

**IMPACT ON THE POWER SYSTEM WITH A LARGE
PENETRATION OF RENEWABLE ENERGY
GENERATION**

Thesis submitted by

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CERTIFICATE FROM THE SUPERVISOR

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Dedicated to-
My parents and my Country

Preface

The present thesis entitled “**Impact on the Power System with a large penetration of Renewable Energy Generation**” is submitted for the degree of Doctor of Philosophy (Engineering) at the Faculty Council of Interdisciplinary Studies, Law and Management, Jadavpur University, Kolkata. The research work presented here was carried out under the supervision of **Prof. Ratan Mandal, School of Energy Studies, Jadavpur University**, and **Dr. Soumya Chatterjee, Electrical Engineering Department, National Institute of Technology Durgapur**, in between the period of December 2018 to July 2025. To the best of my knowledge, this work is original except where acknowledgements and references are made to previous work. Neither this nor any substantially similar thesis has been or has been submitted for any other degree, diploma or other qualification at any other University.

The integration of renewable energy into existing power systems introduces new challenges in maintaining power quality. Incorporating modern machinery and hybrid topologies creates disturbances across various categories, making it difficult to identify disturbance patterns and develop prevention strategies. This thesis focuses on detecting power quality disturbance signals and mitigation methods. It presents two case studies: one involving random switching due to power factor correction and another addressing relay coordination changes resulting from implementing photovoltaic (PV) systems in conventional power networks. To identify non-stationary signals, a powerful image processing method—deep learning and adaptive superlet transform (ALST)—is employed. The proposed model achieves great accuracy for simulated and real-life PQDE classification, respectively, offering superior performance with less computational time and memory compared to existing CNN models. Additionally, the thesis introduces hybrid harmonic mitigation techniques to enhance power quality in grid-connected photovoltaic (PV) systems. The proposed hybrid system effectively reduces power loss and mitigates all odd-order harmonics, lowering power loss and improving overall power quality. A counter-filter implementation approach targeting specific harmonic orders is also presented, analyzing the overall operation using an ETAP simulation of the IEEE bus system. This counter-filter technique highlights a new mitigation process that helps maintain system power quality.

While pursuing a PhD can be lonely, it is also impossible without the help of others. As mentioned earlier, Prof. Ratan Mandal, Professor at the School of Energy Studies, Jadavpur University, and Dr. Soumya Chatterjee, Assistant Professor in the Electrical Engineering Department at the National Institute of Technology, Durgapur, supervised my Ph.D. work. I appreciate each of them for offering valuable insights into my research. Their ongoing support, guidance, and deep understanding of the subject have been essential for the successful completion of my Ph.D. Finally, I want to thank everyone who helped make this effort possible.

Abstract

The impact of renewable energy generation on the analysis of the existing power system network is crucial for maintaining power quality. The network, which follows standard operating procedures, has changed due to the integration of non-conventional sources. The advanced and hybrid power system network faces numerous new challenges to ensure optimal power quality. The introduction of modern machinery and hybrid topology creates significant unknown disturbances across different categories. Today, it poses a real challenge to identify disturbance patterns and develop prevention strategies. Machine learning significantly aid in identifying disturbances, and the hybrid concept of power quality disturbance can improve power quality within a specific limit. In this thesis, the author presents a novel deep learning approach for identifying power quality disturbances along with a hybrid filter designed to mitigate these disturbances while preserving power quality. A brief overview of the present thesis work is given below.

The study aimed to assess the potential impacts and challenges of renewable energy integration in existing systems, focusing on power quality and harmonic analysis implementation methods with mitigation, as detailed in **Chapter 1**.

The Power Factor Correction Technique significantly impacts a grid-connected PV system by comparing different percentages of PV generation injection with the conventional grid. Compensation with PV injection significantly impacts an existing grid system. Additionally, the protection system's relay coordination changes during different fault conditions. In this case, the system generates non-stationary signals which create Power Quality Disturbance(PQD). The overall concept is described in **Chapter 2**.

Deep learning and adaptive superlet transform (ALST) have been used to detect and classify power quality disturbance events (PQDE) in grid-connected PV systems. Synthetic PQDEs were transformed into 2-D time-frequency RGB images using ASLT, resulting in enhanced resolution and distinct representations of events even at high noise levels. The CNN architecture was then used for feature extraction and classification. The proposed model achieved 99.52% and 98.18% accuracies for simulated and real-life PQDE classification, with superior performance and less computational time and memory compared to existing CNN models in **Chapter 3**.

Chapter 4 introduces hybrid harmonic mitigation techniques to improve power quality in grid-connected photovoltaic (PV) systems. The integration of PV generation into conventional grid systems has become a significant concern, necessitating an analysis of its impact on the existing grid and the application of preventive methods. Two basic mitigation techniques, Single Tune Passive Filter (STPF) and Phase Sifting Transformer (PST), are implemented in hybrid mode. The STPF mitigates higher and lower odd-order harmonics but has disadvantages like power loss, switching, and resonance. A hybrid mitigation method is introduced to maintain lower harmonics and power loss in grid-connected PV systems.

The single-tuned passive filter (STPF) is intended to reduce order harmonics in an IEEE system. However, the author discovered that the STPF can generate harmonics for other buses in the system due to parallel resonance between the source and the passive filter. This resonance can produce a significant harmonic current at the Point of Common Coupling (PCC). To overcome this issue, a counter-filter implementation approach is devised to decrease the harmonic production produced by the STPF in **Chapter 5**.

The study examines the integration of large-scale photovoltaic systems into IEEE bus-based power networks using ETAP-based simulations. It reveals that increased PV penetration impacts system parameters like power factor, fault current ratings, and harmonic distortion. The integration of PV leads to a declining power factor, requiring dynamic reactive power compensation using capacitor banks based on Direct Normal

Irradiance (DNI). The study also highlights the importance of protection coordination, which involves real coordination of PV-connected hybrid systems and backup protection relay sequence changes.

The system produces complex non-stationary signals, which can be detected using Adaptive Stockwell Transform (ASLT) and a custom lightweight CNN, achieving high classification accuracy up to 99.52%. The study also discusses harmonic mitigation, combining single-tune passive filters (STPFs) and phase-shifting transformers, which improves harmonic suppression efficiency by up to 95% and reduces system losses. The study proposes a counter-filter strategy to ensure harmonic attenuation across all buses, preserving system-wide power quality in **Chapter 6**

Chapter 7 describes the future plan of this Thesis, the impact of renewable energy on existing power systems, and methods to enhance power quality. The deep learning method will be used to analyze PQDEs with different classes of non-stationary signals, and a hardware setup for PQDE generation will be fabricated.

The research also explores hybrid power production systems, focusing on transformer efficiency and losses, and the K-factor to reduce harmonics in grid-connected PV systems. A hybrid approach using a single-tune passive filter is proposed to obtain a lower-order K-factor with increased loads.

The use of a rotary inverter with advanced controller circuits as an alternative to static inverters addresses the issue of odd-order harmonics and improves power quality. This method can overcome drawbacks and change the scenario of DC to AC conversion, ensuring better performance and efficiency in renewable energy systems.

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List of Symbols and Abbreviations

Symbol	Description
ACC	Accuracy
ASLT	Adaptive superlet transform
BN	Batch normalization
CNN	Convolutional neural network
CWT	Continuous wavelet transform
DFA	Detrended fluctuation analysis
DG	Distributed generation
DWT	Discrete wavelet transform
DNI	Direct Normal Irradiance
ETAP	Electrical transient analyzer program
GM	Geometric mean
PQDE	Power quality disturbance event
PL	Pooling layer
PV	Photovoltaic
RAP	Rank base average pooling
RE	Renewable energy
RELU	Rectified linear unit
RNN	Recurrent neural networks
ST	Stockwell transform
SLT	Superlet transform
SNR	Signal-to-noise ratio
SPE	Specificity
SEN	Sensitivity
SVM	Support vector machines
STPF	Single tuned Passive Filter

Symbol	Description
THD	Total Harmonics Distartion
T-F	Time-frequency
TFR	Time frequency representation

Chapter:1
Introduction

1. Introduction

1.1 Impact of Renewable energy on the existing Power system

India has one of the world's biggest synchronous grids, with 408714 MW* of installed capacity, 211856** MW of peak demand, and 444383* circuit km of AC and 19375* km of DC transmission network throughout the nation [1,2]. Renewable penetration in the Indian power grid has increased dramatically in recent years, with 165943* MW of installed capacity from solar, wind, hydro, and other RE sources as of October 2022. In the future, with a non-fossil capacity augmentation of 500 GW by 2030, the Indian power system's complexity is predicted to expand multi-fold.[3]Grid-India (formerly POSOCO) # is India's national power system operator (ISO). It oversees the whole grid through five regional control centers (RLDCs) and one national control center (NLDC). To maintain dependable and secure operations under highly renewable energy regimes, it's important to consider shifting grid situations during system and operational planning analysis.[4,5][*Source of data: Central Electricity Authority, **Source of data: Grid-India: NLDC,# Grid Controller of India Ltd. (Grid-India) was previously known as Power System Operation Corporation Ltd. (POSOCO)]Integrating renewable energy sources into India's power system has had a profound positive and challenging impact. Here's a detailed look at the various aspects.

The Positive Impacts Renewable energy sources, such as solar and wind, diversify the energy mix and reduce reliance on fossil fuels like coal and gas. This diversity stabilizes the power supply and strengthens the energy system's resilience to variations in fuel prices. Renewable energy sources dramatically reduce greenhouse gas emissions and air pollution compared to typical fossil fuels. This move is critical in combating climate change and improving air quality. It drives economic growth and employment creation. Solar farms, wind parks, and other renewable infrastructure investments benefit local economies and create job possibilities. Energy Security: India enhances its energy security by harnessing domestic renewable resources. Reducing reliance on imported fuels decreases vulnerability to geopolitical and market uncertainties. also, the push for renewable energy has driven technological advancements and innovations in energy storage, grid management, and energy efficiency.

Basic Challenges are 1. Grid Integration and Stability, Renewables like solar and wind are intermittent and dependent on weather conditions. Integrating these variable sources into the grid requires advanced grid management technologies and backup systems to ensure a stable and reliable power supply.2.Infrastructure development, expanding renewable energy infrastructure, such as transmission lines and storage facilities, is necessary to accommodate the growing share of renewables. This development involves significant investment and planning.3.Regulatory and Policy Framework, India needs a robust regulatory and policy

framework to support renewable energy integration. This includes clear policies on grid access, incentives, and standards to encourage investment and development.⁴ Financial and Economic Considerations, While renewable energy costs have decreased, the initial capital investment for renewable projects can be high. Balancing financial viability with long-term benefits requires careful planning and support mechanisms. 5. Land and Resource Use, Large-scale renewable projects, such as solar farms, require significant land areas, impacting land use and local ecosystems. Effective planning and management are needed to minimize negative environmental and social impacts

Ongoing Efforts and Future Outlook India has made tremendous progress in increasing its renewable energy capacity, with ambitious plans for solar, wind, and other renewable sources. The National Solar Mission and other state-level projects strive to build renewable energy infrastructure and enhance grid integration. Future initiatives are anticipated to focus on: Improving Grid Flexibility: Investing in smart grids and energy storage technology to better manage the fluctuation of renewable sources. Implementing supporting policies and incentives to encourage investment in renewables and grid infrastructure. Enhancing renewable energy efficiency via research and innovation.

Overall, while integrating renewable energy into India's power system presents challenges, the benefits far outweigh the drawbacks. With continued focus on innovation, investment, and supportive policies, India can further enhance its renewable energy capabilities and contribute to a more sustainable and resilient energy future.^{[6][7]}

1.2 Present scenario of Renewable energy resources in India:

India has made significant strides in developing its renewable energy capacity. The country's energy mix includes a variety of renewable sources, mainly focused on solar, wind, biomass, and hydropower. Below is an overview of key renewable sources in India.

I. Solar power is the most significant contributor to India's renewable energy growth. As of 2023, India's solar installed capacity was over 70 GW, to achieve 100 GW by 2022, which is now expected to be met slightly later. The geographical advantage in India's vast land area, particularly in states like Gujarat and Rajasthan, receives high solar insolation, making it ideal for large-scale solar projects. Key Initiatives are Jawaharlal Nehru National Solar Mission (JNNSM) Launched in 2010, which aims to promote solar power, International Solar Alliance (ISA) India is a founding member of ISA, promoting solar energy worldwide.

II. Wind Energy in India is the world's fourth-largest wind power producer, with an installed capacity of over 42 GW by 2023. Key Regions in the wind farms are concentrated in Tamil Nadu, Gujarat, Maharashtra, and Karnataka. The country has set a goal of 60 GW of wind power by 2022 Offshore Wind Projects are still in the early stages, and offshore wind projects are being explored, especially along India's long coastline.

III. Hydropower in India has a rich history of hydropower development and is one of the world's biggest producers of hydroelectricity, with an installed capacity of around 50 GW.

Large hydropower projects were traditionally the backbone of India's renewable energy sector. Challenges in the hydropower face issues like environmental concerns, displacement of people, and dependency on monsoons. Small Hydropower Projects: Small hydropower projects, with a capacity below 25 MW, also contribute to the renewable energy portfolio. IV. Biomass Energy in India comes from a variety of organic materials like agricultural waste, wood, and crop residues. The installed capacity of biomass power and cogeneration projects stands at around 10 GW. India's agrarian economy provides vast potential for biomass and bioenergy, and several states like Punjab and Haryana are leading in biomass utilization. India is also focusing on waste-to-energy technologies, which convert municipal solid waste into electricity and heat. V. Other Emerging Sources of Geothermal Energy although still under development, India has some geothermal potential in areas like Ladakh, Himachal Pradesh, and Gujarat. Tidal Energy with a vast coastline, India is also exploring the potential of tidal energy, though commercial development is in a nascent stage. VI. Key Government Policies and Targets: National Action Plan on Climate Change (NAPCC): Launched in 2008, this framework includes eight national missions, with the National Solar Mission being one of the key components.

Renewable Energy Target for 2030: India has set an ambitious goal to achieve 500 GW of renewable energy capacity by 2030, aligning with its commitment to reduce carbon emissions under the Paris Agreement. Increased Foreign Investment: India's renewable energy sector has attracted significant foreign investment, with policies encouraging private sector participation.[8-11].

1.3 Impacts of solar PV generation on power system operations:

The increasing use of PV systems in electric power networks reduces grid resilience. The size and placement of the PV system significantly influence power system operations at both the transmission and distribution levels. IEEE Standard 929-2000 categorizes PV systems into three main categories: small (up to 10 kW), intermediate (between 10 and 500 kW), and big (more than 500 kW). PV systems in the first two categories are installed at the distribution level, while those in the third category are installed at the sub-transmission/transmission system level.

