The operation of a UPQC can be explained from the analysis of the idealized equivalent circuit shown in Fig. 14.16. Here, the series converter is represented by a voltage source VC and the shunt converter is represented by a current source IC. Note that all the currents and voltages are 3 dimensional vectors with phase coordinates. Unlike in the case of a UPFC (discussed in chapter 8), the voltages and currents may contain negative and zero sequence components in addition to harmonics. Neglecting losses in the converters, we get the relation

$$\langle V_L, I_C \rangle + \langle V_C, I_S \rangle = 0$$

where X,Ydenote the inner product of two vectors, defined by

$$\langle X, Y \rangle = \frac{1}{T} \int_0^T X^t(\tau) Y(\tau) d\tau.$$

Let the load current IL and the source voltage VS be decomposed into two Components given by

$$I_L = I_L^{1p} + I_L^r$$

$$V_S = V_S^{1p} + V_S^r$$

Where I1p L contains only positive sequence, fundamental frequency components. Similar comments apply to V 1pS . IrL and V rS contain rest of the load current and the source voltage including harmonics. I1pL is not unique and depends on the power factor at the load bus. However, the following relation applies for I1p L .

$$P_L = \langle V_L, I_L \rangle = \langle V_L, I_L^{1p} \rangle$$

This implies that hIrL ; VLi = 0. Thus, the fundamental frequency, positive sequence component in IrL does not contribute to the active power in the load. To meet the control objectives, the desired load voltages and source currents must contain only positive sequence, fundamental frequency components and

$$P_L = |V_L^* \, I_S^*| \cos\phi_l = |V_S^{1p} I_S^*| \cos\phi_s$$

where V ¤ L and I¤S are the reference quantities for the load bus voltage and the source current respectively. Ál is the power factor angle at the load bus while Ás is the power factor angle at the source bus (input port of UPQC). Note that V ¤ L(t) and I¤S (t) are sinusoidal and balanced. If the reference current (I¤C) of the shunt converter and the reference voltage (V ¤ C) of the series converter are chosen as

$$I_C^* = I_L^*, \quad V_C^* = -V_S^r + V_C^{1p}$$

with the constraint

$$\langle V_C^{1p}, I_S^* \rangle = 0$$

we have,

$$I_S^* = I_L^{1p}, \quad V_L^* = V_S^{1p} + V_C^{1p}$$

Note that the constraint (14.30) implies that V 1p C is the reactive voltage in quadrature with the desired source current, I¤S . It is easy to derive that

$$\langle V_C^*, I_S^* \rangle = 0 = \langle I_C^*, V_L^* \rangle$$

The above equation shows that for the operating conditions assumed, a UPQC can be viewed as a inaction of a DVR and a STATCOM with no active power °ow through the DC link. However, if the magnitude of V ¤ L is to be controlled, it may not be feasible to achieve this by injecting only reactive voltage. The situation gets complicated if V 1p S is not constant, but changes due to system disturbances or fault. To ensure the regulation of the load bus voltage it may be necessary to inject variable active voltage (in phase with the source current). If we express

$$V_C = V_C^* + \Delta V_C, I_C = I_C^* + \Delta I_C$$

$$I_S = I_S^* - \Delta I_C, V_L = V_S^{1p} + V_C^{1p} + \Delta V_C$$

$$\langle I_S, \Delta V_C \rangle + \langle V_L, \Delta I_C \rangle = 0$$

In deriving the above, we assume that

$$\langle I_S, V_C^* \rangle = 0 = \langle V_L, I_C^* \rangle$$

This implies that both ¢VC and ¢IC are perturbations involving positive sequence, fundamental frequency quantities (say, resulting from symmetric voltage sags). the power balance on the DC side of the shunt and series converter. The perturbation in VC is initiated to ensure that

$$|V_C^* + \Delta V_C + V_S| = |V_L| = \text{constant}.$$

Thus, the objective of the voltage regulation at the load bus may require exchange of power between the shunt and series converters.

Remarks

1. The unbalance and harmonics in the source voltage can arise due to uncompensated nonlinear and unbalanced loads in the upstream of the UPQC.
2. The injection of capacitive reactive voltage by the series converter has the advantage of raising the source voltage magnitude.

3.3. Superiority of UPQC over Other Devices

Each of Custom Power devices has its own benefits and limitations. The UPQC is expected to be one of the most powerful solutions to large capacity loads sensitive to supply voltage and load current disturbances /imbalance. The most effective type of these devices is considered to be the Unified Power Quality Conditioner (UPQC). There are numerous reasons why the UPQC is preferred over the others. UPQC is much flexible than any single inverter based device. It can simultaneously correct for the unbalance and distortion in the source voltage and load current where as all other devices either correct current or voltage distortion. Therefore the purpose of two devices is served by UPQC only.

3.4. SYSTEM ARCHITECTURE AND VSC SIZING

3.4.1. System Architecture

The structure of grid integrated PV-UPQC system is depicted. It is the combination of a series compensator and a shunt compensator connected in back-to-back configuration with a common dc-link. The series compensator is connected to the grid side through three- phase series injection transformers (Tse). The shunt compensator is connected to the load side in parallel through interfacing inductors (Lf). The interfacing inductors are assigned to limit the high-frequency current components that are uncontrollable by the converters, which arises due to dynamic condition such as the condition of sharp load current change. A PV array is connected to the dc link using a reverse blocking diode. The MPPT algorithm used for PV array in the proposed system is the widely used P&O method. An R- L load is connected through a three-phase diode bridge rectifier.

3.4.2. Sizing of Series and Shunt VSC

The rating of series VSC depends upon the maximum compensating voltage and the maximum grid current [14]. The maximum compensating voltage depends on amount of grid voltage sag to be compensated. The VA rating of the series VSC is given as follows:

$$S_{series} = P_{Series} = 3V_{SE}I_{SE} = 3 * \frac{bV_r}{\sqrt{3}} * \frac{P_{PV}^{MPP} - P_{load}^{minm}}{\sqrt{3} * V_r}$$
$$= 3 * \frac{0.5 * 415}{\sqrt{3}} * 54.67 = 19.6\, kVA$$

P MPP P V is the PV power at MPP (55.3 kW), P minm load is the minimum load demand (minimum load considered 20 kVA 0.8 P.F), and Vr is the rated line voltage of the system (415 V). Pseries is the active power rating of series VSC, VSE is the per phase rms voltage injected by the series VSC and b is the maximum amount of voltage sag per phase (b = 0.5 p.u). The rating of shunt VSC depends upon the PV-generated power at MPP, reactive power, and harmonic power to be compensated corresponding to peak load . In addition, it has to handle the power injected by the series VSC during voltage sag condition as the series VSC power flows through the shunt VSC.

$$
\begin{aligned}
S_{sh} &= \sqrt{\left(P_{PV}^{MPP} + P_{se}\right)^2 + Q_{load}^2 + H_{har}^2} \\
&= \sqrt{(55.3 + 19.6)^2 + (25 * 0.6)^2 + (0.2 * 0.8 * 25)^2} \\
&= 76.5\ kVA
\end{aligned}
$$

where Q_{Load} is the maximum reactive power requirement of the load (as maximum load of 25 kVA 0.8 P.F is considered) and harmonics is the maximum harmonic power corresponding to maximum load. The grid provides the active power demand of the load, and shunt VSC handles the non-active power (harmonic and reactive power) of the load demand and power produced by PV and by keeping this in mind, sizing of the VSC is done. However, during uncertain rise in non-active part of the load demand (i.e., reactive and harmonic power), the current through the VSC switches will be more than the rated and will damage the switch. This undesired scenario can be avoided by limiting the amount of non-active power provided by the shunt VSC to its rated value.

3.5. CONTROL SCHEME OF PV-UPQC

The control proposition for PV-UPQC in a distribution system requires effective controller for both the shunt and series compensator to harness maximum benefit out of the functionalities of UPQC. The proposed NN-based controller for the system has the advantages of mitigating grid and load-induced PQ issues of voltage sag/swell, harmonics, current harmonics, unity power factor operation at PCC, dc-link voltage regulation, incorporation of feed-forward component for the proper balance of power among PV, grid and load. So, despite of the more cost of UPQC due to two VSCs as compared with other compensators with only one VSC (such as DVR and DSTATCOM), UPQC is chosen, prioritizing the overall health of system especially consumers. Here, a variable leaky LMS algorithm (VLLMS) based control is implemented on a grid integrated PV fed UPQC to generate switching signals for series and shunt VSC both in dynamic and steady condition.