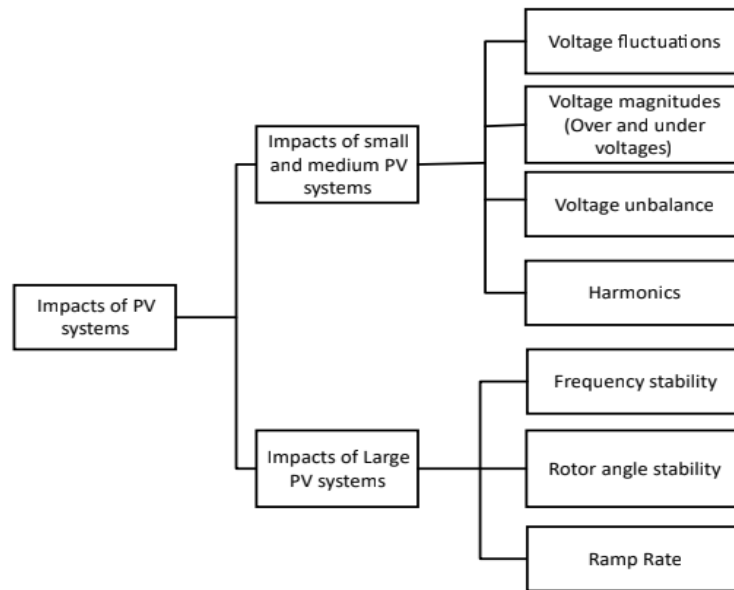


Fig.1.1 Description of the type of impact of the PV system on the Grid

In this thesis, the author concentrates on solar power generation for its maximum availability in India, it has a great impact on power quality. The impact of the PV system, whether that is small-scale or large-scale scale generates power quality issues related to voltage, frequency, and harmonics, description of the type of impact in Fig1.1 which are described in section 1.4.

After the Implementation of many types of non-conventional sources like solar, wind, biomass, small hydro, and others, some major issues are very important to analyze the Quality of power, Disturbance (power mismatch, grid integration problem, harmonics, compensation process, protection, etc).In this thesis, the main objective is to identify these disturbances and find the solution.

1.4 Issues related to Power quality:

The phrase "electric power quality" (PQ) generally refers to conventional and Non-conventional AC power generation, transmission, distribution, and usage. The AC supply systems are contaminated for several causes, including forced factors like voltage distortions and notches, equipment failure, and faults (about 40%), and environmental factors like lightning, flashovers, and storms (about 60%). Because certain customers' equipment draws non-sinusoidal current and behaves like a nonlinear load, it contaminates the supply system. Power quality is therefore measured in terms of the supply system's voltage, current, or frequency variation, which might cause the equipment belonging to the customer to malfunction or fail. The voltage at the point of common coupling (PCC), where many loads are coupled, can cause power quality issues such as voltage harmonics, surges, spikes, notches, sag/dip, swell, imbalance, fluctuations,

glitches, flickers, outages, and so forth. The supply system is experiencing these issues due to several system disruptions or the existence of different nonlinear loads, such as furnaces, UPSs, and adjustable speed drives (ASDs). However, low power factor, reactive power burden, harmonic currents, unbalanced currents, and an excessive neutral current in poly-phase systems due to unbalancing and harmonic currents created by some nonlinear loads are some power quality issues associated with the current pulled from the AC mains. These power quality problems cause the failure of banks of capacitor, enlarged losses in the distribution system and electric machines, vibrations, noise, overvoltage, excessive current due to resonance, negative sequence currents in generators from different motors, especially heating of the rotor, de-rating of cables, breakdown of the dielectric, interference with communication systems, signal interference and malfunctions of relay and breaker, false metering, interferences to the motor controllers and digital controllers, and so on.

In the presence of Non-conventional sources like solar, and wind with the conventional grid system power quality maintenance at a permissible level is very difficult nowadays. so it generates a great challenge to maintain power quality whenever designing and utilizing a grid-connected hybrid system. The evolution of techniques for mitigating power quality problems in existing systems and future equipment has led to a new direction of research and development for engineers in power electronics, power systems, electric drives, digital signal processing, and sensors. This has changed the scenario of power electronics, as most equipment using power converters needs modifications to meet new requirements. Some well-developed converters are becoming obsolete, necessitating the evolution of circuit configurations for specific applications. Organizations like IEEE and IEC have developed standards and benchmarks to enforce on customers, utilities, and manufacturers to minimize or eliminate power quality problems[12]

1.4.1 Effects of Power Quality Problems

Power quality issues impact utilities, customers, and manufacturers, causing financial losses due to process interruptions, apparatus damage, production loss, raw material wastage, and data loss. In automated industrial processes like semiconductor manufacturing, pharmaceutical industries, and banking, even a small voltage dip can cause significant disruptions. Protection systems and measuring instruments also suffer from these issues. Odd order harmonic current increase losses in electrical equipment and distribution systems, leading to energy expenditure, poor utilization of utilities' assets, overloading power capacitors, noise and vibrations, and interference with electronic appliances and communication networks.

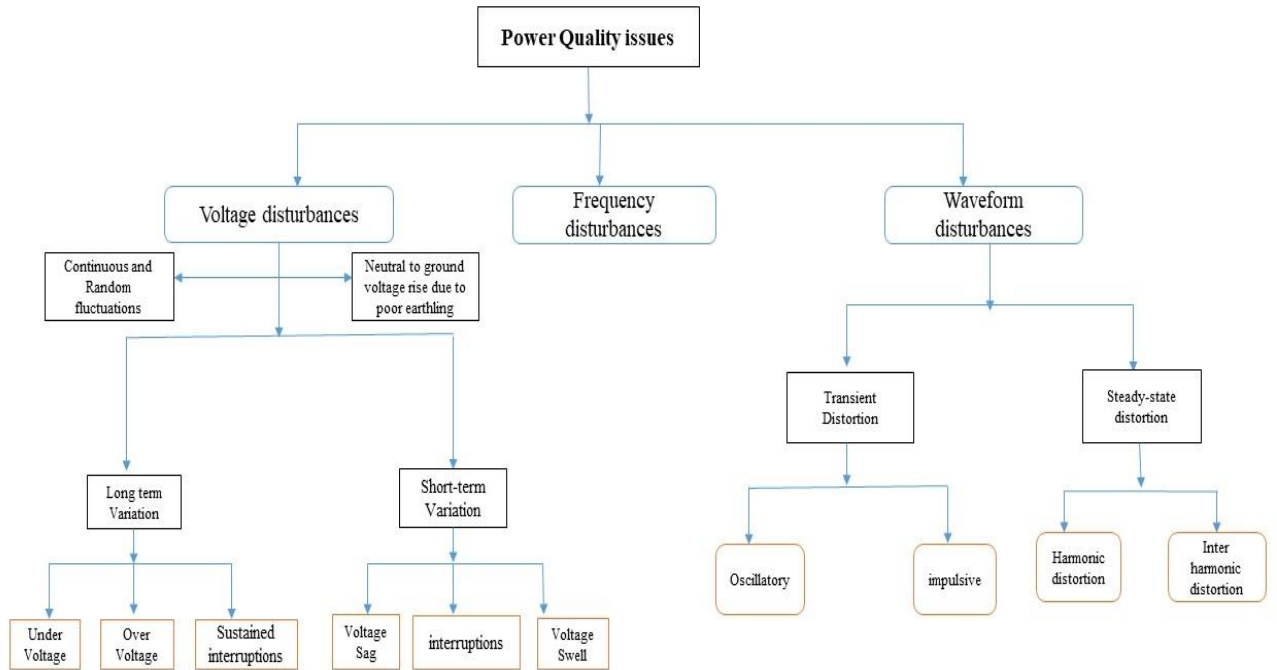


Fig:1.2 Types of Power Quality Issues in Power System.

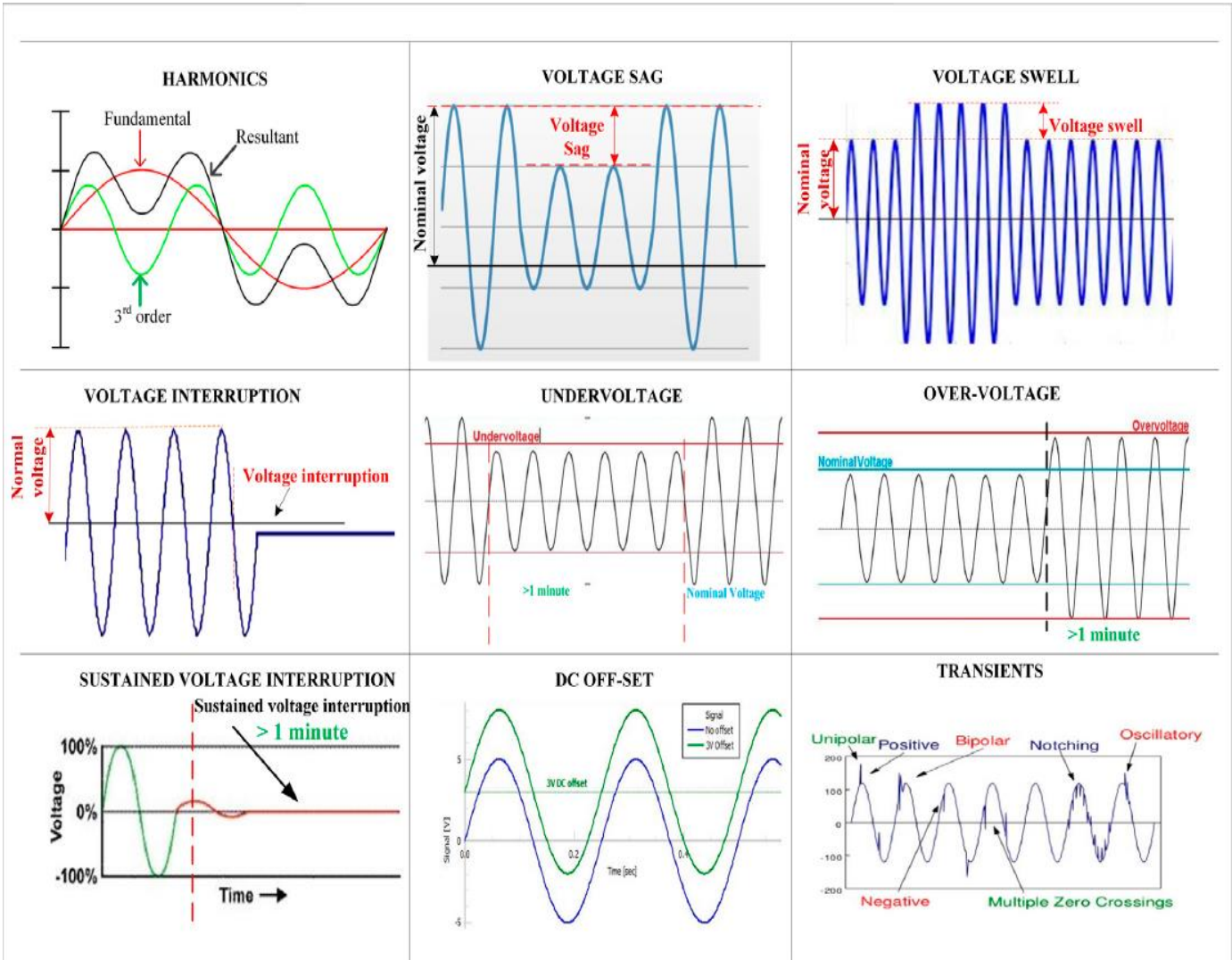


Fig:1.3 Waveforms of Different Types of Power Quality Issues

In Fig.1.3 represents some waveforms of different power quality issues, mostly non-stationary signals. In power quality analysis there are two basic signals stationary signals which show constant characteristics over time example a steady state AC signal with minimum harmonics and constant current drawn from a stable load, and another is non non-stationary signal the characteristics of this signal change significantly over time. In power quality issues or power quality disturbance events (PQDE) the non-stationary signals with single-class or multiple-class interrupt the power quality. These non-stationary signals are generated from different nonlinear loads sudden voltage dips, surges, harmonics, and transients which occur periodically in the power system network. In the present time when renewable sources contribute a specific percentage of power generation, this PQDE occurs randomly by these non-stationary signals. Now this is a big challenge to identify and analyze the power quality for hybrid systems. Table 1 also indicates different PQDE with category and course effects.

Table:1.1 Power Quality Problems, Causes and Effects

Problems	Category	Categorization	Causes	Effects
Transients	Impulsive	Rise, PeakTime, and Duration	Lightning Strikes, Transformer energization, Capacitor Switching	Power system resonance
	Oscillatory	Peak Magnitude and frequency components	Line, Capacitor, or Load Switching	System resonance
Short-duration Voltage Variation	Sag	Magnitude Duration	Motor Starting, Single line to ground faults	Protection malfunction, Loss of production
	Swell	Magnitude Duration	Capacitor switching, large Protection malfunction, load switching faults	Protection malfunction, stress on computers, and home appliances
	Interruption	Duration	Temporary faults	Loss of production, malfunction of fire alarms
Long-duration voltage Variation	Sustained Interruption	Duration	Faults	Loss of production
	Under Voltage	Magnitude Duration	Switching on loads, Capacitor de-energization	Increased losses heating
	Over Voltage	Magnitude Duration	Switching on loads, Capacitor energization	Damage to household appliances
Voltage Imbalance waveform distortion	DC offset	Symmetrical Components volts, Amperes	Single-phase load, Single Phasing. Geomagnetic disturbance, Rectification	Heating of motors,, Saturation transformers
	Harmonics	THD, Harmonic Spectrum	ASDs, Nonlinear Loads	Increased losses, poor power factor
	Inter Harmonics	THD, Harmonic Spectrum	ASDs, Nonlinear Loads	Acoustic noise in power equipment Damage to
	Notching	THD, Harmonic Spectrum	Power electronic converters	Damage to capacitive components
	Noise	THD, Harmonic	Arc furnaces	Capacitor overloading
Voltage Flicker		Frequency of Occurrence, Modulation Frequency	Arc furnaces, arc lamps	Human health, irritation, headache, migraine
Voltage Fluctuations		Intermittent	Load Changes	Protection malfunction, light intensity changes

1.5 International Standards of Power Quality

The IEEE and IEC standards describe the quality of the power which have to be maintained for power quality management. The standards define the limits of power quality. The requirements of the standards are Power quality assurance, safety, Identification of disturbance.

A. IEEE Standards

- I. IEEE 519-2014: Harmonic Control in Electrical Power Systems.
- II. IEEE 1159-2019: Recommended Practice for Monitoring Electric Power Quality
- III. IEEE 1459-2010: Definitions for measuring Electric Power Quantities Under Sinusoidal, Non-Sinusoidal, Balanced, or Unbalanced Conditions.
- IV. IEEE 1547-2018: Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces.
- V. IEEE 1564-2014: Guide for Voltage Sag Indices
- VI. IEEE 1250-2018: Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances.
- VII. IEEE 1100-2021: Recommended Practice for Powering and Grounding Sensitive Electronic Equipment.

B. IEC Standards

1. IEC 61000 Series: Electromagnetic Compatibility (EMC)
2. IEC 62586 Series: Power Quality Measurement
3. IEC 61000-4-30: Power Quality Measurement Methods
4. IEC 61000-4-11: Voltage Dips, Short Interruptions, and Voltage Variations
5. IEC 61000-4-15: Flickermeter – Functional and Design Specifications.
6. IEC 61000-4-34: Testing for Voltage Dips, Short Interruptions, and Variations at Medium Voltage
7. IEC 61000-4-13: Harmonics and interharmonics Measurement
8. IEC 61000-4-27: Unbalance Measurement
9. IEC 61850: Communication Networks and Systems for Power Utility Automation.

1.6 Harmonics in PV system:

Harmonics in photovoltaic (PV) systems are a critical aspect to understand for ensuring efficient and reliable operation. Harmonics refers to the distortion in the electrical current or voltage waveform that deviates from the ideal sinusoidal waveform. Here's a breakdown of how harmonics can impact PV systems and what can be done to manage them.

I. Sources of Harmonics in PV Systems

Inverters: PV systems often use inverters to convert the direct current (DC) generated by the solar panels into alternating current (AC). Inverters can introduce harmonics due to their switching actions and electronic components.

Non-linear Loads: Any non-linear load connected to the PV system, such as certain types of LED lighting, variable frequency drives, or computers, can generate harmonics.

II. Impact of Harmonics and Power Quality: Harmonics can affect the quality of the power output, leading to inefficiencies and potential damage to sensitive equipment.

System Performance: High levels

of harmonic distortion can reduce the efficiency of the PV system, affecting the overall performance and energy yield. Equipment Lifespan: Prolonged exposure to harmonics can lead to overheating and premature failure of electrical components, such as transformers and cables. Regulatory Compliance: Many regions have standards and regulations regarding harmonic levels to ensure system performance and safety. Exceeding these limits can lead to compliance issues. III. Harmonic Analysis: Using specialized equipment like power quality analyzers, you can measure and analyze harmonic levels in the system. This analysis helps in identifying the sources and determining the extent of harmonic distortion. Total Harmonic Distortion (THD): This is a key metric used to quantify the overall harmonic distortion in the system. It's calculated as a percentage of the fundamental frequency. IV. Mitigating Harmonics: Filter Installation: Harmonic filters, such as passive filters or active filters, can be installed to reduce harmonic distortion. Passive filters are designed to target specific harmonic frequencies, while active filters can dynamically adjust to varying harmonic conditions. Design Considerations: Proper design and sizing of inverters and other system components can minimize the introduction of harmonics.

For instance, using inverters with better harmonic performance characteristics can help. Maintenance and Monitoring: Regular maintenance and monitoring of the system can help identify and address harmonic issues before they impact performance. [13]

V. Regulatory Standards: IEEE Standards: In the U.S., standards such as IEEE 1547 provide guidelines for harmonics in PV systems. IEC Standards: Internationally, standards like IEC 61000-4-7 and IEC 61000-4-30 offer guidelines on harmonic measurement and limits.

1.6.1 Harmonic Mitigation Technique:

In contemporary power system networks that connect several nonlinear loads, power quality is a crucial prerequisite. The introduction of harmonic components via power electronics switches and non-linear loads has a significant effect on power distribution or transmission networks. At present to mitigate Harmonics there are many methods as well as models implemented in the system. The following fig.4 describes the type of Mitigation Technique.

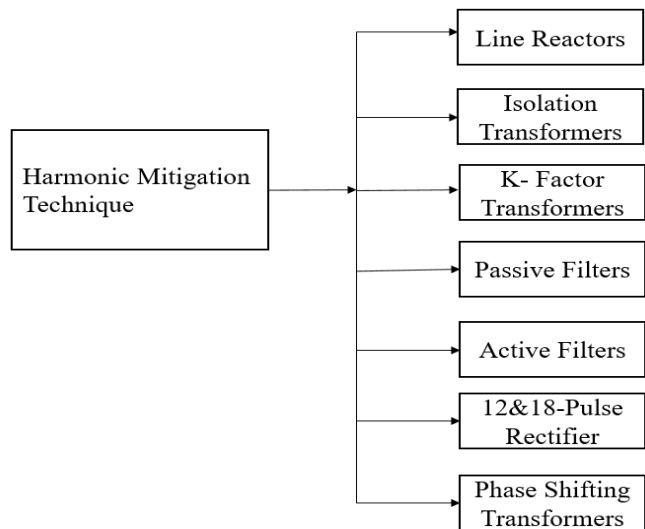


Fig.1.4 Different types of harmonics mitigation techniques

I. Line Reactor: Line Reactors are a modest and cost-effective method of odd order harmonics by connecting in series with a non-linear load like an ASD. They absorb voltage transients and attenuate harmonics, preventing voltage source ASD from tripping on over-voltage. The magnitude of harmonic distortion depends on the effective impedance of the reactor. Line reactors offer low cost and can significantly reduce harmonics when the appropriate percent impedance is used. For harmonic mitigation 5% impedance line reactor should be installed before the drive of motor or other 6-pulse non-linear load.[14] II. Isolation Transformer: An isolation transformer has physically distinct main and secondary windings, usually separated by an electrostatic shield. This shield prevents noise from one system from traveling through the transformer and into sensitive electronics. Shielded isolation transformers are widely used in power conditioning because they protect sensitive loads from utility transients and noise. They also keep harmonics generated by end-user non-linear equipment out of the utility's system. Isolation transformers are dry-type, natural air-cooled transformers with functional insulation by design.[15] III. K-factor of Transformer: The K-factor is a technique for calculating the lifetime of transformers that contain individual harmonic components. It works well for eliminating or attenuating harmonics, and phase change transformers can also be utilized.

Distribution equipment manufacturers have created K-factor transformers to securely handle nonsinusoidal loads and sustain harmonic load currents. The K factor in power system shows the number of harmonics present and is proportional to the harmonic currents.[16] IV. Passive filter: A passive filter is a device that uses passive components—such as inductors, capacitors, and resistors—to reduce harmonic distortion. Unlike active filters, passive filters are tuned to specific harmonic frequencies, making them a simpler, more cost-effective solution for certain applications. Passive filters work by creating a low-impedance path for specific harmonic frequencies, allowing the harmonic currents to be diverted away from

the rest of the power system. The filter is typically connected in parallel with the non-linear load, and it provides an alternate path for the harmonic currents, thus reducing the overall distortion in the system.

Components of Passive Filters

Inductors (L): Inductors oppose changes in current and are used to block higher-frequency harmonic currents.

Capacitors (C): Capacitors store and release electrical energy, offering low impedance to high-frequency harmonic currents, and are used to bypass them.

Resistors (R) Resistors dissipate energy in the form of heat and dampen resonances within the filter.

Types of Passive Filters are Single-Tuned (Band-Pass) Filters, Double-Tuned Filters, High-Pass Filters, and C-Type Filters.[17]

V. Active filter: Active Power Filters (APFs) are advanced devices that use power electronics to monitor and compensate for harmonics in real time. The main concept behind APFs is to inject harmonic currents that are equal in magnitude but opposite in phase to the harmonic currents present in the system, thereby canceling out the distortion. Types of Active filters are 1.Shunt Active Filters 2. Series Active Filters 3. Hybrid Active Filters.Active filters operate based on sophisticated control algorithms, such as: Instantaneous reactive power theory (also called p-q theory) and synchronous reference frame theory power control These algorithms allow the active filter to quickly and accurately identify the harmonic components and inject the appropriate compensating current or voltage[18]

VI.12 & 18 Pulse transformers:a 12-pulse rectifier is essentially two 6-pulse rectifiers connected in parallel or series, with a phase shift introduced between the two sets of rectifiers to cancel out certain harmonics. The most common configuration is achieved using a transformer with a phase shift of 30° between the two secondary windings one connected in a delta configuration and the other in a wye configuration. This phase shift helps cancel out specific harmonics generated by each of the 6-pulse rectifiers. In a 12-pulse rectifier, the phase shift between the two sets of rectifiers results in the cancellation of lower-order harmonics, particularly the 5th and 7th harmonics. The harmonics generated by the 12-pulse rectifier are of the order $n = kp \pm 1$, where $p = 12$, resulting in the following harmonic orders: 11th harmonic (660 Hz), 13th harmonic (780 Hz), 23rd harmonic (1380 Hz), 25th harmonic (1500 Hz). These higher-order harmonics are less detrimental to the power system because they have lower magnitudes and can be more easily filtered out using passive filters. As a result, the total harmonic distortion (THD) is significantly reduced when using a 12-pulse rectifier. An 18-pulse rectifier consists of three 6-pulse rectifiers, with transformer windings providing phase shifts of 20° between each set of rectifiers. This configuration allows for the cancellation of even more harmonics compared to a 12-pulse rectifier, making it suitable for applications where harmonic mitigation is critical. The 18-pulse rectifier generates harmonics of the order $n = kp \pm 1$, where $p = 18$. This results in the elimination of the lower-order harmonics, including the 5th, 7th, 11th, and 13th odd order harmonics. The remaining harmonics are higher in order and have much lower magnitudes: 17th harmonic (1020 Hz), 19th harmonic (1140 Hz), 35th harmonic (2100 Hz), and 37th harmonic (2220 Hz). The reduction in both the magnitude and order of the harmonics results in a much cleaner power supply and further reduces the need for additional filtering[19][20]

VII. Phase-shifting

Transformer: A phase-shifting Transformer is a specially designed transformer that introduces a specific phase shift between its primary and secondary windings

This phase shift allows harmonic currents from different sources to cancel each other out, thereby reducing the overall harmonic distortion in the power system network. Phase-shifting transformers are commonly used in conjunction with multi-pulse rectifiers, such as 12-pulse or 18-pulse systems, where they play a key role in harmonic cancellation. The key principle of phase-shifting transformers is based on harmonic cancellation. In a multi-pulse rectifier system, the harmonic currents generated by each set of rectifiers are out of phase with each other. By introducing a phase shift between the outputs of the rectifiers, the harmonic components can be made to cancel out through destructive interference. This significantly reduces the total harmonic distortion (THD) in the system.

VIII. Harmonic Cancellation in Multi-Pulse Rectifiers

12-Pulse Rectifier: In a 12-pulse rectifier, two 6-pulse rectifiers are connected to the secondary windings of a phase-shifting transformer. The transformer is configured with delta and wye (star) windings that introduce a 30° phase shift between the two sets of rectifiers. This phase shift cancels out the 5th and 7th harmonics, resulting in much lower harmonic distortion compared to a standard 6-pulse rectifier.

18-Pulse Rectifier: An 18-pulse rectifier uses three sets of 6-pulse rectifiers, with a transformer that introduces a 20° phase shift between each set. This configuration cancels out even more harmonic components, particularly the 5th, 7th, 11th, and 13th harmonics.

24-Pulse Rectifier: In a 24-pulse rectifier, four sets of 6-pulse rectifiers are used, with the transformer introducing a 15° phase shift between each set. This setup eliminates a broad range of harmonics, resulting in very low THD levels. [21]

1.7 General idea of signal processing and machine learning methods

Evaluating transient detection and protection in power systems is challenging owing to their complicated infrastructure and rapid reactivity. This task is critical for operational concerns since it monitors stability status and limits [1]. Conventional power systems have low sample frequencies, making it difficult to monitor power system transients. Wide-area measurement systems (WAMS) also phasor measurement units (PMUs) have enabled real-time security assessments. Local measuring devices may not cover specific regions and may fail temporarily or permanently. As a result, developing a complete model has become critical. The existing literature offers signal processing and machine learning approaches to understanding power system transients. Signal processing involves examining voltage and current signals in time and frequency domains to identify stable or unstable states.

1.7.1 Application of Machine Learning in Power Quality

Machine learning significantly improves power quality monitoring, diagnosis, and management in electrical systems by integrating intelligent, automated, and adaptive solutions, with key applications including [22-23]. Machine learning (ML) has become a powerful tool for improving power quality (PQ) in modern electrical

systems. It enhances disturbance detection and classification using models like Support Vector Machines (SVM), Decision Trees, Neural Networks (NNs), and Convolutional Neural Networks (CNNs), which accurately classify voltage sags, swells, flickers, harmonics, and transients. Fault detection and diagnosis use Random Forests, k-Nearest Neighbors (k-NN), and Recurrent Neural Networks (RNNs), reducing downtime and boosting system reliability. Long Short-Term Memory (LSTM) networks and hybrid ARIMA-ML models forecast disturbances, enhancing grid stability. Feedforward Neural Networks (FNNs) and regression models improve waveform quality by identifying harmonic sources. Load profiling and optimization use clustering and reinforcement learning for efficient energy use and cost reduction. Unsupervised models like Autoencoders and Isolation Forests handle anomaly detection, while Gradient Boosting Machines assess voltage stability under variable conditions. Noise filtering and signal reconstruction use Generative Adversarial Networks (GANs) and Denoising Autoencoders for accurate data analysis.

1.8 Problem Identification

This thesis is based on the identification and prevention of power quality disturbances caused by renewable energy sources in the existing system. Power systems generate different types of signals, either stationary or non-stationary, with single or double classes. At the present time, the complexity of the signal increases with the presence of renewable sources in conventional systems. This thesis concentrates on generating a unique technique for the identification of power quality disturbance events (PQDE) and a hybrid approach to power quality

improvement. In the power quality disturbance events (PQDE), many types of classes are included, like sag, swell, harmonics, flicker, etc., and a combination of them. These PQEDs are generated from different operational conditions like power mismatch and over-powering of the power system network. To improve the power quality problem, many types of techniques like filters, Dynamic Voltage Restorer, Static Synchronous Compensator (STATCOM), Synchronous Condenser, Distribution Static Compensator (D-STATCOM), and Flexible AC Transmission Systems (FACTS) do not accure and increase the operational cost for the present PQEDs due to its complexity. To overcome this problem, hybrid mitigation techniques can be a way to activate the target.

1.9 Aim and objective of the thesis

The Central Electricity Authority has recorded substantial advancements in production and transmission capacity that enable India's transition to a renewable-powered grid [1][2]. The increasing use of renewable energy (RE) raises technical concerns such as voltage fluctuations, harmonics, and system instability [3][4][5]. To address these concerns, intelligent techniques and planning models are being investigated for long-term grid resilience [6][7]. National organizations such as MNRE, SECI, and IWPA play critical roles in policy implementation and RE expansion [8][10][11], while worldwide insights from the IEA promote sustainable energy planning [9]. Non-linear loads and RE sources introduce harmonics, which have an influence on power quality and equipment life. Active and passive filters [14][17][18], multi-pulse rectifiers [19][20], K-transformers [16], and phase-shifting transformers [21] are some examples of mitigation approaches. IEEE and

IEC standards and guidelines provide crucial guidance for power quality management [12][13][15]. Machine learning techniques are increasingly being used in smart grids to identify and classify power quality events, hence improving problem diagnosis and response [22][23].

This analysis aims to understand the various impacts of integrating a significant share of renewable energy generation into the existing power system, such as wind, solar, and hydropower. As the global transition to low-carbon energy sources accelerates, evaluating how these technologies affect modern power grids' reliability, stability, economic performance, and technical requirements is crucial. The key objective of this thesis is to identify the impacts of the unidentified challenges and propose a possible solution to maintain stable operation in the existing power system network.