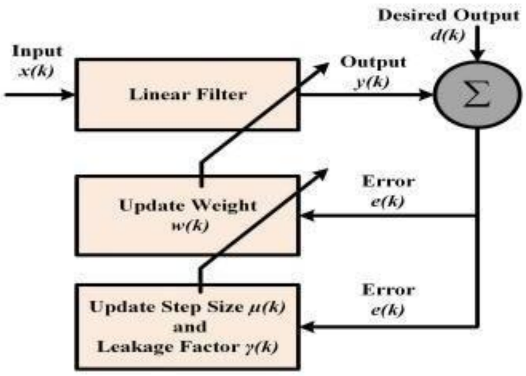


Fig.3.3. Block diagram of VLLMS algorithm

3.5.1. VLLMS Algorithm

The block diagram in Fig. 2 represents the stepwise implementation of the VLLMS algorithm. The VLLMS algorithm is a neural network-based soft computing technique that adaptively updates the weight parameters to track the changes occurring in a system. The basic expressions involved in the VLLMS algorithm are given in the following

$$
\begin{aligned}
y(\kappa+1) &= w^T(\kappa)\cdot x(\kappa)\\
e(\kappa) &= d(\kappa) - y(\kappa)\\
w(\kappa+1) &= \{1-2\mu(\kappa)\gamma(\kappa)\}w(\kappa) + 2\mu(\kappa)e(\kappa)x(\kappa)\\
\gamma(\kappa+1) &= \gamma(\kappa) - 2\mu(\kappa)\rho e(\kappa)x^T(\kappa)w(\kappa-1)\\
\mu(\kappa+1) &= \lambda\mu(\kappa) + \gamma(\kappa)P^2(\kappa)\\
P(\kappa) &= \beta P(\kappa-1) + (1-\beta)e(\kappa)e(\kappa-1)
\end{aligned}
$$

where κ is the discrete-time instant, $x(\kappa)$ is the input, $y(\kappa)$ is the actual output, $d(\kappa)$ is the desired output, $w(\kappa)$ is the weight or gain which is tuned iteratively in such a way that error ($e(\kappa)$) converges to minimum value. $\gamma(\kappa)$ is the varying leakage factor that prevents the weight from over parameterization and under parameterization of the weight. $\mu(\kappa)$ is the variable step size, $P(\kappa)$ represents the error autocorrelation of $e(\kappa)$ and $e(\kappa-1)$, β is exponential weighting parameter which controls the average estimation time ($0<\beta<1$). λ and ρ are convergence time controlling parameters ($0<\lambda<1$ and $\rho>0$). By choosing $x(\kappa)$ and $d(\kappa)$ from a system and feeding it through the VLLMS algorithm the weights are updated by following given earlier after every time instant.

3.5.2. Control Strategy of Shunt Compensator of UPQC

The control scheme of shunt compensator is given First, the instantaneous voltages of phase a, b, and c at PCC

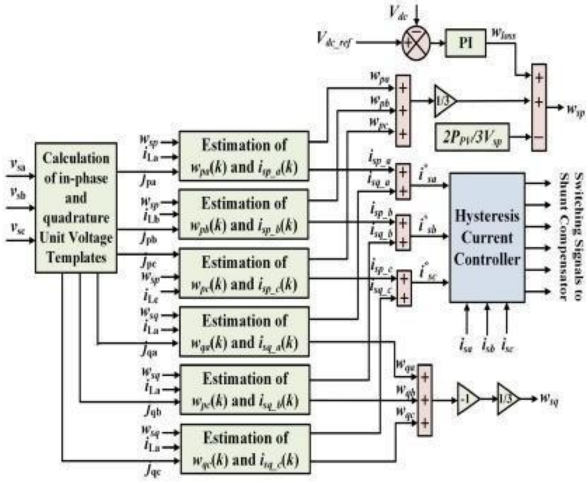


Fig3.4.Proposed VLLMS control scheme for shunt compensator.

(vsa, vsb, vsc) are measured. Then using these phase voltages, magnitude (Vsp) of PCC voltage is determined as follows:

$$V_{sp} = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}.$$

The in-phase unit templates of source voltage are computed as follows [20]:

$$j_{pa} = \frac{v_{sa}}{V_{sp}}, \quad j_{pb} = \frac{v_{sb}}{V_{sp}}, \quad j_{pc} = \frac{v_{sc}}{V_{sp}}.$$

The quadrature unit templates are calculated as follows:

$$j_{qa} = \frac{-j_{pb} + j_{pc}}{\sqrt{3}}, \; j_{qb} = \frac{\sqrt{3}j_{pa}}{2} + \frac{(j_{pb} - j_{pc})}{2\sqrt{3}},$$
$$j_{qc} = \frac{-\sqrt{3}j_{pa}}{2} + \frac{(j_{pb} - j_{pc})}{2\sqrt{3}}.$$

Next is the extraction of fundamental active component of load current. The in-phase unit templates (jpa, jpb, jpc) of grid voltage as input x(κ) and load current (iLa, iLb, iLc) as the desired output d(κ) for each phase, are fed to the VLLMS algorithm. Then, the amplitude of the fundamental active component of load current for each phase (wpa, wpb, wpc) is calculated iteratively. The amplitude of fundamental active component for phase a of load current is determined as follows:

$$w_{pa}(\kappa+1) = w_{pa}(\kappa)\{1 - 2\mu_{pa}(\kappa)\gamma_{pa}(\kappa)\}$$
$$+ 2\mu_{pa}(\kappa)e_{pa}(\kappa)j_{pa}(\kappa)$$
$$e_{pa}(\kappa) = i_{La}(\kappa) - j_{pa}(\kappa) \times w_{pa}(\kappa)$$
$$\gamma_{pa}(\kappa+1) = \gamma_{pa}(\kappa) - 2\mu_{pa}(\kappa)\rho e_{pa}(\kappa)j_{pa}(\kappa)w_{pa}(\kappa$$
$$\mu_{pa}(\kappa+1) = \lambda\mu_{pa}(\kappa) + \gamma_{pa}(\kappa)P_{pa}^2(\kappa)$$
$$P_{pa}(\kappa) = \beta P_{pa}(\kappa-1) + (1-\beta)e_{pa}(\kappa)e_{pa}(\kappa-1).$$

In a similar fashion, the fundamental active components of load current for phases b and c are determined. Similarly, by considering the quadrature unit template of voltage (jqa, jqb, jqc) as input and load current as desired output, reactive component of load current (wqa, wqb, wqc) is iteratively determined. The amplitude of reactive component for phase a of load current is obtained as follows:

$$w_{qa}(\kappa+1) = w_{qa}(\kappa)\{1 - 2\mu_{qa}(\kappa)\gamma_{qa}(\kappa)\}$$
$$+ 2\mu_{qa}(\kappa)e_{qa}(\kappa)j_{qa}(\kappa)$$
$$e_{qa}(\kappa) = i_{La}(\kappa) - j_{qa}(\kappa) \times w_{qa}(\kappa)$$
$$\gamma_{qa}(\kappa+1) = \gamma_{qa}(\kappa) - 2\mu_{qa}(\kappa)\rho e_{qa}(\kappa)j_{qa}(\kappa)w_{qa}(\kappa -$$
$$\mu_{qa}(\kappa+1) = \lambda\mu_{qa}(\kappa) + \gamma_{qa}(\kappa)P_{qa}^2(\kappa)$$
$$P_{qa}(\kappa) = \beta P_{qa}(\kappa-1) + (1-\beta)e_{qa}(\kappa)e_{qa}(\kappa-1).$$

In the similar manner, the fundamental reactive components for load current of phases b and c are determined. Then, average of fundamental active component and reactive component is calculated as follows:

$$w_{pavg} = \frac{w_{pa}(\kappa) + w_{pb}(\kappa) + w_{pc}(\kappa)}{3}$$
$$w_{qavg} = \frac{w_{qa}(\kappa) + w_{qb}(\kappa) + w_{qc}(\kappa)}{3}.$$

There exist certain active power losses due to switching of VSCs of the UPQC and is provided by the dc-link voltage. To maintain the dc-link voltage, this loss is imparted by the source. This component is determined by comparing the dc-link voltage (Vdc) and reference dc-link voltage (Vdcref).

$$e_{dc}(\kappa) = V_{dcref}(\kappa) - V_{dc}(\kappa)$$
$$w_{loss}(\kappa+1) = w_{loss}(\kappa) + k_p\{e_{dc}(\kappa+1) - e_{dc}(\kappa)\}$$
$$+ k_i e_{dc}(\kappa+1).$$

With kp as the proportional constant and ki as the integral gain constant of dc-link PI controller. The amount of active current contribution by the PV array (wpv) is given as follows:

$$w_{PV} = \frac{2P_{PV}}{3V_{sp}}$$

Then, the resultant reference so

$$i_{sp\_a} = w_{sp}j_{p\_a}, \quad i_{sp\_b} = w_{sp}j_{pb}, \quad i_{sp\_c} = w_{sp}j_{pc}$$
$$i_{sq\_a} = w_{sq}j_{qa}, \quad i_{sq\_b} = w_{sq}j_{qb}, \quad i_{sq\_c} = w_{sq}j_{qc}$$
$$i^*_{sa} = i_{sp\_a} + i_{sq\_a}, \quad i^*_{sb} = i_{sp\_b} + i_{sq\_b}, \quad i^*_{sc}$$

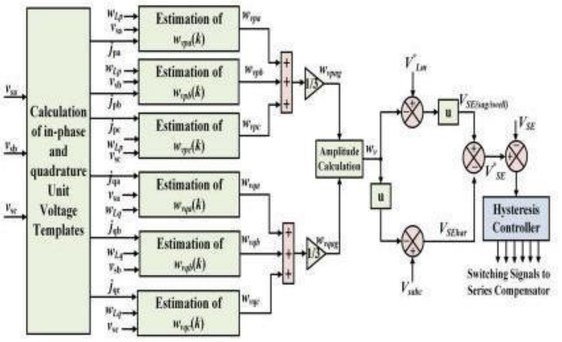


Fig.3.5.Proposed VLLMS control scheme for series compensator.