The general key specific objectives of the thesis are the Grid Stability and Reliability Evaluation, analysis of Power Quality, assessment of Transmission and Distribution Infrastructure Requirements, Impact on Conventional Power Plants, Carbon Reduction, and Environmental Impact. In this thesis, the author concentrated on PV-integrated generation-related impacts as they contribute 15-20% of the total installed power capacity in India.

1.10 Scope of the Present Work:

The objective was to identify the possible impacts and challenges of the analysis method that can be generated due to renewable energy integration into the existing system. For this purpose, the method of implementing power quality and harmonic analysis with mitigation has been described in **Chapter 1**.

Identifies two important impacts for a grid-connected PV system first one is the impact of the Power Factor Correction Technique, which compares the different percentages of PV generation injection with the conventional grid. The involvement of compensation with PV injection generates a major impact on an existing grid system, and the second one is the effect of the protection system during different types of fault conditions. the relay coordination of the system changes whenever the PV system is injected into the grid. In this two case system generates different non-stationary signals which create Power Quality Disturbance (PQD). The overall concept is described in **Chapter 2**.

A new technique for detecting and classifying power quality disturbance events (PQDE) using adaptive superlet transform (ALST)--based time-frequency analysis and deep learning. Synthetic PQDEs were generated and transformed into 2-D time-frequency RGB images using ASLT. These images showed enhanced resolution and distinct representations of events, even at high noise levels. The PQDEs were then fed into a lightweight customized convolutional neural network (CNN) architecture for feature extraction and classification.

The proposed model achieved 99.52% and 98.18% accuracies for simulated and real-life PQDE classification, with superior performance compared to other time-frequency representation methods and less computational time and memory compared to existing CNN models. The framework can diagnose PQDE events in both noise-free

and strong noisy environments. **Chapter 3** indicates a noble concept of detecting and classifying Power Quality disturbance signals in grid-connected PV systems by Deep Learning.

Chapter 4 proposes hybrid harmonic mitigation techniques to improve power quality in grid-connected PV systems. In this chapter, integrating photovoltaic (PV) generation into conventional grid systems has become a significant concern, necessitating the analysis of its impact on the existing grid and applying preventive methods to maintain power quality. In this chapter, two basic mitigation techniques, Single Tune Passive Filter (STPF) and Phase Sifting Transmitter (PST), are implemented in hybrid mode. The phase-shifting transformer method offers minimal power loss and voltage fluctuations but is not effective for higher odd harmonics. In the case of a single-tune passive Filter (STPF), it is used to mitigate higher as well as lower odd-order harmonics, with some disadvantages like power loss, switching, and chances of resonance. In grid-connected PV systems, a hybrid mitigation method has been introduced to maintain lower harmonics and power loss, and enhance power quality.

The single-tuned passive filter (STPF) is designed to mitigate order harmonics in an IEEE system. However, the author found that the STPF can cause harmonic generation for other buses in the same system due to parallel resonance between the source and the passive filter. This resonance can generate a large harmonic current at the Point of Common Coupling (PCC). To address this issue, a counter-filter implementation method is implemented to mitigate the harmonic generation caused by the STPF in **Chapter 5**

1.11 Reference:

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Chapter:2

Studies of Renewable Energy Impacts on Existing Power System networks

2.1 Introduction

Integrating renewable energy (RE) sources into existing power system networks has profound impacts on the grid's technical, economic, and operational aspects. PV-connected grid systems generate different types of power quality issues discussed in the previous chapter. This chapter highlights two significant impacts of a grid-connected PV system. The impact of the Power Factor Correction Technique, which compares PV generation injection percentages with conventional grids, and the protection system's effect during fault conditions, where relay coordination changes when the PV system is injected into the grid. In two cases, it is not directly involved in generating power quality disturbance event (PQDE) but generates single and multiple class non-stationary signals, which negatively impact power quality in the grid. fundamental power frequency voltage and current waveforms, and harmonics distortions due to non-linear loads like transformers and rectifiers are examples of stationary waves. In the case of non-stationary waves, transient overvoltages, oscillatory transients, fault-induced traveling waves, switching surges, sudden load disconnection, and resonance, protection systems due to faults are examples. This thesis introduces two case studies, which can generate different non-stationary signals that affect the power quality of the grid-connected PV system.

2.2 Study of Power Factor Correction Technique for a Grid-connected PV System

In recent years, injecting renewable energy into existing systems has been a new challenge for a fast-growing country like India. In a hybrid generation, fossil fuel-based and renewable-based sources are involved. The effect of renewable energy on every parameter of the system is very important to study for maintaining the proper stability of the system. Direct Normal Irradiance (DNI) is one of the major parameters that regulate solar generation. This frequent change in solar generation has a great impact on the power factor of a hybrid system. To compensate for the power factor with a compensation device for a PV-connected system, a relation between power factors and PV generation. In this Chapter, the author established a relationship between Direct Normal Irradiation, which regulates the PV generation and the power factor of the system to make the system more stable and economical. In this Chapter, the author use an ETAP simulation model to investigate the effect of the PV generation on the power factor and correction technique.

In India, the core energy provider is conventional sources, which are universal economies. Last 10 years the energy demand has increased exponentially which creates an issue for power distributors in India. It is the only way to solve this problem is to introduce renewable energy in the power sector .as because most part of the country includes a high number of sunny days and the daily irradiance PV (Photo voltaic) generation system can make a better option for the power compensation in India. [1].

The leading aim of this work is to study the performance of the grid-connected photo voltaic generation with respect to Direct Normal Irradiance (DNI). The analysis includes active power analysis and power factor by load flow technique at the grid side of the solar farm. In this Chapter, the author implement an ETAP simulation model for suitable operation. The overview of photo voltaic generation was simulated in ETAP-12.6 as a single-line diagram. The photo voltaic panel rating increases with 20%, 30%, and 40% of the total load. [2].

2.3 Load flow using electrical transient analyzer program (ETAP)

Load flow in ETAP software performs power flow analysis and voltage difference calculations with approximately correct and reliable results. Incorporated options like equipment analysis, alerts load flow result analyzer when a mismatch or fault occurs in the network and automatic and symbolic graphics which give a complete idea about the electrical system.

ETAP load flow calculation program calculates different parameters like bus voltage, branch power factors, line currents, and power flows of the overall electrical network. The features in ETAP for swing, are both options for voltage-regulated, and unregulated power sources with unlimited power grids and generator connections. This load flow tool is also capable of performing analysis on both radial and loop systems.

2.4 Photovoltaic Generation System

Sunlight to Direct Current (DC) electricity (i.e. light energy to electrical energy) converts using PV cells. Change controller work as control the power from solar panel which reverses back to solar panel get cause of panel damage. When sunlight is not available (i.e. night) then the storage of electric power is used from the battery system. To convert Direct Current into Alternating Current, this system is connected to an inverter [3].

To make a solar module, the numbers of solar cells are connected electrically with series and parallel combinations to make a solar array. To produce a high amount of electric energy this configuration is required [4].

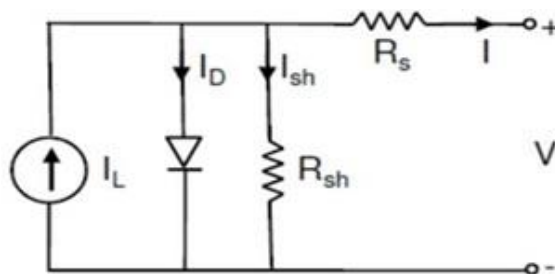


Fig.2.1 PV Circuit diagram

Fig.1 shows the equivalent circuit of the solar cell, where Current Source = I_{ph} , Shunt Resistance = R_{sh} , and Series Resistance = R_s . The value series resistance (R_s) is less than the value of shunt resistance (R_{sh}), so we can be neglected for simplification. Boltzmann constant = K , Diode ideality factor = N , and cell temperature = T . The Load current equation is shown below ^[5]The photo voltaic systems are of two type namely (i) stand-alone systems (ii) grid-connected systems [6].

The advantage of the grid-connected system; it can operate without a battery which makes it more economical. In this Chapter, the author try to establish a model without a storage system and analyze the performance of the system.

2.5 Power Factor Correction

The power factor determines how effectively the power is utilized. It depends on active power and reactive power drawn by an industry/consumer. Industrial loads, mostly induction motors draw active and reactive power depending on the mechanical load on the induction machine. In industrial drive where variable speeds are involved, one uses variable voltage variable frequency drive by which the power factor becomes low.

Electricity bill is collected for active power and reactive power. However, if we can decrease the reactive power, then the electricity bill shall be reduced.

An ideal power factor is unity. Thus, it is always recommended to use reactive power compensators within the industrial premises or within a township.

In this work, reactive power is generated through capacitor bank locally. The experiment has been carried out with in an educational institute. The reactive powers drawn are compensated through three phase capacitor banks, so the current drawn from the distribution transformer is reduced. This has an effect of reducing the electricity bill. The losses in the distribution transformer have also been reduced. In a large substation associated with a township / educational institute. Improvement in power factor shall reduce the losses to a large extent.

The static compensators for reactive power can be used all 24 hours. However, it is most effective during the peak load hours, i.e., from 05:00 PM to 11:00 PM (It may vary from state to state within India). The financial burden increases during any additional load in the peak hours. Thus, it is required to compensate the reactive power fully during the peak hours. In an industry, there are high-power induction motors with low mechanical loads. There are also transformers that have low loads. This equipment draws a large lagging current. These reactive powers can be compensated by a static reactive power compensator. We also need a harmonic filter to improve the power factor. The inverter-driven AC motors where the power factor is low (0.50 to 0.75) [8] need compensation. The irradiance of solar power is defined as the rate at which solar energy falls onto a surface. In the case of solar irradiance, power is usually measured by the per unit area so irradiance is typically quoted as

W/m² (watt per square meter). To calculate the expected output, the peak capacity of the system multiplied by energy production per peak capacity (kWh/kWp) gives the total energy generation each year [9].

$$G_0 = 24.S [1 + 0.33 \cos(2.\pi.n)]$$

$$[\cos \varphi . \cos \delta . \sin \omega s + \omega s . \sin \varphi . \sin \delta] \text{ W/m}^2$$

where,

S = the solar constant

n = the days' number of the year

φ = the latitude of the considered location

δ = the declination of the Earth

ωs = the solar angle

2.6 Overview of the network for analysis

At 11 kV bus voltage grid (U1) operates which is connected a rating of 630 kVA step down transformer (T1) in series. Loads are connected in parallel through Bus4 and Bus9 respectively. Capacitor bank (CAP3) with rating of 5.4 kVAR connected at Bus4.

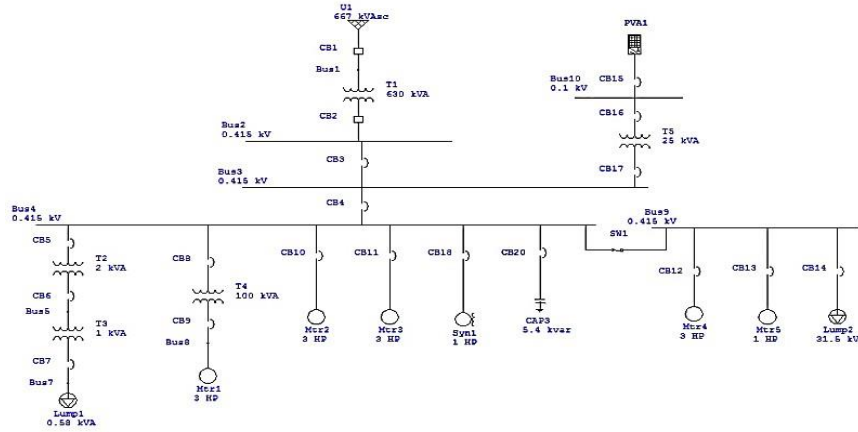


Fig. 2.2 Single-line diagram of the network

Table 2.1 Data of the Single-line diagram

Transformer Data			
	Rating	Primary Voltage	Secondary Voltage
Transformer (T1)	630 kVA	11 kV	0.415 kV
Transformer (T5)	25 kVA	0.1 kV	0.415 kV
Capacitor Bank Data			
	Input Voltage	kVAR/ Bank	No. of Banks
Capacitor Bank(CAP3)	0.415 kV	0.54	10

Table 2.2 The Photovoltaic array (PVA1) is connected through a step-up transformer (T5) with a capacity of 25 kVA at Bus3.

Photovoltaic Arra Data		
Loading	DC Voltage	DC Power
20%	140.88 V	8.461 KW
30%	193.71 V	14.319 KW
40%	228.93 V	16.923 KW

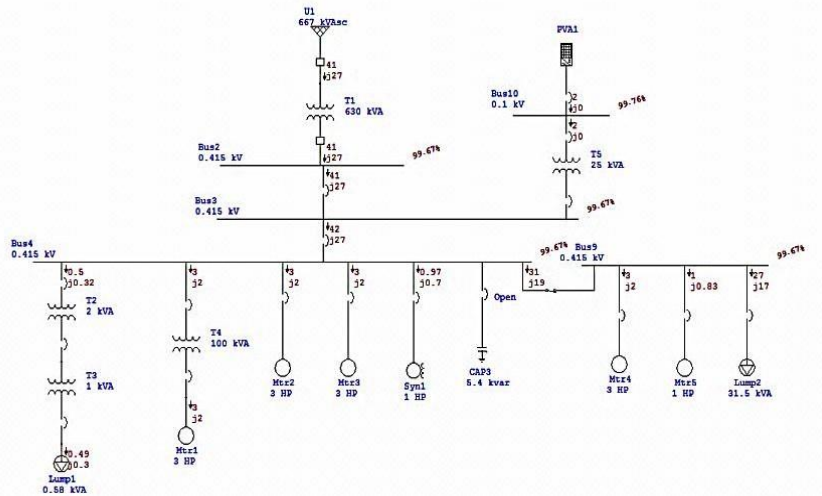


Fig.2.3: Output circuit diagram for a specific irradiation value when Capacitor bank is open

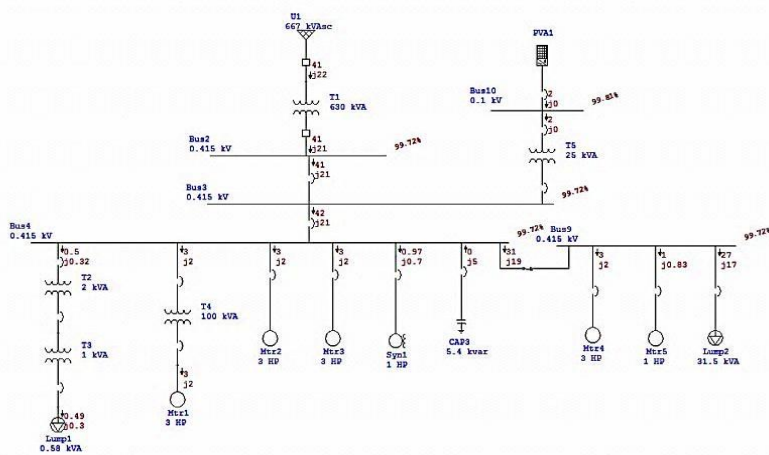


Fig. 2.4: Output circuit diagram for a specific irradiation value when Capacitor bank is close