3.5.3. Control Strategy of Series Compensator of UPQC

The control structure of series compensator is depicted in Fig.3.5. By using VLLMS algorithm, fundamental component of source voltage is extracted. The in-phase unit templates (jpa, jpb, jpc) of source voltage as input and source voltage (vsa, vsb, vsc) as the desired output d(κ) for the phases a, b and c, respectively, are fed to the VLLMS algorithm. Then, the fundamental in-phase component of source voltage for each phase (wvpa, wvpb, wvpc) is calculated iteratively. The amplitude of fundamental in-phase component of source voltage of phase a is determined as follows:

$$\begin{aligned} w_{vpa}(\kappa+1) &= w_{vpa}(\kappa)\{1 - 2\mu_{vpa}(\kappa)\gamma_{vpa}(\kappa)\} \\ &\quad + 2\mu_{vpa}(\kappa)e_{vpa}(\kappa)j_{pa}(\kappa) \\ e_{vpa}(\kappa) &= v_{sa}(\kappa) - j_{pa}(\kappa) \times w_{vpa}(\kappa) \\ \gamma_{vpa}(\kappa+1) &= \gamma_{vpa}(\kappa) \\ &\quad - 2\mu_{vpa}(\kappa)\rho e_{vpa}(\kappa)j_{pa}(\kappa)w_{vpa}(\kappa-1) \end{aligned}$$

$$\mu_{vpa}(\kappa+1) = \lambda\mu_{vpa}(\kappa) + \gamma_{vpa}(\kappa)e^2_{vpa}(\kappa)$$

In the same manner, the fundamental in-phase components of source voltage of phases b and c are determined. Similarly, by using the quadrature unit template of voltage (jqa, jqb, jqc) as input and source voltage as desired output, quadrature component of source voltage (wvqa, wvqb, wvqc) is iteratively determined. The amplitude fundamental quadrature component of source voltage of phase a is determined as follows:

$$
\begin{aligned}
w_{vqa}(\kappa+1) &= w_{vqa}(\kappa)\{1-2\mu_{vqa}(\kappa)\gamma_{vqa}(\kappa)\} \\
&\quad + 2\mu_{vqa}(\kappa)e_{vqa}(\kappa)j_{qa}(\kappa) \\
e_{vqa}(\kappa) &= v_{sa}(\kappa) - j_{qa}(\kappa)\times w_{vqa}(\kappa) \\
\gamma_{vqa}(\kappa+1) &= \gamma_{vqa}(\kappa) \\
&\quad - 2\mu_{vqa}(\kappa)\rho e_{vqa}(\kappa)j_{qa}(\kappa)w_{vqa}(\kappa-1)
\end{aligned}
$$

$$
\mu_{vqa}(\kappa+1) = \lambda\mu_{vqa}(\kappa) + \gamma_{vqa}(\kappa)P^2_{vqa}(\kappa)
$$

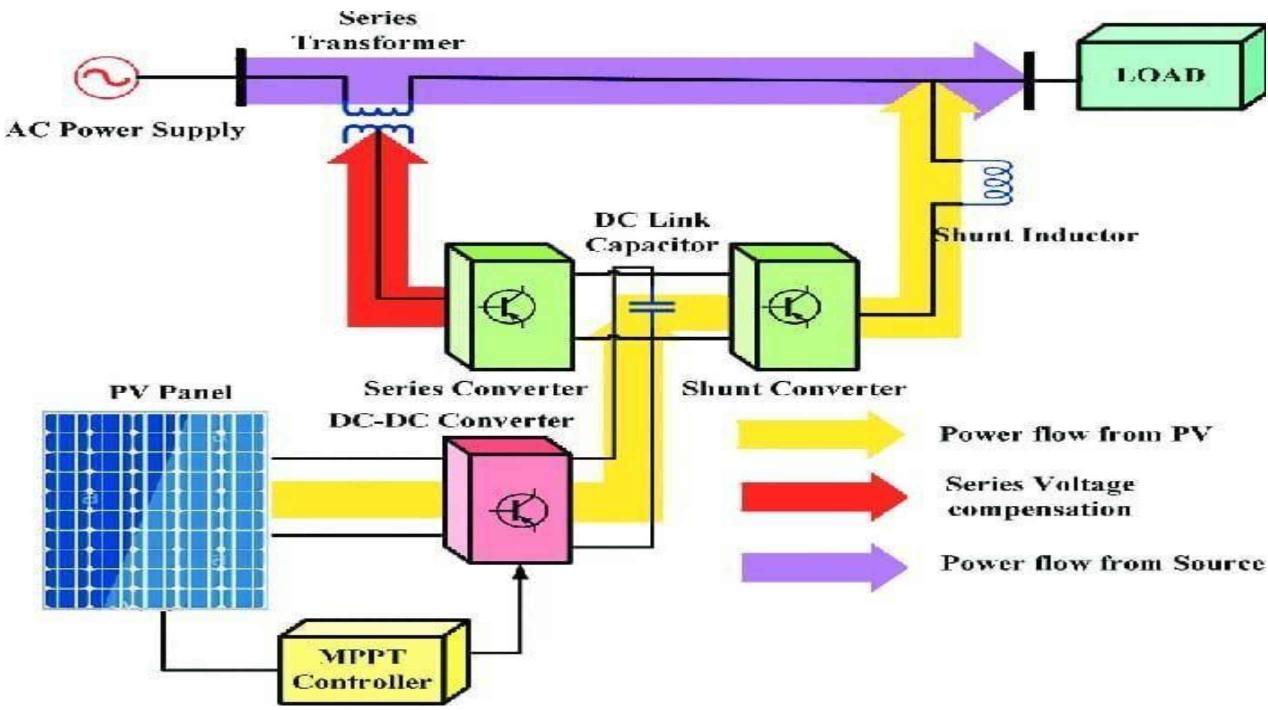


Fig.3.6.Proposed Block Diagram

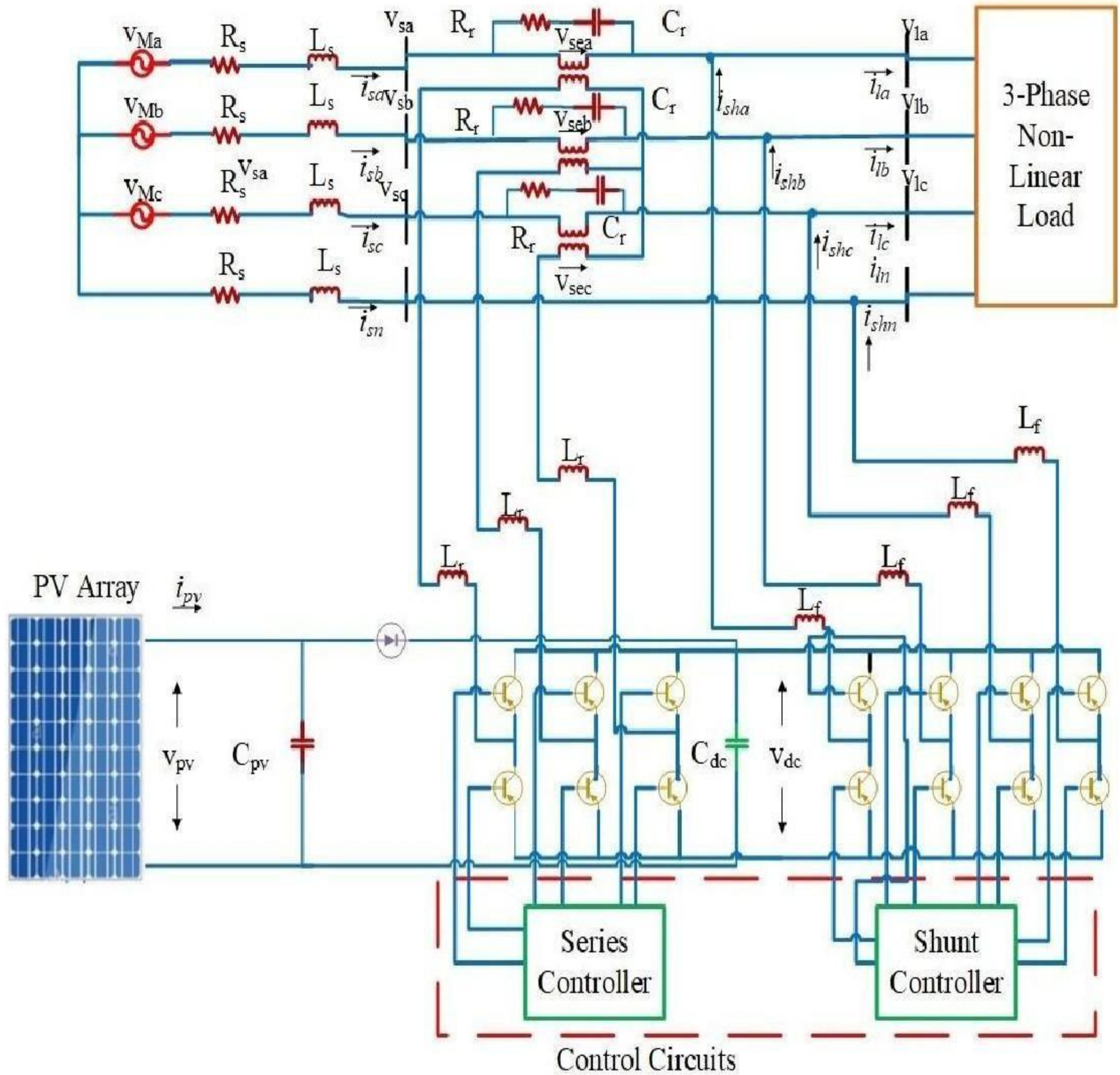


Fig.3.7.Circuit Diagram

CHAPTER 4

SIMULATION AND RESULTS

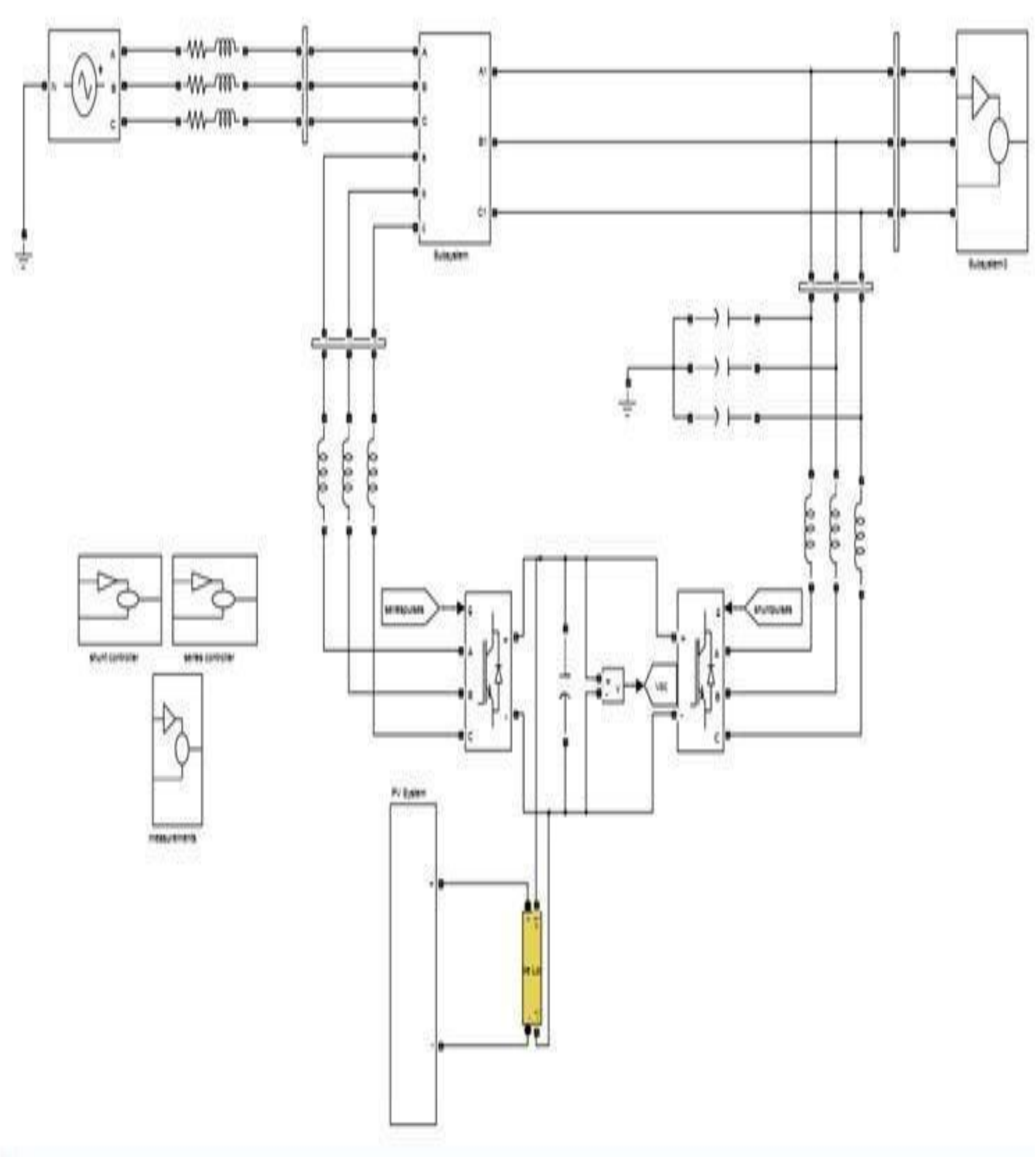


Fig.4.1.Simulink Circuit

Control circuits are Series converter and Shunt converter.