Table:2.3 Power Factor of Different irradiation value (Without capacitor bank)

PV Cell Loading	Time(hr)	Irradiation in Kolkata	Power factor									
			Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 10
20%	09:52	599	81.3	81.5	84.4	84.4	84.4	83.7	85	83.7	84.7	100
20%	10:52	630	81.2	81.3	84.4	84.4	84.4	83.7	85	83.7	84.7	100
20%	11:52	641	81.1	81.3	84.4	84.4	84.4	83.7	85	83.7	84.7	100
20%	12:52	635	81.3	81.3	84.4	84.4	84.4	83.7	85	83.7	84.7	100
20%	13:52	609	81.3	81.4	84.4	84.4	84.4	83.7	85	83.7	84.7	100
20%	14:52	557	81.6	81.7	84.4	84.4	84.4	83.7	85	83.7	84.7	100
20%	15:52	458	82.6	82.5	84.4	84.4	84.4	83.7	85	83.7	84.7	100
20%	16:52	445	82.3	83.5	84.4	84.4	84.4	83.7	85	83.7	84.7	100
30%	09:52	599	79.7	79.8	84.4	84.4	84.4	83.7	85	83.7	84.7	100
30%	10:52	630	79.6	79.7	84.4	84.4	84.4	83.7	85	83.7	84.7	100
30%	11:52	641	79.3	79.4	84.4	84.4	84.4	83.7	85	83.7	84.7	100
30%	12:52	635	79.3	79.5	84.4	84.4	84.4	83.7	85	83.7	84.7	100
30%	13:52	609	79.6	79.7	84.4	84.4	84.4	83.7	85	83.7	84.7	100
30%	14:52	557	80	80.2	84.4	84.4	84.4	83.7	85	83.7	84.7	100
30%	15:52	458	80.9	81.1	84.4	84.4	84.4	83.7	85	83.7	84.7	100
30%	16:52	445	80.9	81.1	84.4	84.4	84.4	83.7	85	83.7	84.7	100
40%	09:52	599	77.7	77.9	84.4	84.4	84.4	83.7	85	83.7	84.7	100
40%	10:52	630	77.3	77.4	84.4	84.4	84.4	83.7	85	83.7	84.7	100
40%	11:52	641	77.1	77.3	84.4	84.4	84.4	83.7	85	83.7	84.7	100
40%	12:52	635	77.2	77.3	84.4	84.4	84.4	83.7	85	83.7	84.7	100
40%	13:52	609	77.6	77.7	84.4	84.4	84.4	83.7	85	83.7	84.7	100
40%	14:52	557	78.3	78.5	84.4	84.4	84.4	83.7	85	83.7	84.7	100
40%	15:52	458	79.6	79.7	84.4	84.4	84.4	83.7	85	83.7	84.7	100
40%	16:52	445	79.6	79.8	84.4	84.4	84.4	83.7	85	83.7	84.7	100

Table 2.4 Power Factor of Different Irradiation value (with capacitor bank)

PV Cell Loading	Time(hr)	Irradiation in Kolkata	Power factor										Capacitor Bank rating KVAR/Bank
			Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 10	
20%	09:52	599	88.3	88.4	90.4	84.4	84.4	83.7	85	83.7	84.7	100	0.69
20%	10:52	630	88.3	88.5	90.6	84.4	84.4	83.7	85	83.7	84.7	100	0.71
20%	11:52	641	88.3	88.4	90.6	84.4	84.4	83.7	85	83.7	84.7	100	0.71
20%	12:52	635	88.3	88.4	90.6	84.4	84.4	83.7	85	83.7	84.7	100	0.71
20%	13:52	609	88.3	81.4	90.5	84.4	84.4	83.7	85	83.7	84.7	100	0.7
20%	14:52	557	88.3	88.5	90.3	84.4	84.4	83.7	85	83.7	84.7	100	0.68
20%	15:52	458	88.3	88.5	89.8	84.4	84.4	83.7	85	83.7	84.7	100	0.62
20%	16:52	455	88.3	88.5	89.1	84.4	84.4	83.7	85	83.7	84.7	100	0.54
30%	09:52	599	88.4	88.5	91.4	84.4	84.4	83.7	85	83.7	84.7	100	0.82
30%	10:52	630	88.4	88.5	91.6	84.4	84.4	83.7	85	83.7	84.7	100	0.84
30%	11:52	641	88.4	88.5	91.6	84.4	84.4	83.7	85	83.7	84.7	100	0.84
30%	12:52	635	88.4	88.5	91.6	84.4	84.4	83.7	85	83.7	84.7	100	0.84
30%	13:52	609	88.4	88.6	91.5	84.4	84.4	83.7	85	83.7	84.7	100	0.83
30%	14:52	557	88.4	88.5	91.2	84.4	84.4	83.7	85	83.7	84.7	100	0.79
30%	15:52	458	88.3	88.4	90.6	84.4	84.4	83.7	85	83.7	84.7	100	0.72
30%	16:52	455	88.3	88.4	90.6	84.4	84.4	83.7	85	83.7	84.7	100	0.72
40%	09:52	599	88.2	88.3	92.2	84.4	84.4	83.7	85	83.7	84.7	100	0.92
40%	10:52	630	88.3	88.6	92.4	84.4	84.4	83.7	85	83.7	84.7	100	0.95
40%	11:52	641	88.4	88.6	92.6	84.4	84.4	83.7	85	83.7	84.7	100	0.95
40%	12:52	635	88.4	88.4	92.4	84.4	84.4	83.7	85	83.7	84.7	100	0.97
40%	13:52	609	88.4	88.4	92	84.4	84.4	83.7	85	83.7	84.7	100	0.95
40%	14:52	557	88.3	88.4	91.4	84.4	84.4	83.7	85	83.7	84.7	100	0.89
40%	15:52	458	88.4	88.4	91.4	84.4	84.4	83.7	85	83.7	84.7	100	0.82
40%	16:52	455	88.4	88.4	91.4	84.4	84.4	83.7	85	83.7	84.7	100	0.82

2.8 Analysis of Relay Coordination in IEEE 9 bus PV integrated Hybrid Power System using ETAP software

In the modern power system of a country like India, there is an important need to design an uninterrupted electrical power system network having adequate security, stability, and reliability. In this present Chapter, an IEEE 9-Bus hybrid system is considered for a short circuit analysis and protection relying on coordination for designing of overcurrent relaying scheme to operate the relay efficiently and disconnect the fault section from the healthy section instantly. It also compares the differences between existing systems with PV PV-connected hybrid systems. Nowadays, when an Electrical Power System adopts a Renewable Energy source with the existing power source of the network, the main challenge is to design a protection scheme to protect the hybrid system where different intermittent sources make a great impact. To design such a power system the behavior of the existing protection scheme needs to be analyzed. In this Chapter, author simulate an IEEE 9- -Bus system using ETAP simulation, and analysis is made through Load Flow Study and Short Circuit Analysis. The study reveals that the behavior of the protection system changes with variations of the renewable energy sources integrated with in the bus system. Also set point of the protection relays varies with the percentage sharing of the load by PV sources compared to the existing scheme. Observation of the behavior of existing protection systems with PV-connected hybrid systems generates a road map to design an accurate protection scheme for hybrid systems.

An abnormal condition, it includes an electrical failure of power system equipment operating at one of the primary voltage within the system that causes a fault in a power system network. Under balanced load conditions, when disturbed by a fault due to either flashover, insulation failure, physical damage or human error excessive high currents flow through the system causes the system to operate in an abnormal state which is not desired. Classification of the short circuit faults in the system as: (i) symmetrical fault, (ii) asymmetrical fault. Symmetrical faults can be as follows; (i) the three phases are short-circuited to each other *i.e.*, L-L-L, (ii) the three phases are grounded *i.e.*, L-L-L-G. The three phases are equally affected and can be called balanced faults. But these faults occur irregularly. Whereas, Asymmetrical faults can be, (i) single phase to ground *i.e.*, L-G, (ii) double phase to ground *i.e.*, L-L-G, (iii) phase to phase faults *i.e.*, L-L, in which the single phase to ground fault occurs frequently [11, 12]. In the present work, a short circuit analysis is carried out to ensure the stability of the power system network and to confirm the safety of the general public also it will help to determine the ratings of protective equipment. Here, the minimum device rating is determined considering the maximum steady-state short circuit current and the relay coordination is analyzed based on the minimum steady-state short circuit value of the power system network. In this case, the circuit breaker can safely isolate the faulty circuit

but a proper protection scheme with proper selection and settings of protective devices *i.e.*, fuse, circuit breaker, and relays are needed [13-19]. In this Chapter, a single-line diagram of an IEEE 9-bus PV-connected system based on actual data is considered and simulated in ETAP software for analysis purposes. The short circuit characteristic has been analyzed at the different buses at different fault conditions using the IEC standard in the ETAP platform.

2.9 Relay Setting

The protective relay is used for detecting the fault current that send the trip signal to the circuit breaker. In every zone of the power system network a primary relay installed to protect the system. If the primary relay does not operate then the fault is cleared by backup relay. If the relay has quick response to identify the fault at suitable time and send the signal to the auxiliary devices then only it can implement relay coordination [20]. Therefore, a suitable relay setting is required for any particular network. The protective relay has two types of settings: (i) plug setting for deciding the time of relay operation, (ii) plug setting for deciding the current required to pick up for the relay [21]. After the main relay operation, an adequate time has to be given to operate the backup relay *i.e.*, relay coordination. In this Chapter, author show the over current relay coordination of IEEE 9-bus system using ETAP’s star view. The star view feature in ETAP presents relays with their associated characteristic curves, and circuit breaker with their actions and opening times.

- A. Overcurrent Relay Setting: The actual current flowing in the relay expressed as a multiple of current setting *i.e.*, pickup current is known as the plug setting multiplier (PSM) [22].To find the PSM, it is given by in equation 1 as follows:

$$PSM = \frac{I_{fl}}{CTR \times I_P} \dots\dots\dots(1)$$

where, I_{fl} = Fault Current, CTR = Rated current of CT (secondary), I_P = Current setting of Relay or Pickup Current. The primary current of CT is selected by the maximum load current which is passed through the primary side of CT. The pickup value of the relay is set in such a manner that it can operate both in normal load conditions and in certain overload supply. The current setting of relay could be set on 110% of the full-load current or more (up to 200%). Therefore maximum allowable load must be less than the pickup value. To find out the Pickup Current Setting, the following equation 2 is considered.

$$I_P = \frac{K_r \times I_{fl}}{K_d \times CTR} \dots\dots\dots(2)$$

where, I_{fl} = Full-load current, K_r = Reliability coefficient, it is taken as 1.3, K_d = The drop-off

coefficient, it is taken as 0.95. To find out the operating time of normal inverse time overcurrent relay is given as equation 3.

$$T_{op} = \frac{0.141 \times (TMS)^1}{(PSM)^{0.02-1}} \dots\dots\dots(3)$$

where, T_{op} = Relay operation time, TMS = Time Multiplier Setting

- c. Coordination Time Interval: The coordination time interval is the time of coordination between the primary and backup protective devices. The coordination time interval should lie between 0.2 seconds to 0.4 seconds [23]. The coordination time interval can be expressed as,

$$T_{backup} - T_{main} \geq \text{Coordination Time Interval}$$

- d. Setting Instantaneous Unit: Instantaneous units are more effective when the source impedance is low in comparison to the impedance of the power system elements being protected. There are two basic advantages: (i) They reduce the operating time of the relay for critical system fault, and (ii) the Relay consists of different characteristics to avoid the loss of selectivity in a protection system.

The settings of instantaneous units vary with the location and the condition of different types of system elements being protected. There are three groups of elements given by:

- a) Lines between substations: The settings of instantaneous units are carried out at the next substation at least 125% of the maximum fault level.
- b) Distribution lines: 6 to 10 times the rated current can be set for the setting of the instantaneous units at the outgoing feeders.
- c) Transformer units: On the primary side of the transformer, the instantaneous element of the overcurrent relay is installed. The value of that instantaneous element should be set at a value between 125 to 150% of the existing short-circuit current at the secondary side.

2.10 Concept of Photovoltaic Generation

photovoltaic power generation system uses PV cells directly into solar energy, i.e., light energy, to electrical energy. The number of solar cells connected in electrical series and parallel combination to make a solar module and a solar array, respectively.

The equivalent circuit diagram of the solar cell is shown in Fig. 1. The load current can be determined using equation 4 as given below [24]:

$$I_L = I_{ph} - I_s \left[\exp \frac{q(V+I.R_{se})}{N.K.T} - 1 \right] - \frac{(V+I.R_{se})}{R_{sh}} \dots \dots \dots (4)$$

where, I_L = the output load current by the PV cell, I_{ph} = the photo-generated current which is proportional to the area of the photo voltaic cell and the intensity of the incident light. When the ambient temperature rises then the value of the photo voltaic current is slightly rising, R_{se} = series resistance, R_{sh} = shunt resistance which is greater than the series resistance (R_{se}), K = Boltzmann constant, N = ideal factor of the diode and T = temperature of the cell. The present work deals with the performance analysis of PV connected IEEE 9-bus system without a storage system. The grid-connected system is more economical because it can operate without a battery storage system [25].

2.11 Methodology with discussion

To analyze the relay coordination of a PV-connected IEEE 9-bus system author follow the following steps of as given below:

STEP 1: Load flow Analysis on IEEE 9-bus system to obtain the maximum current value of different load buses.

STEP 2: Short Circuit Analysis on IEEE 9-bus system to obtain maximum fault current value of different load bus.

STEP 3: From Load Flow and Short Circuit Analysis the value of current helps us to establish Relay Coordination of PV-connected IEEE 9-bus system.

Fault at bus: BUS 14

	3-Phase	L-G	L-L	L-L-G
Initial Symmetrical Current (kA, rms)	2.475	2.521	2.444	2.581
Peak Current (kA)	6.220	6.335	6.141	6.486
Breaking Current (kA, rms, symm)		2.521	2.444	2.581
Steady State Current (kA, rms)	2.475	2.521	2.444	2.581

Fault at bus: BUS 15

	3-Phase	L-G	L-L	L-L-G
Initial Symmetrical Current (kA, rms)	2.348	2.401	2.316	2.450
Peak Current (kA)	5.715	5.846	5.638	5.965
Breaking Current (kA, rms, symm)		2.401	2.316	2.450
Steady State Current (kA, rms)	2.348	2.401	2.316	2.450

2.12 Load flow analysis data

Table:2.5 Three Alternator and without PV array connected IEEE 9-Bus

Monitoring Bus	Rated kV	Load Flow		Current in Amp.	% Power factor
		MW	MVAR		
Bus 1	16.5	71.468	26.187	2560.9	93.9
Bus 2	18	163.0	7.129	5105.6	99.9
Bus 3	13.8	85	-10.599	3496.3	-99.2
Bus 14	230	-125.043	-50.008	339.1	92.9
Bus 15	230	-90.143	-30.048	235.3	94.9
Bus 16	230	-100.001	-34.986	261.8	94.4

Table:2.6 Three Alternators and with PV array connected IEEE 9-Bus system

Monitoring Bus	Rated kV	Load Flow		Current in Amp.	% Power factor
		MW	MVAR		
Bus 1	16.5	-58.314	40.628	2391.2	-82
Bus 2	18	163.0	10.251	5110.8	99.8
Bus 3	13.8	85	-8.506	3486.7	-99.5
Bus 14	230	-122.989	-49.186	336.3	92.9
Bus 15	230	-89.170	-29.723	234	94.9
Bus 16	230	-99.875	-34.942	261.6	94.4

2.13 Short circuit analysis data

Table:2.7 Fault occurs at load Bus 14, Bus 15, Bus 16 with three alternators and without PV, IEEE 9-Bus system

Fault Bus 16

	3-Phase	L-G	L-L	L-L-G
Initial Symmetrical Current(KA,rms)	2.549	2.024	2.656	2.679
Peak Current(KA)	6.506	5.166	6.779	6.838
Break Current(KA,rms,symm)		2.024	2.656	2.679
Steady state Current(KA,rms)	2.549	2.024	2.656	2.679

Table:2.8 Fault occur at load Bus 14, Bus 15, Bus 16 with three alternators and with PV system (Different DNI) [14,17]

Fault Bus 14

	3-Phase			L-G			L-L			L-L-G		
Irradition	641	599	191	641	599	191	641	599	191	641	599	191
Initial Symmetrical Current(KA,rms)	2.475	2.475	2.475	2.521	2.521	2.521	2.444	2.444	2.444	2.582	2.582	2.582
Peak Current(KA)	6.219	6.219	6.219	6.334	6.334	6.334	6.14	6.14	6.14	6.486	6.486	6.486
Break Current(KA,rms,symm)				2.521	2.521	2.521	2.444	2.444	2.444	2.582	2.582	2.582
Steady state Current(KA,rms)	2.475	2.475	2.475	2.521	2.521	2.521	2.444	2.444	2.444	2.582	2.582	2.582

Fault Bus 15

	3-Phase			L-G			L-L			L-L-G		
Irradition	641	599	191	641	599	191	641	599	191	641	599	191
Initial Symmetrical Current(KA,rms)	2.348	2.348	2.348	2.402	2.402	2.402	2.316	2.316	2.316	2.451	2.451	2.451
Peak Current(KA)	5.714	5.714	5.714	5.714	5.714	5.714	5.637	5.637	5.637	5.637	5.965	5.965
Break Current(KA,rms,symm)				2.402	2.402	2.402	2.316	2.316	2.316	2.451	2.451	2.451
Steady state Current(KA,rms)	2.348	2.348	2.348	2.402	2.402	2.402	2.316	2.316	2.316	2.451	2.451	2.451

Fault Bus 16

	3-Phase			L-G			L-L			L-L-G		
Irradition	641	599	191	641	599	191	641	599	191	641	599	191
Initial Symmetrical Current(KA,rms)	2.549	2.549	2.549	2.024	2.024	2.656	2.656	2.656	2.316	2.679	2.679	2.679
Peak Current(KA)	6.505	6.505	6.505	5.165	5.165	5.165	6.778	6.778	6.778	6.778	6.778	6.778
Break Current(KA,rms,symm)				2.024	2.024	2.024	2.656	2.656	2.656	2.679	2.679	2.679
Steady state Current(KA,rms)	2.349	2.349	2.349	2.024	2.024	2.024	2.656	2.656	2.656	2.679	2.679	2.679

2.14 Relay coordination simulation

Following methods are followed to have short circuit fault analysis simulation for relay coordination [28].

CASE 1: Fault occurs at Bus 14

A. Without PV connected IEEE 9-bus system:

The circuit breaker trip in this following sequence i.e., CB50→CB5→CB9, Circuit breaker of CB5 and CB9 are used for backup protection. Figure 4 shows simulation of fault that occurs at Bus 14 without PV connected IEEE 9-bus system where ‘×’ indicate relay operating.

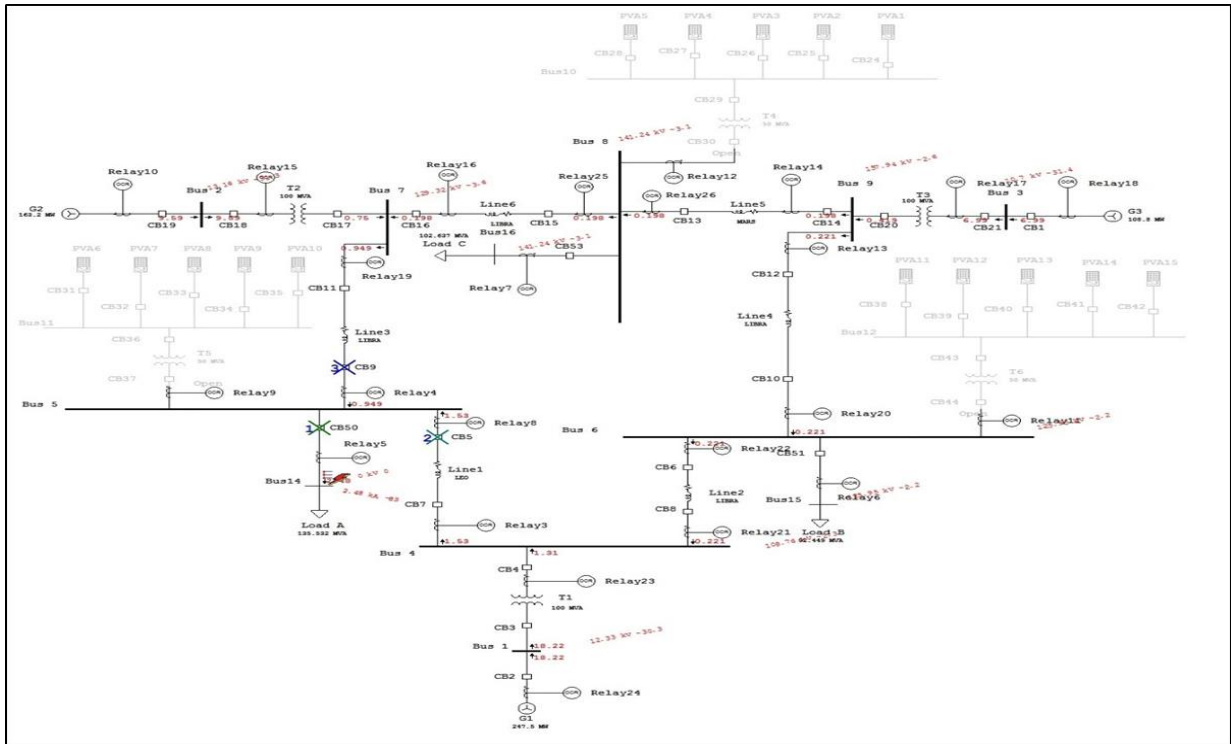


Fig.2.5 Simulation of fault occurs at Bus 14 without PV connected IEEE 9-bus system (× indicate relay operation)

B. With PV-connected IEEE 9-bus system:

The circuit breaker trip in this sequence i.e., CB50→CB37→CB44, Circuit breaker of CB37 and CB44 are used for backup protection. Figure 5 shows the simulation of a fault that occurs at Bus 14 with PV connected IEEE 9-bus system where ‘×’ indicates relay operating.

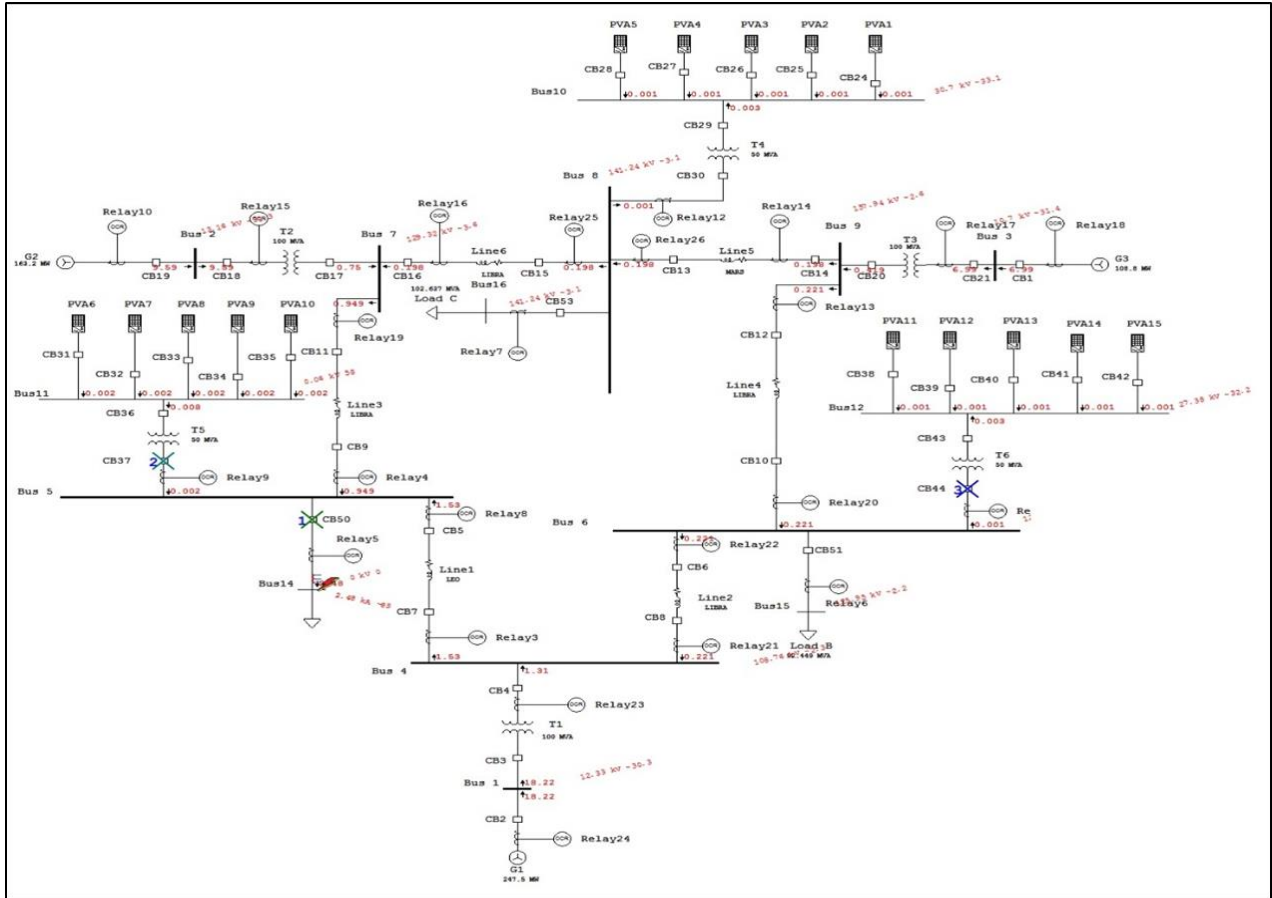


Fig. 2.6 Simulation of fault occurs at Bus 14 with PV connected IEEE 9-bus system (× indicate relay operation)

CASE 2: Fault occurs at Bus 15

A. Without PV connected IEEE 9-bus system:

The circuit breaker trip in this sequence i.e., CB6→CB51→CB13, Circuit breaker of CB51 and CB13 are used for backup protection. Figure 6 shows simulation of fault that occurs at Bus 15 without PV connected IEEE 9-bus system where ‘×’ indicate relay operating.

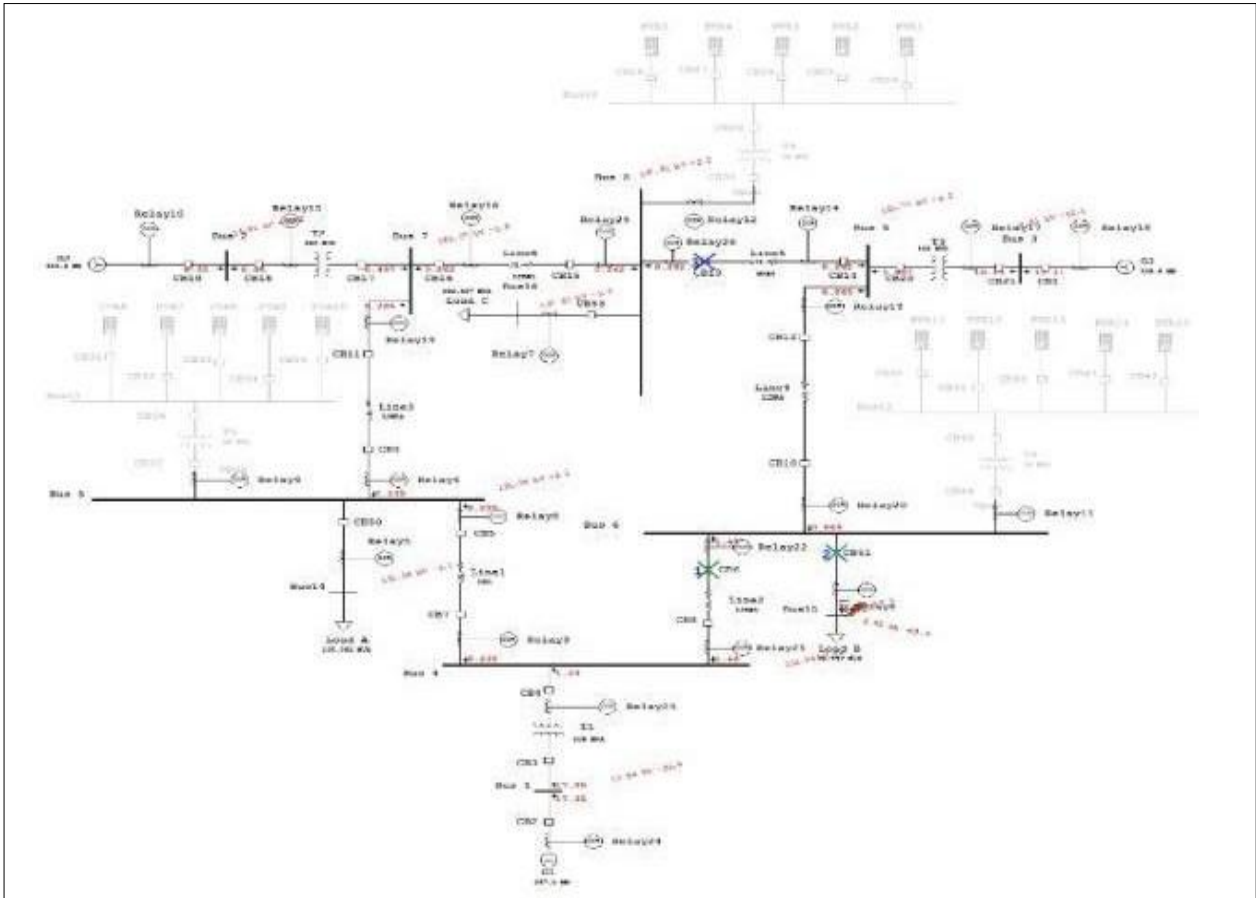


Fig. 2.7 Simulation of fault occurs at Bus 15 without PV connected IEEE 9-bus system (× indicate relay operation)

B. With PV connected IEEE 9-bus system:

The circuit breakers trip in this sequence i.e., CB6→CB51→CB44, Circuit breaker of CB51 and CB44 are used for backup protection. Figure 7 shows simulation of fault that occurs at Bus 15 with PV connected IEEE 9-bus system where ‘×’ indicate relay operating.