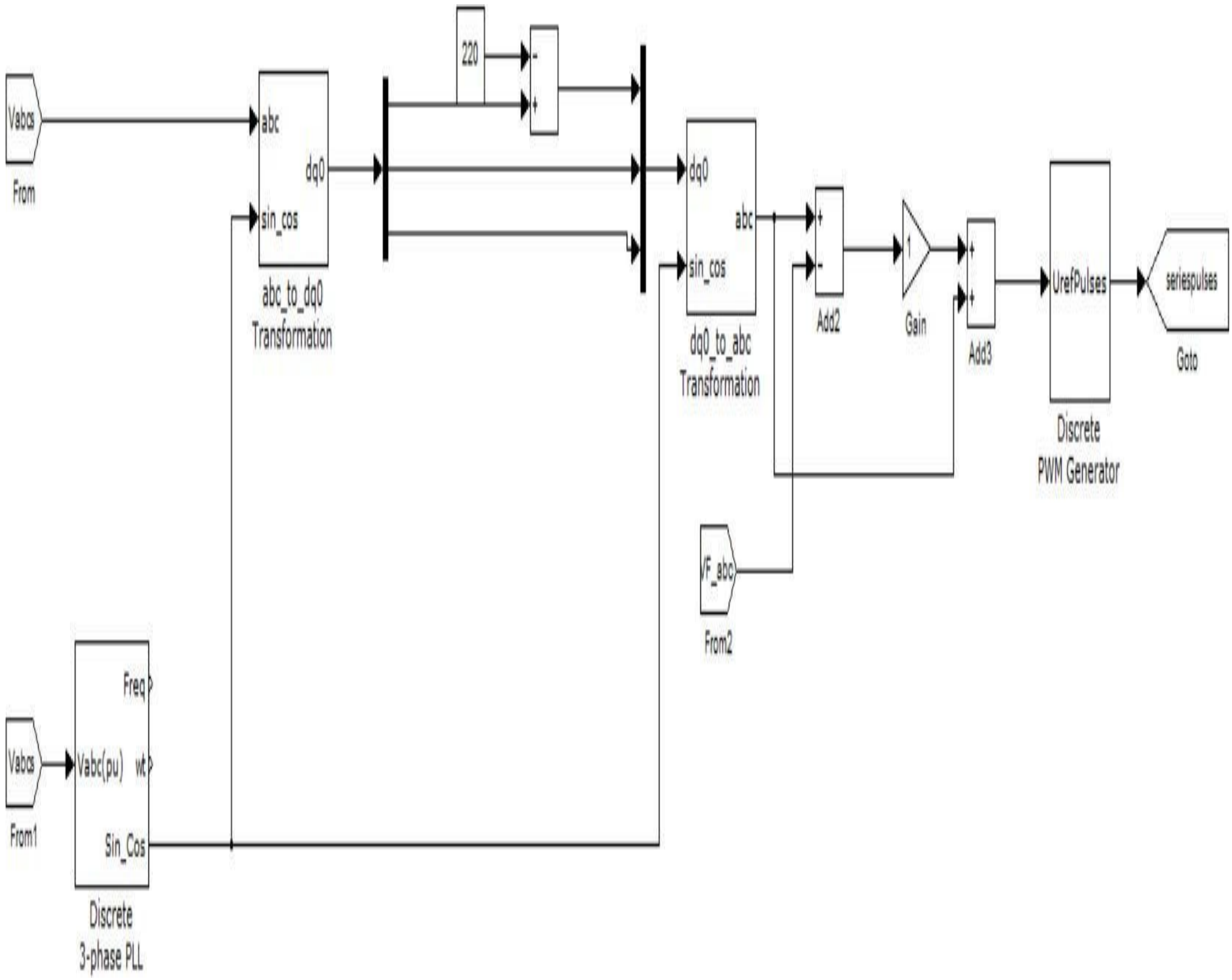


Fig.4.2.Series Converter

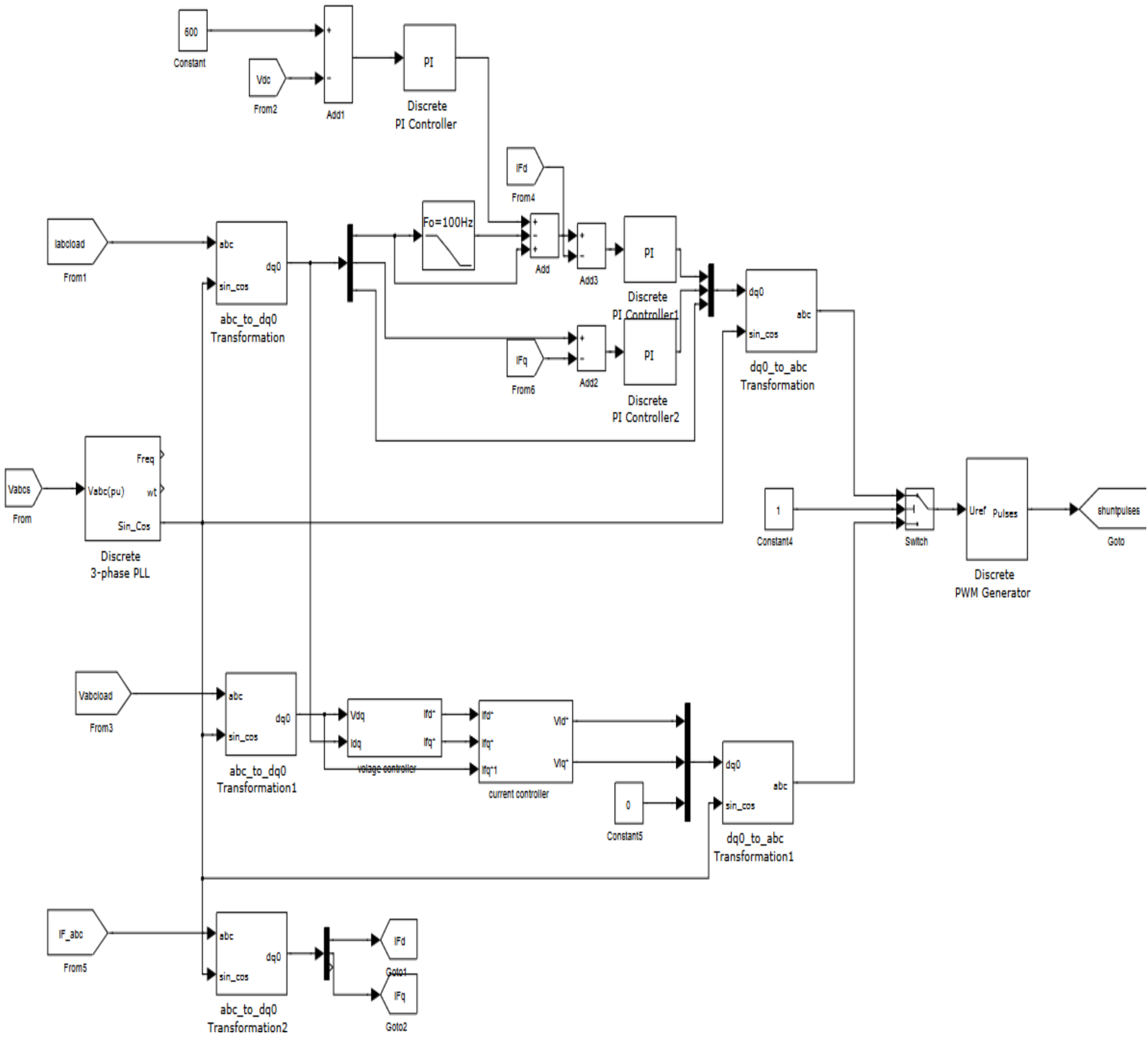


Fig.4.3.Shunt Converter

Fig.4.4.shows the condition of voltage sag and swell occurring in the grid side. At time instant t = 0.2 s, and t = 0.3 s voltage swell of 0.3 p.u and voltage sag of 0.5 p.u is faced by the system. The series compensator successfully compensates both swell and sag in the voltage immediately without the use of LPF for the extraction of fundamental component of grid voltage resulting into a pure sinusoidal voltage of nominal magnitude at the load end

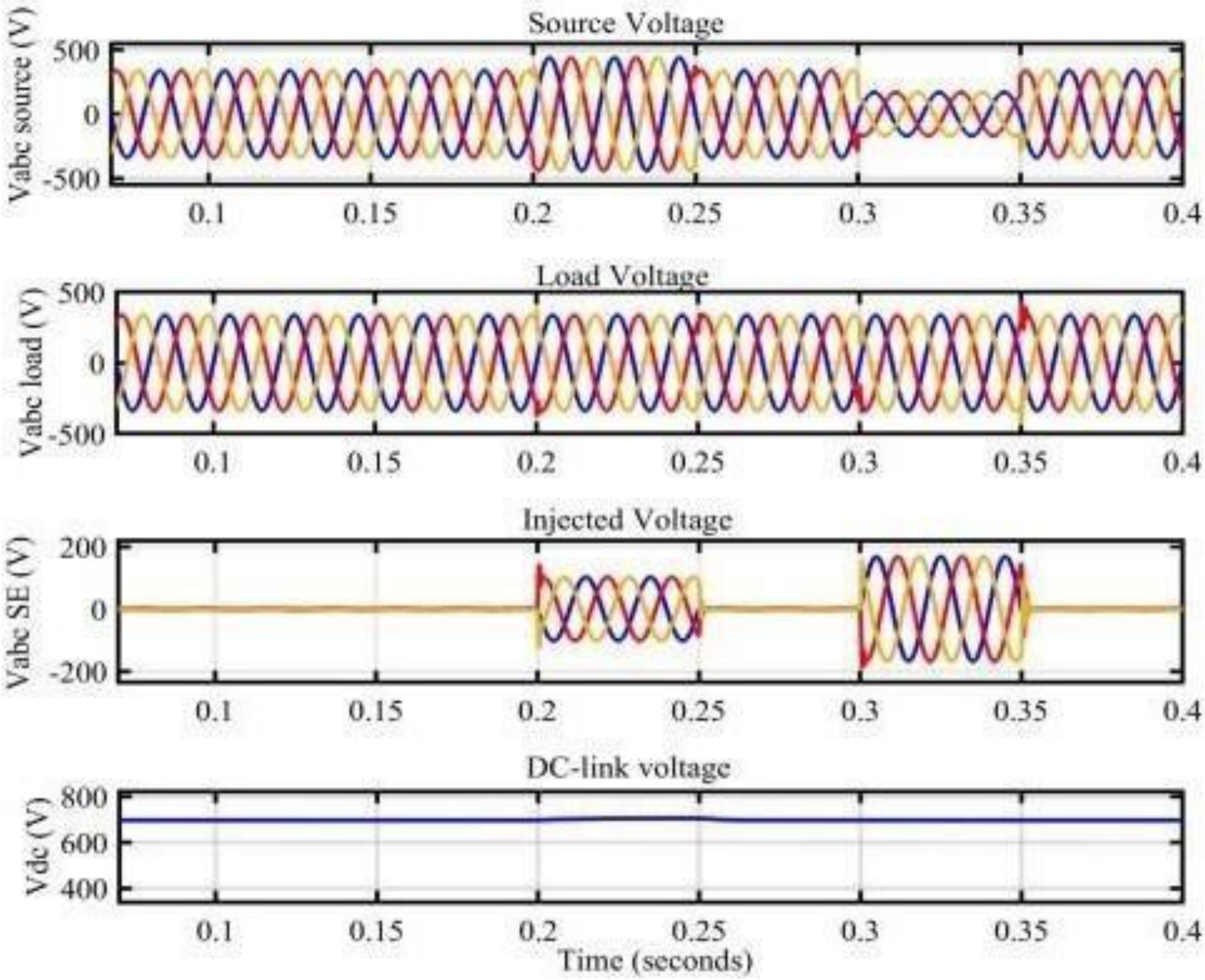


Fig.4.4.Behaviour of the PV-UPQC during voltage sag and swell condition.

Fig.4.5. shows the performance of the series compensator in compensating harmonics present in the source voltage. It can be seen that the harmonics are completely removed from the load voltage and hence makes the load voltage suitable for sensitive loads. Fig. 4.6(a) and (b) show the THD of source voltage and load voltage. The proposed control technique has reduced the THD of voltage from 31.62% to 1.27% which is within the IEEE 519 standards.

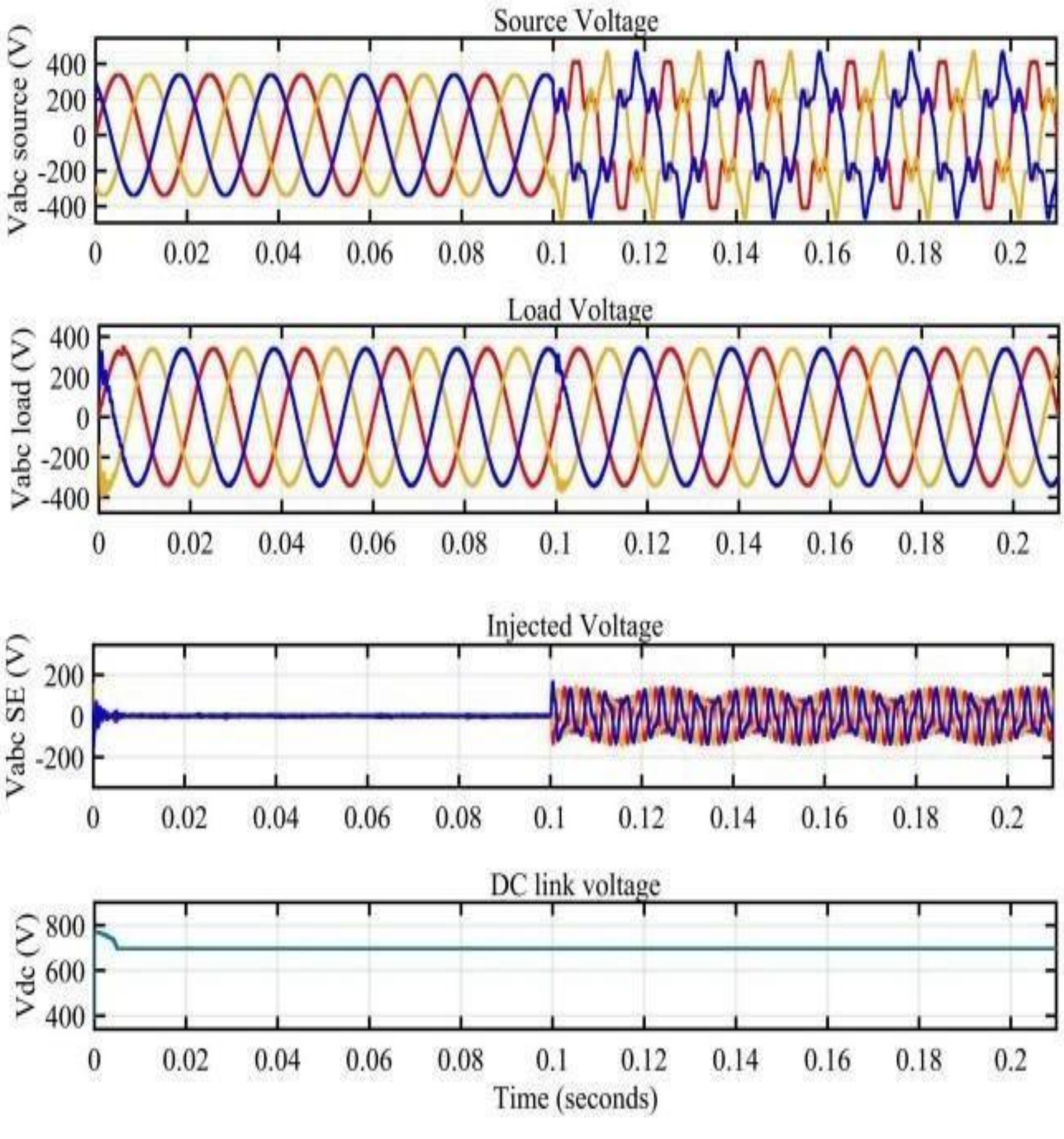


Fig.4.5. Behaviour of PV-UPQC under highly distorted source voltage

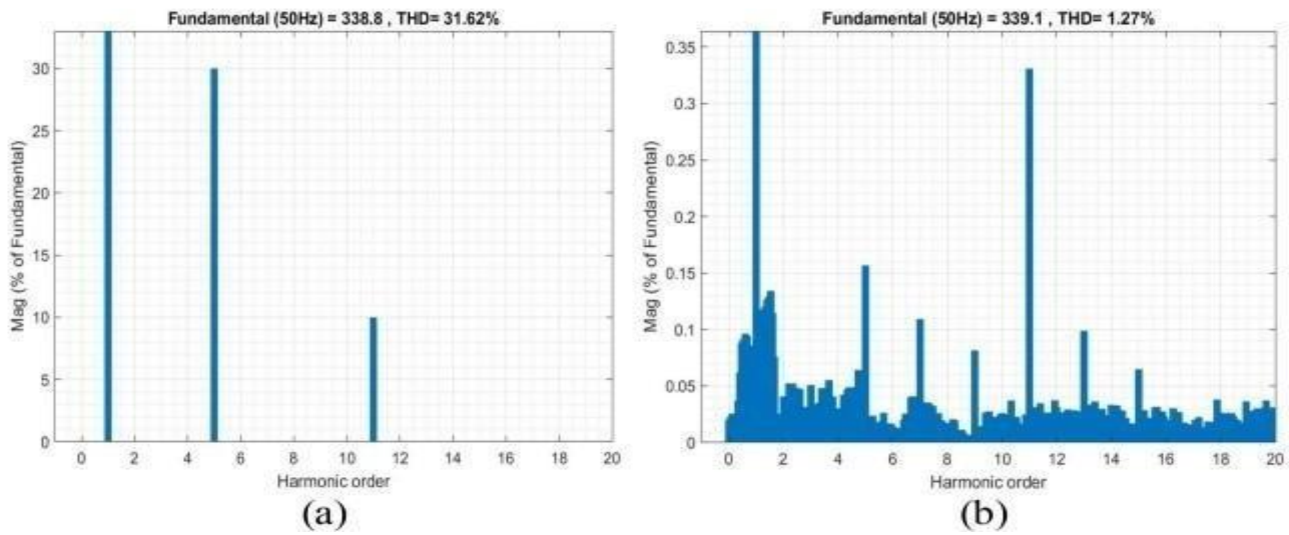


Fig.4.6.THD content of (a)Source Voltage and (b)Load voltage

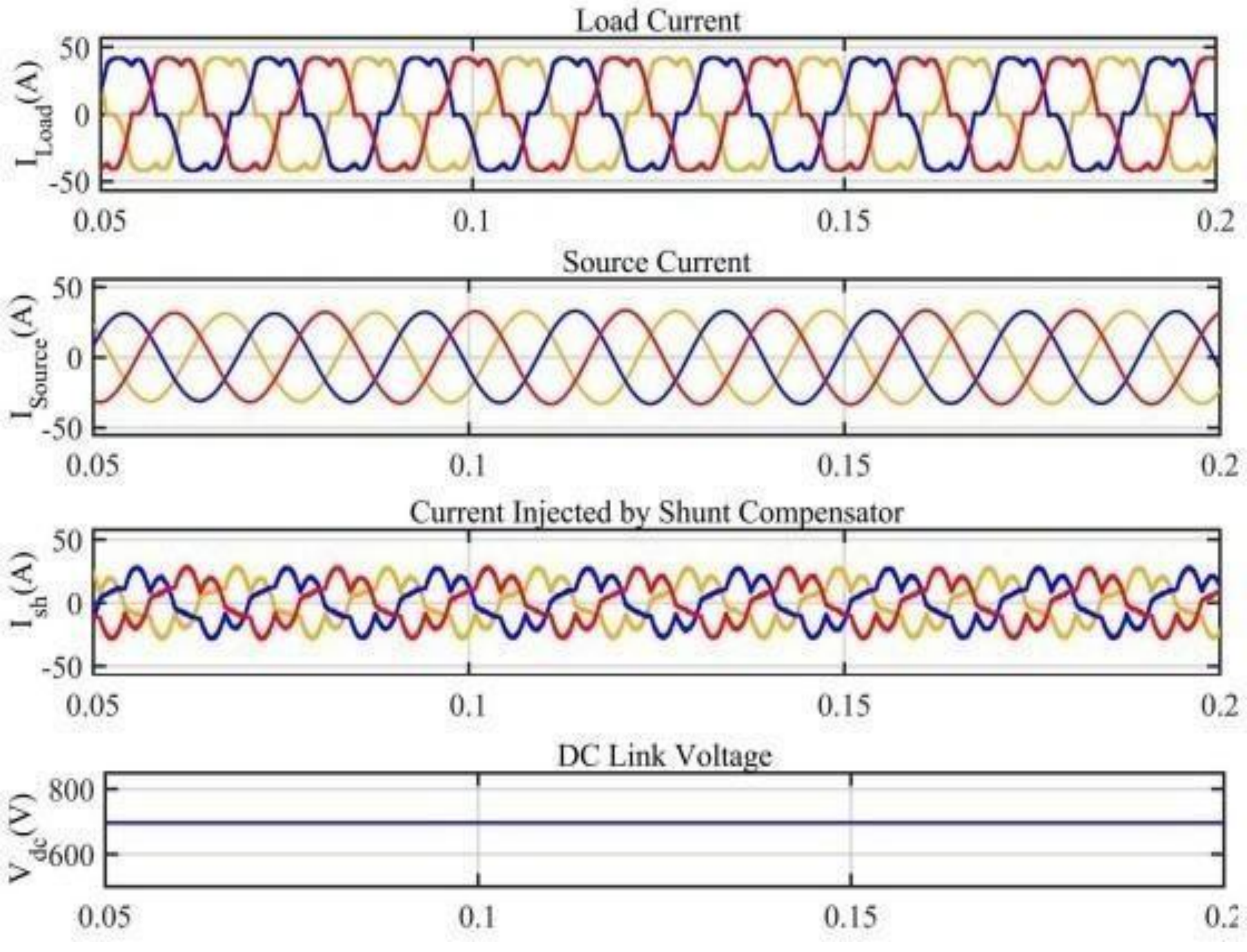
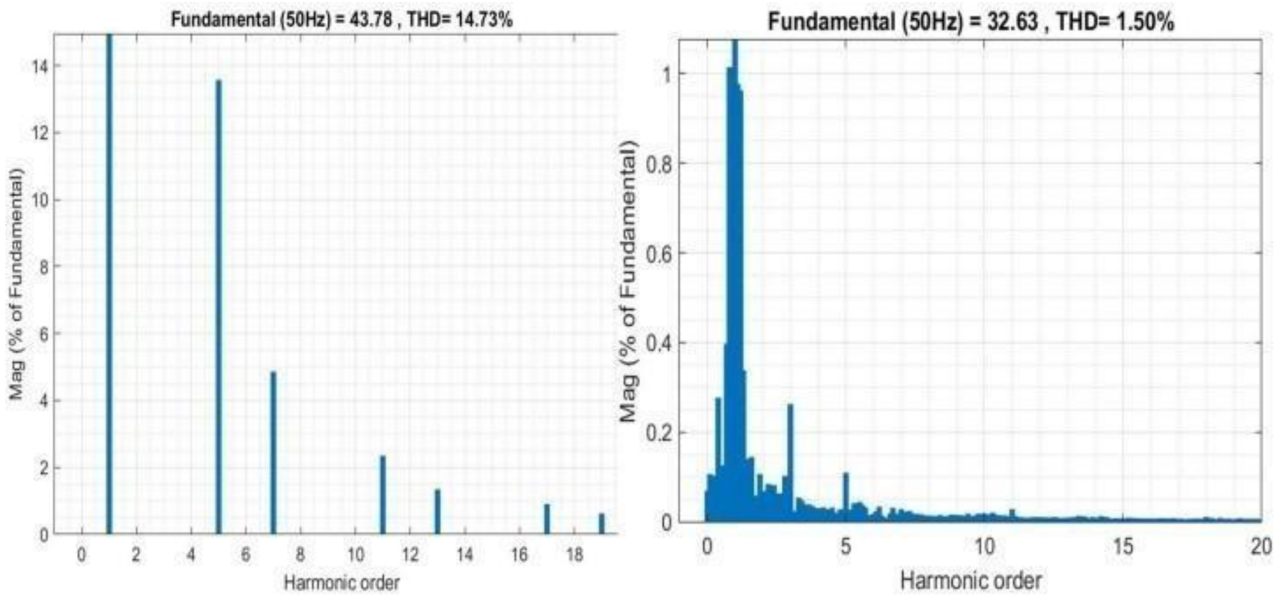