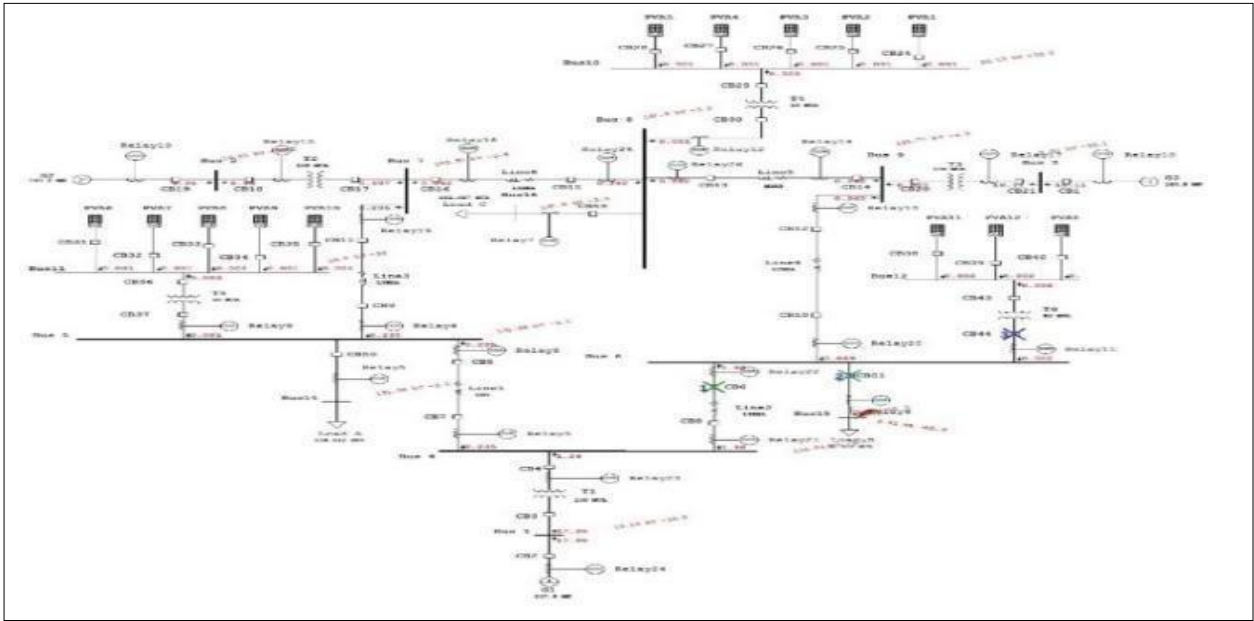


Fig. 2.8 Simulation of fault occurs at Bus 15 with PV connected IEEE 9-bus system (× indicate relay operation)

CASE 3: Fault occurs at Bus 16

A. Without PV-connected IEEE 9-bus system:

The circuit breaker will trip in this sequence i.e., CB53→CB13→CB15. Circuit breakers of CB13 and CB15 are used for backup protection. Figure 8 shows the simulation of a fault that occurs at Bus 16 without PV connected IEEE 9-bus system where ‘×’ indicates relay operating.

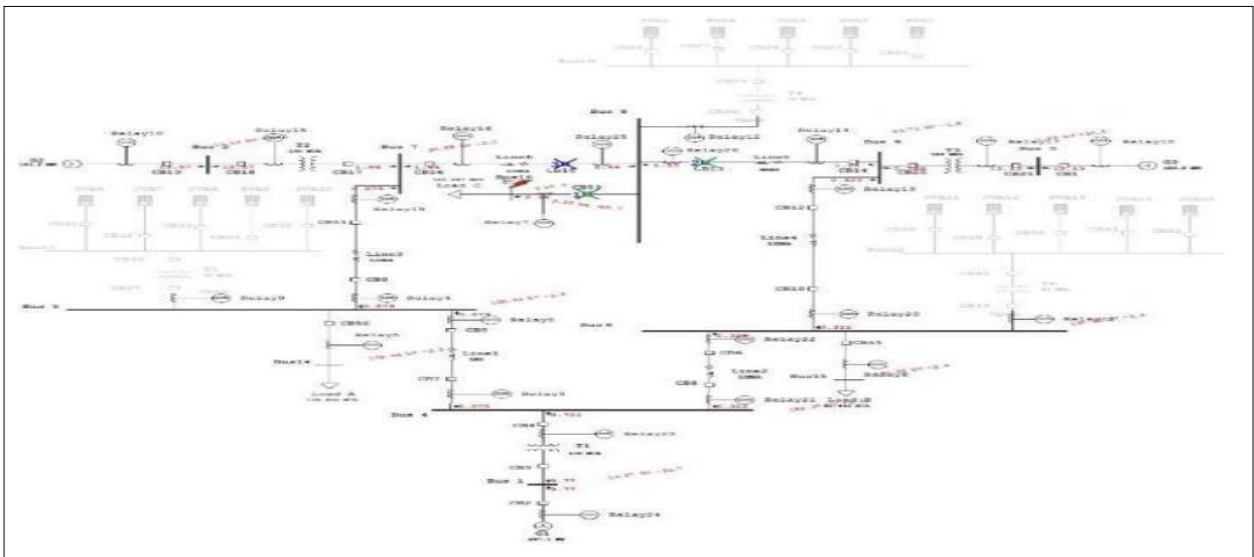


Fig. 2.9 Simulation of fault occurs at Bus 16 without PV connected IEEE 9-bus system (× indicate relay operation)

B. With PV-connected IEEE 9-bus system:

The circuit breaker will trip in this sequence i.e., CB53→CB13→CB15. The circuit breakers of CB13 and CB15 are used for backup protection. Figure 9 shows the simulation of a fault that occurs at Bus 16 with PV connected IEEE 9-bus system, where ‘×’ indicates relay operating.

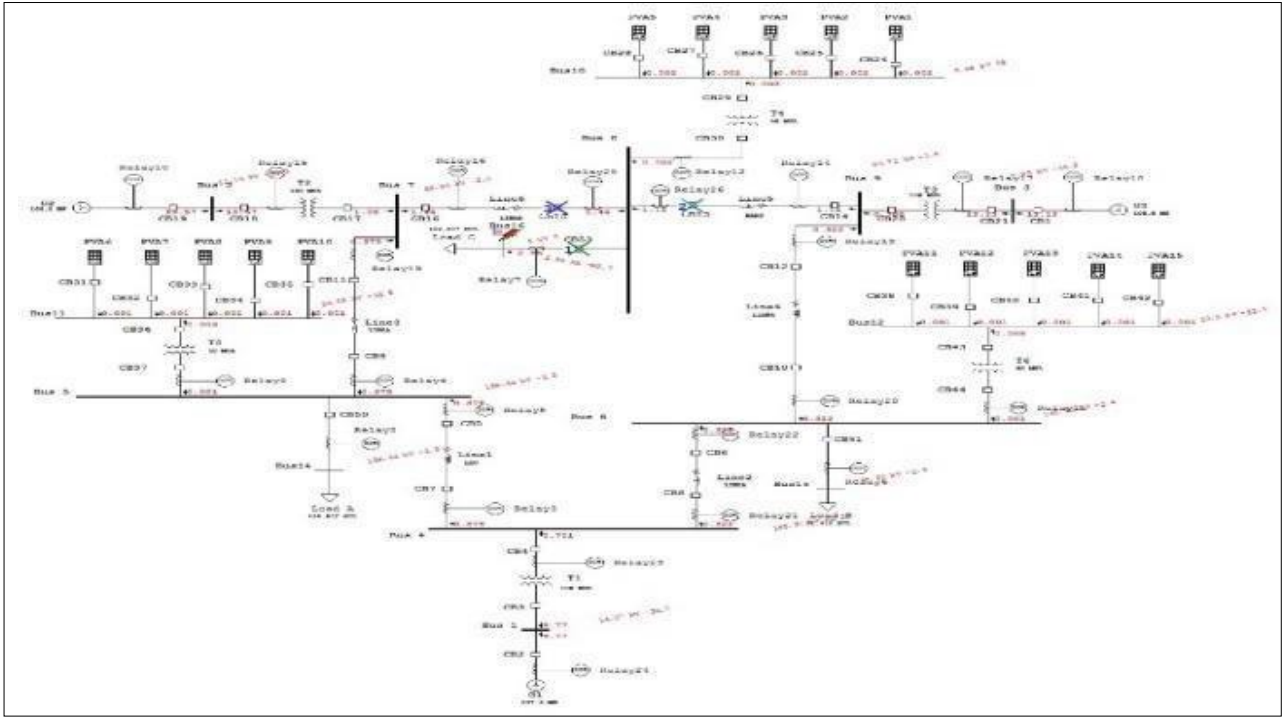


Fig. 2.10 Simulation of fault occurs at Bus 16 with PV connected IEEE 9-bus system (× indicate relay operation)

2.15 Result and Discussion:

In this Chapter author implements a hybrid system as shown in Fig.2 which is a simulation model of a machine laboratory where different experiments are considered as a load of the simulation network. The supply of the machine laboratory is considered as a grid in the simulation model. PV modules that are connected with the simulation model with different percentage generations. All input data are given in Table 1 and Table 2.

In Case-I the power factor changes with different DNI (Direct Normal Irradiance) values for a span of 12 hours duration shown in Table 3. To obtain this output data author analyzes the Load Flow solution on the simulation model Fig.2 using ETAP. Output data indicate that a change in DNI (Direct Normal Irradiance) directly affects on power factor. It is observed that DNI (Direct Normal Irradiance) is inversely proportional to the power factor. It is necessary to compensate the system power factor by some compensation device to maintain the stable operation of the system. In Case II, the author introduces a variable capacitor bank to maintain a constant power

factor for different DNI (Direct Normal Irradiance). Table 4 indicates output data after compensation using a capacitor bank. The value of the capacitor not only depends on the load it is also depending on the PV generation. In this Chapter to maintain a constant power factor capacitor switching technique has been implemented with respect to PV generation.

All result indicates that the power factor of the PV-connected hybrid system varies with the PV generation. In this section, the author introduces 20%, 30%, and 40% of PV generation in the system. After observing simulation results, it is clear that more PV generation decreases the power factor of the system. To maintain a constant bandwidth (0.8 to 0.9) for power factor variation, the magnitude of the capacitor banks with respect to DNI is a superior technique and very important to make the system economical in terms of compensation cost.

2.16 Conclusion

The present work deals with the problems related to large-scale solar energy integration into the conventional grid. A short circuit analysis is carried out to determine the ratings of protective equipment. A single line diagram of an IEEE 9-bus PV-connected system based on actual data is considered, and a simulation is done using ETAP software for analysis purposes. The short circuit characteristic has been analyzed at the different buses at different fault conditions using the IEC standard in the ETAP platform. The relay operating sequence with PV and without PV connected IEEE 9-bus system is identified, and a few steps are specified corresponding to the fault occurring at different buses in the network. Figures 2.1 to 2.10 are the outputs of the simulation results with different case studies, giving a complete idea about how the relay operation sequence gets changed with PV and without PV during fault conditions. It is also observed that in the case of a PV-connected bus, the rating of the fault current is very low to sense that fault current; therefore, the C.T. ratio should be low compared with other C.T. ratios.

In these two cases, the system generates non-stationary signals with multiple classes. These types of non-stationary signals create power quality disturbance events (PQDE) Power Factor Correction Technique for a Grid-connected PV System generates signals like Time-varying Harmonics, Transient Disturbances, Voltage Flicker, and Interharmonics, in case of Relay Coordination in IEEE 9 bus PV integrated Hybrid Power System generates signals like Voltage Sags/Swells, Current Transients, Harmonic Distortion, and Intermittent Fault Signatures. This signal can be used as a real-time training signal for identification tools.

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Chapter:3

Deep Learning Aided Power Quality Disturbance Detection with Improved Time-frequency Resolution

3.1 Introduction

Accurate identification of power quality disturbances is important for reliable operation of power system networks as it may lead to unwanted and premature failure of power system components. Considering the above said fact, in this Chapter, a novel technique for the detection and classification of power quality disturbance events (PQDE) is proposed employing adaptive superlet transform (ALST)-based time-frequency analysis and deep learning technique. ALST is a powerful signal processing tool for the analysis of non-stationary signals in time-frequency frame. To this end, synthetic PQDEs were initially generated following IEEE std. 1159-2009. The generated 1D PQDEs were transformed to 2-D time-frequency RGB images using ASLT. The transformed time-frequency images of 1D PQDEs employing ALST showed enhanced resolution in time- frequency frame and showed distinct representations of different events even in presence of very high noise level. The obtained PQDEs obtained using ASLT were finally fed as inputs to a designed lightweight customized convolutional neural network (CNN) architecture for automated feature extraction and classification. In addition, the performance of the proposed model was further evaluated using benchmark CNN models and also on real-life PQDE signals. It has been found that the proposed method returned 99.52% and 98.18% accuracies for the classification of simulated PQDEs and real-life PQDEs, respectively. The performance of the proposed CNN-aided ASLT is superior compared to other time-frequency representation methods and requires less computational time and memory compared to existing CNN models. Besides, the proposed framework is capable of diagnosis of power quality disturbance events in both noise-free and strong noisy environments.

In recent times, with the development of smart grids, more numbers of renewable energy (RE) sources like photovoltaic (PV) and wind energy are integrated into the distribution network [1-2]. Most of the RE based distributed generation (DG) systems require power electronic based converters and inverters, which may allow high level of energy penetration. High penetration of distributed generation (DG) systems can lead to sudden voltage fluctuation, transient, sag, swell, notch, harmonics and power factor collapse [1-2]. generated in grid-connected DG system due to the connection of heavy nonlinear loads, sudden load changes, fault and switching of lines. These power quality disturbance events (PQDEs) have detrimental effects on power system operation. The PQDEs can result in unwanted tripping of circuit breakers and protective relays, insulation damage of transformers and other high voltage equipment and malfunctioning of digital equipment [3], incurring huge financial loss. Therefore, reliability of smart grid can be affected which is not desirable from economical point of view [4]. Considering the fact, accurate classification and diagnosis of different PQDEs are important to prevent maloperation of expensive power system equipment and at the same time to ensure reliability of power transmission and distribution network. In addition, it has been reported in many

recent literature that power quality detection is also important in the context of energy management for microgrid operation [5-10] with renewable energy integration. Several methods and strategies of energy management in smart grid environments have been reported in existing literature [11-15]. So, for reliable operation of microgrids detection of power quality is an important problem to address.