Fig.4.7. Behaviour of the proposed system with non-linear load condition.

The behavior of the shunt VSC in the presence of non-linear load can be seen in Fig.4.7, the shunt compensator eliminates the harmonics introduced by the load into the grid current without the use of LPF. In addition, it can be seen that with the help of shunt VSC, PV and grid are together feeding the requirements of the load. Fig. 4.8(a) and (b) show the THD of load current and source current. The proposed control technique has reduced the THD of current from 14.73% to 1.50% which is within the IEEE standards.



(a) (b)

Fig.4.8. THD content of (a) load current (b) source current

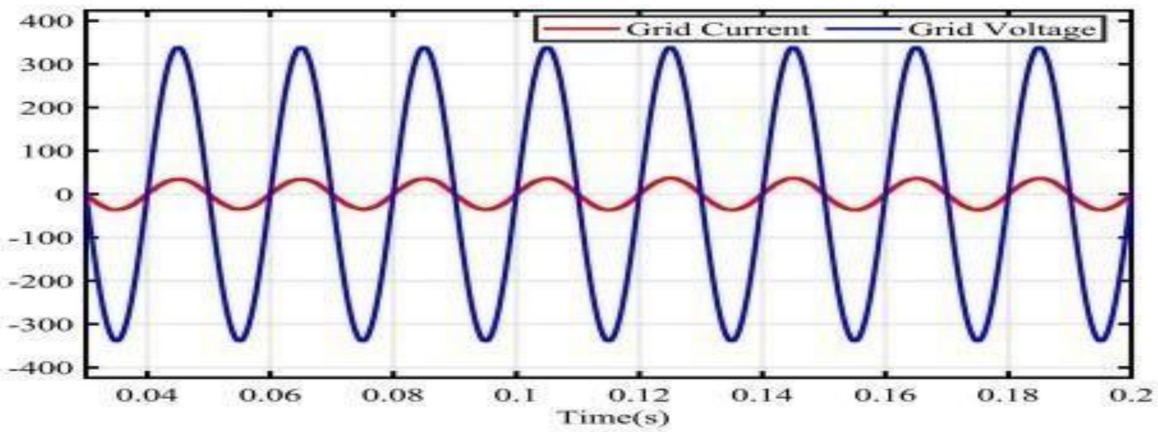


Fig.4.9. In-phase relation between current and voltage at PCC.

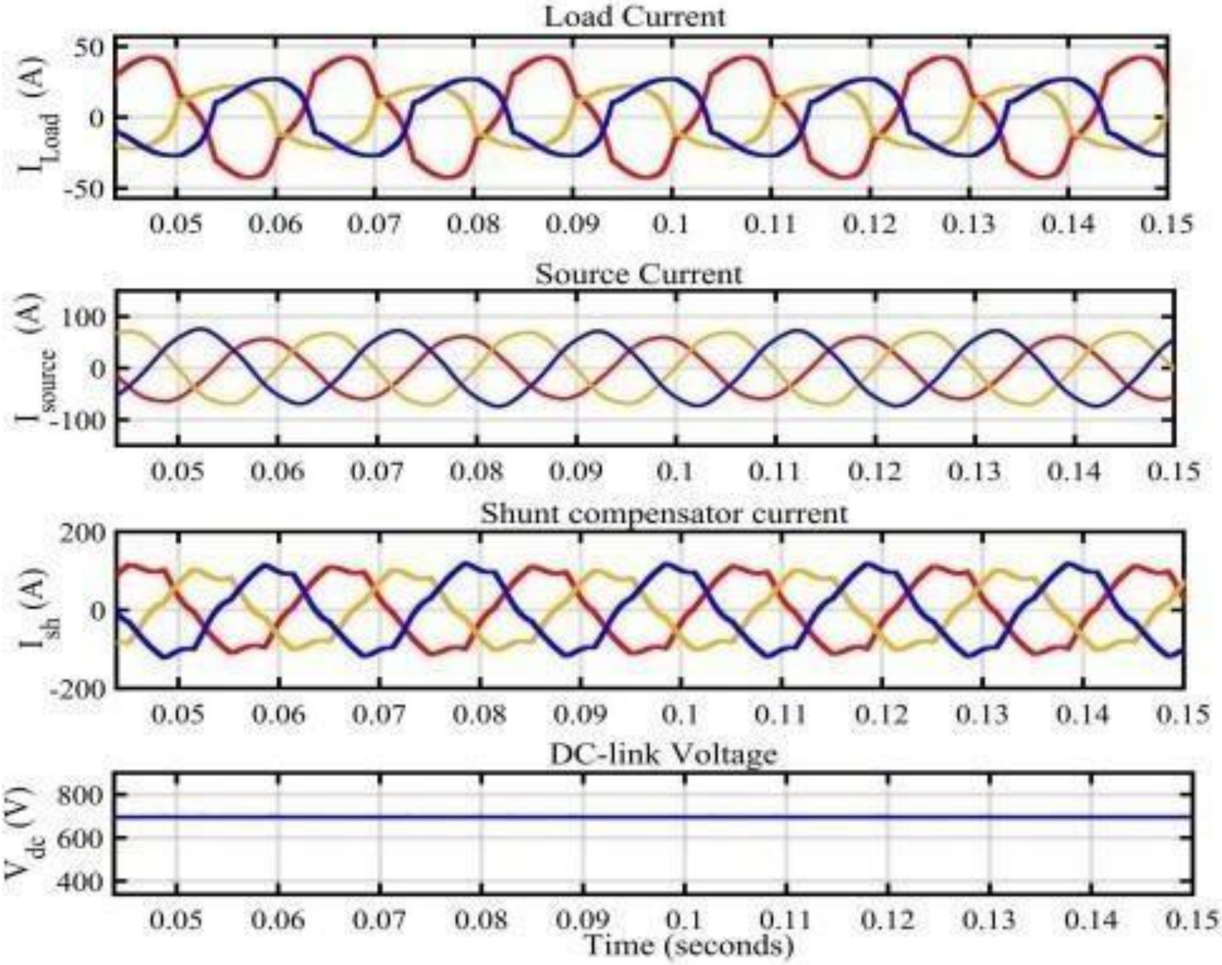
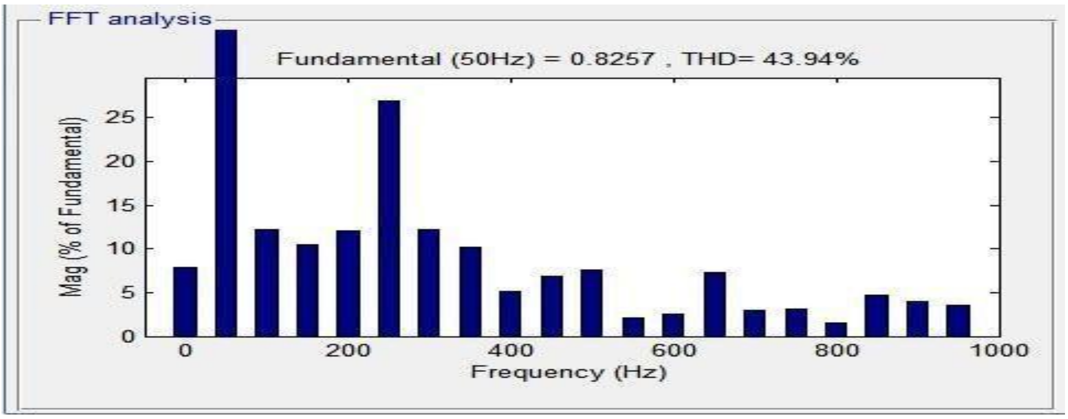


Fig.4.10.Behaviour of the system under highly unbalanced load condition

Table.4.1.Components and its specifications

Parameters	Value
Grid	110 V, 50 Hz
Interfacing inductor (shunt VSC)	2 mH
Interfacing inductor (series VSC)	4 mH
DC-link capacitor	4400 μF
DC-link voltage	210 V
Non-linear RL load	80 Ω/30 mH
SPV voltage and current at MPP	240 V, 4.1 A
SPV power at MPP	600 W



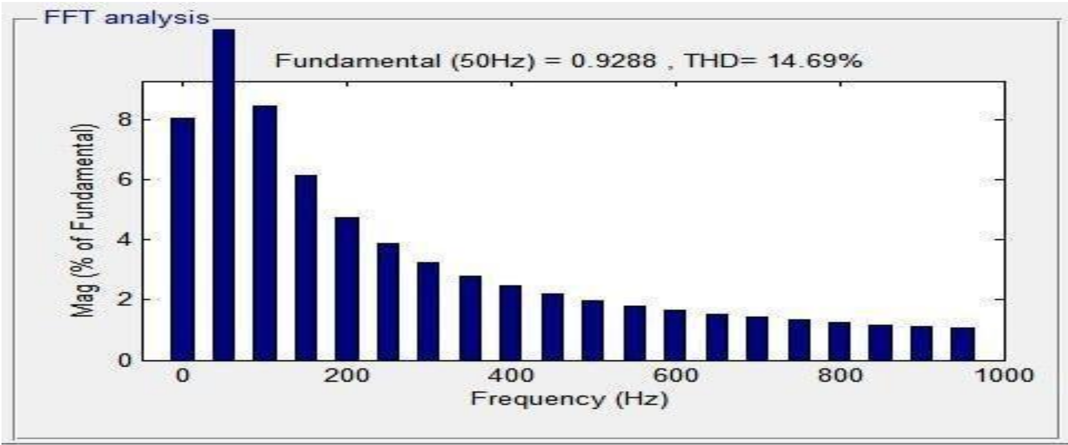


Fig.4.11.THD content for DSTATCOM

Table.4.2.System parameters of DSTATCOM

Parameter	Value
AC source voltage & frequency	$V_s = 415$ V , f = 50 Hz
Line Impedance	$L_s = 40$ mH, $R_s = 1.57\ \Omega$
Unbalanced R-L load	$R_a = 50\ \Omega$, $L_a = 200$ mH $R_b = 75\ \Omega$, $L_b = 225$ mH, $R_c = 25\ \Omega$, $L_c = 175$ mH
Nonlinear load(Three phase diode rectifier)	$R_d = 125\ \Omega$, $L_d = 30$ mH
Filter parameter	$L_f = 5.0$ mH
DC-side capacitance, resistance and voltage	$C_{dc} = 4000\ \mu$F, $R_{dc} = 6000\ \Omega$ $V_{dc} = 400$ V
Controller Parameter (Proportional and PI)	$K_{p1} = 0.6$, $K_{p2} = -0.2$, $K_i = -40$
Power Converter	IGBTs/diodes

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

CHAPTER 5

5.1. CONCLUSION AND FUTURE SCOPE

Performance analysis has been done by comparing the power quality of each compensator.

DSTATCOM is proved to compensate current levels under faulty conditions. Current harmonics has been reduced considerably. Harmonics generated at load side has THD of 43.94% which has been compensated to 14.69% at PCC. Even the current level increased during fault duration has also been compensated to a desired level.

UPQC is proved to compensate current and voltage levels under faulty conditions. Voltage and current harmonics has been reduced considerably. Current harmonics generated at load side has THD of 14.73% which has been compensated to 1.5% at PCC. Voltage Harmonics generated at source side has THD of 31.62% which has been compensated to 1.27% at load end. Even the current and voltage level during fault duration has also been compensated to a desired level. The shunt compensator is working satisfactorily under suddenly varying load and load unbalanced condition and makes the grid current sinusoidal by successfully compensating for load reactive power demand, and load harmonics. Series compensator efficiently compensates higher-order harmonics in source voltage. The load terminal voltage is maintained at the rated value by the series compensator, under sudden variation in grid voltage level (sag and swell). Also, the series compensator successfully eliminates the harmonics present in the source side and prevents it from reaching to the load side. The performance of the proposed scheme is further enhanced by the incorporation of PV array. Burden on the grid is reduced due to the interconnection of PV array. Under load deficit condition, PV array feeds extra generated power to the source. Under voltage swell, the performance of UPQC is improved due to active power provided by the PV Array

While Unified Power Quality Conditioners (UPQC) offer significant potential for enhancing power quality in PV-integrated distribution networks, certain limitations may constrain their effectiveness in certain scenarios. As such, future research endeavours can focus on addressing these limitations and expanding the scope of UPQC applications. One such limitation is:

Adaption to Dynamic Grid Conditions: UPQC systems may encounter challenges in adapting to rapidly changing grid conditions, such as fluctuating solar irradiance levels or sudden load variations. Future research could explore adaptive control strategies and predictive algorithms to enhance UPQC responsiveness and ensure optimal performance under dynamic operating conditions. Additionally, integrating advanced grid monitoring and forecasting technologies could enable UPQC systems to anticipate grid disturbances and proactively adjust their control parameters, thereby improving overall system robustness and reliability.

Explore the application of genetic algorithms to optimize the control parameters and topology of Unified Power Quality Conditioners (UPQC) in PV-integrated distribution networks. Genetic algorithms can enable the automatic tuning of UPQC settings to maximize power quality improvement, enhance fault tolerance, and adapt to dynamic grid conditions, leading to more efficient and resilient power quality enhancement solutions.

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