In existing literature, various signal processing and machine learning techniques have been proposed over the years for accurate detection and classification of PQDEs. Non-stationary signal processing tools like discrete wavelet transform (DWT) [16], wavelet packet transform [17], tunable Q factor Wavelet transform [4], empirical wavelet transform

Wigner-Ville distribution [19], different versions of Stockwell transform (ST) [20-22] are used to analyze different PQDEs in joint time-frequency (T-F) plane. In [23], the degree of nonlinearity in PQDEs has been analyzed through detrended fluctuation analysis (DFA). Based on DFA analysis, several features have been extracted which were found to be useful to diagnose single and mixed PQDEs. In addition to signal processing, many machine learning algorithms like recurrent neural network (RNN) [24], support vector machines (SVM) [25], decision tree [3] etc. have been implemented for classification of PQDEs based on features extracted from analysis of PQDEs using aforesaid signal processing techniques.

Though the existing methods are proven to be useful for classification and identification of both single and mixed PQDEs, most of the frameworks are based on handcrafted feature extraction techniques. The handcrafted feature extraction technique not only requires prior expertise but also depends on human intervention which often imposes the risk of misclassification due to selection of redundant features [26].

The problem related to the manual feature extraction process can be overcome by deep learning (DL). The benefit of deep learning algorithms is that it can learn meaningful and significant features from input signal or image data automatically. Hence, eliminates the requirement of handcrafted feature extraction and hence can be used in real-time applications. Application of DL has been reported in existing literature for a variety of applications [27-40]. Hence, in this study, deep learning algorithm has been implemented to classify PQDEs.

Convolutional neural network (CNN) is one of the efficient DL algorithms effectively used in PQDE classification [41-43]. As the PQDEs are recorded as 1-D time domain signal, 1-D CNN can be employed for its automatic feature extraction and classification. It is noteworthy to mention that CNN delivers promising results in feature extraction and classification from input image compared to 1-D signal [23]. Considering this issue, in several literatures, time-domain PQDEs have been transformed into 2-D image format such as T-F spectrograms and then the images are classified using a CNN model [22-23,19]. For conversion of 1D PQDEs to T-F spectrogram images, Stockwell transform (ST) [23], continuous wavelet transform (CWT) [43] etc. have been implemented in existing literature. However, conversion of 1D PQDEs to 2D images using existing T-F spectrogram methods has some limitations from the practical point of view which are discussed below.

The problem of using ST based time-frequency (T-F) analysis is that a Gaussian window is used to probe the signal, which is not signal adaptive and offers poor resolution in T-F frame. Another important issue is the signal noise. The time- frequency image obtained using ST is noisy when the signal to noise ratio (SNR) of the input signal is low. Recently, it has been reported in [23, 44], that detection of PQDEs in noisy environment is more challenging and several attempts have been made by the researchers to precisely detect PQDEs in noisy environment. To provide better resolution of T-F images under noisy environment, it is necessary to modify the Gaussian window by optimizing its parameters [25]. Even then the T-F spectrogram is not completely devoid of noise which makes it difficult to identify different PQDEs. In the case of CWT, the resolution in T-F plane depends on the number of cycles (bandwidth). Increasing the number of cycles will lead to precise frequency resolution while decreasing number of cycles provide better temporal resolution [45]. Thus, there is always a trade-off between time and frequency resolution in joint time-frequency analysis following uncertainty principle. Considering the above said facts, in this study, a novel signal processing technique has been proposed for analysis of PQDEs using superlet.

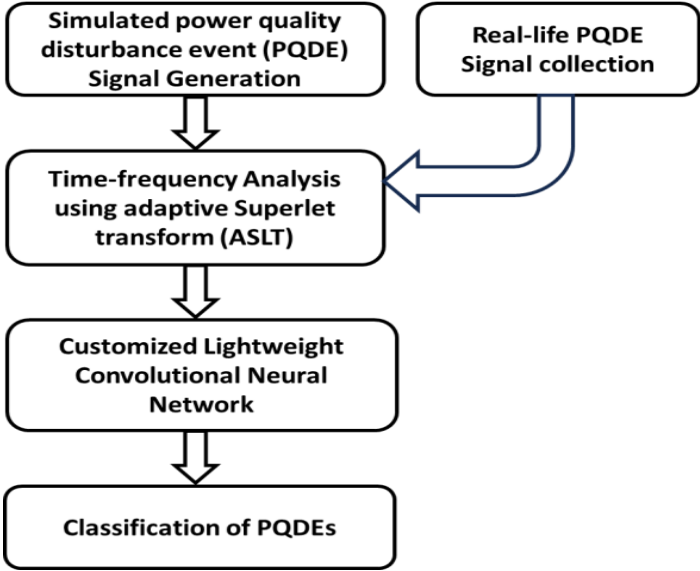


Fig.3.1. Block diagram of the proposed PQDE classification framework. The superlet

transform (SLT) is an improvement over CWT, where the number of cycles of mother wavelet are varied by combining shorter wavelets for (better temporal resolution) and longer wavelets (for better frequency resolution) to obtain better time-frequency resolution [46]. To make the SLT adaptive in nature, adaptive superlet transform (ASLT) has been proposed by varying the order as a function of the central frequency to achieve better time and frequency representation of any signal [45]. Application of ASLT in the context of analysis of bearing fault detection in induction motors [46] and biomedical signal analysis [48] has been

reported in existing literature. In this study, ASLT has employed to analyze PQDEs in joint T-F frame. Thus, ASLT is not only signal adaptive but gives better T-F resolution compared to ST, which uses a Gaussian window only. In other words, the superlet transform overcomes the problem of time-frequency resolution suffered by both CWT and ST. Thus, the proposed method offers distinct advantages over existing methods and hence used for analysis of PQDEs.

To this end, the synthetic 1D PQDEs were initially simulated using mathematical relations as prescribed in IEEE std. 1159-2009. Following this, joint T-F analysis of 1D PQDEs was conducted by converting the signals from time domain to T-F domain. The T-F representation of PQDEs yields distinct 2-D RGB images for different PQDEs. A lightweight 2D CNN architecture has been configured to classify the 1D PQDE signal transformed into 2-D images. In addition, several benchmark CNN models have been used to compare classification performance.

The novel contributions of the present work are briefly explained as follows:

1. A novel framework employing adaptive superlet transform is proposed for the first time to analyze single and multiple-class PQDEs in a time-frequency frame.
2. The performance of ASLT was compared with the Stockwell transform to indicate the superiority in analyzing PQDEs in both noisy and noise-free environments.
3. A lightweight CNN model has been designed to classify the time-frequency PQDE images.
4. Ablation studies with benchmark CNN models have been done to indicate the superiority of the proposed CNN model.
5. The proposed method has been validated on real-life PQDE signals to verify the practicability of the proposed method.

The flowchart of the proposed PQDE detection method is shown in Fig.1.

3.2 PQD Event Generation

A. Numerical Models for generation of PQDEs

In power system, PQDE event data can be acquired through continuous monitoring over a long duration. However, uncertainty in occurrence of PQDEs can lead to scarcity in real time data. Considering this issue, in this Chapter, single and combined PQD events were generated employing the numerical model prescribed in IEEE std. 1159-2009 [47]. The signals were generated using MATLAB programming at a sampling frequency of 10kHz. It is to be mentioned here that PQDE data generated using the prescribed numerical models closely resemble real life data [23]. Using the numerical model described in [47], 22 PQDEs were generated in this Chapter. The details of the eighteen PQD events are presented in Table.3.1. In Table 1, class label '1' and '2' indicate single and double class of PQDEs, respectively. The single and double PQDEs were generated to test the practicability of the proposed PQ detection model. This is done because, in several literatures, it is reported

that more than one PQDEs can occur at same time [9]. Considering this issue, in this Chapter, along with single multiple PQD events were generated concatenating numerical models of the corresponding single PQD events. In addition, a white gaussian noise component (SNR value 30 dB) was added to the synthetic PQD data, which closely resembles real-life PQDE data.

3.3 Theoretical Background

A. Superlet transform

The superlet transform (SLT) was proposed by Moca et al. in [48] as an improvement of continuous wavelet transform (CWT) to improve resolution of any non-stationary signal in time-frequency frame.

CWT provides a trade-off between time and frequency resolution in joint T-F domain analysis. For e.g., CWT using a ‘Morlet’ wavelet with less number of cycles provides precision temporal information but poor frequency resolution. On the contrary, increasing the number of cycles of the “Morlet” wavelet will lead to poor temporal resolution and accurate frequency resolution. To overcome the aforesaid issue, basic idea of the “superlet” was proposed which improves the TFR by combining both shorter wavelets (with high time resolution, less cycles) with longer wavelets (more cycles with poor time resolution), simultaneously. In the other words, the superlet transform makes use of “Morlet” wavelets having fixed central frequency (ω), and different numbers of

Table 3.1. Description of PQD events

SignalLabel	Description	Classlabel
PQDE1	Sine	1
PQDE2	Harmonics	1
PQDE3	Sag	1
PQDE4	Swell	1
PQDE5	Flicker	1
PQDE6	Transient	1
PQDE7	Interruption	1
PQDE8	Notch	1
PQDE9	Harmonics with Sag	2
PQDE10	Harmonics with Swell	2
PQDE11	Harmonics with Flicker	2
PQDE12	Harmonics with Interruption	2
PQDE13	Harmonics with Transient	2
PQDE14	Sag with Flicker	2
PQDE15	Swell with Flicker	2
PQDE16	Sag with Transient	2
PQDE17	Swell with Transient	2
PQDE18	Transient with Interruption	2
PQDE19	Harmonics with Interruption	2
PQDE20	Notch with Harmonics	2
PQDE21	Notch with Interruption	2
PQDE22	Transients with Harmonics	2

cycles progressively (for better frequency resolution or constrained bandwidth). Mathematically, superlet transform can be expressed as [48]:

$SLT_{\omega,k} = \{\Psi_{\omega,c} | c = c_1, c_2, \dots, c_k\}$ (1) In equation (1), $SLT_{\omega,k}$ is the superlet transform with centre frequency ω and k is the order of the superlet, $\Psi_{\omega,c}$ is the mother wavelet with centre frequency ω and c is the number of cycles. In the case of SLT, the number of cycles can be selected either additively or multiplicatively, which are given by $c_i = c_1 + i - 1$, for $i = 2, \dots, k$ and $c_i = i \cdot c_1$, respectively. In the other words, SLT is a multi-ordered wavelet transform, which covers multiple frequency bandwidth with fixed centre frequency.

Also, a superlet with fixed centre frequency and order $k=1$, is analogous to CWT. The computation of SLT is done in the same way as that of CWT with the exception that here SLs are used instead of wavelets. The response of SLT to any arbitrary signal $g(t)$ is defined as the geometric mean GM of the responses of individual wavelets in the set which is expressed as:

$$R[SLT_{\omega,k}] = \sqrt[k]{\prod_{n=1}^k R[\Psi_{\omega,c_n}]} \quad (2)$$

In the above equation, $[\Psi_{\omega,c}]$ is the response of the i^{th} wavelet to any signal. In the case of complex wavelets like Morlet or Gabor, complex convolution is used, and the equation (2) can be modified as:

$$[SLT_{\omega,k}] = \sqrt{2} \times g(t) * \Psi_{\omega,c_n} \quad (3)$$

In equation (3), $*$ indicates complex convolution operation $\sqrt{2}$ is a term used strictly for the analytic wavelets and $g(t)$ is any arbitrary signal. It is to be mentioned here that $\sqrt{2}$ is strictly used for the analytic wavelets like the complex Morlet or Gabor. This is because the analytic wavelet recovers only half the power of a real signal. Since Morlet wavelet is used here, so $\sqrt{2}$ is used in (5). The SLT can estimate the oscillation packets present in any non-stationary signal at the central frequency, ω . The magnitude of ALST is computed by taking the GM of the magnitude of each individual wavelet. Finally, the magnitude of SLT is squared to obtain the time-frequency scalogram.

B. Adaptive superlet transform

In [24], the concept of adaptive superlet transform was proposed where the order of the central frequency of the superlets were adjusted to tackle the problem of decreasing bandwidth as the frequency increases. An adaptive superlet transform (ASLT), starts with low order, $k=1$, that can estimate low frequencies. The order k is then increased monotonically as a function of central frequency (ω) as follows [24]:

$$ASLT_{\omega,k} = SLT_{\omega,k} |k = p(\omega) \quad (4)$$

so that the improved resolution for both time and frequency is attained for the entire frequency domain. In equation (4), p is an integer. The general choice to order linearly using the following equation [24]:

$$p(\omega) = k_{min} + \left[(k_{max} - k_{min}) \frac{\omega - \omega_{min}}{\omega_{max} - \omega_{min}} \right] \quad (5)$$

In equation (5), k_{min} and k_{max} denotes the orders corresponding to the smallest and largest central frequencies ω_{max} and ω_{min} , respectively and $[\]$ is the nearest integer operator. When the desired frequency range of interest is wider, then it is recommended to use ASLT while SLT may be used for narrower frequency bands. Since the frequency of PQDEs can fluctuate over a wide range from standard power frequency (50Hz) to several kHz for high frequency transients, therefore, author have used ALST for analysis of PQDEs to achieve better resolution in T-F frame.

C. Convolutional neural network

Convolutional neural network (CNN) is a class of deep neural network which is used extensively in the field of computer vision. CNN can be used for different purposes i.e. from automated feature extraction to classification. CNN can be deployed for image as well as signal classification. The advantage of CNN over traditional neural networks is that the feature extraction and classification is fully automated with no manual intervention. The CNN follows a hierarchical structure which consists of an input layer, convolution layer, pooling layer, fully connected layer and a softmax layer. The basic structure of CNN consists of the following layers [23]

- ***Input layer:***

This is the first layer of CNN architecture. In input layer, image is given as input. The input image needs to be resized accordingly before feeding into the convolution layer.

- ***Convolution layer:***

Convolution layer (CL) is the core block of CNN architecture which comprises of a set of learnable filters known as “kernel”. In this layer, input image or output of previous layer is transversely convolved with kernels to extract feature map. The spatial convolution operation of two variable (i, j) functions $f(i, j)$ and $g(i, j)$ can be mathematically expressed as:

$$f(i, j) * g(i, j) = \iint_{a, b=-a}^a f(a, b) \cdot (i - a, j - b) da db \quad (6)$$

In (6), a and b indicate the shift of functions (i, j) and (i, j) .

is noteworthy to mention that performance of a CL depends on some factors such as size of kernel and the number of kernels. During convolution operation, kernels are moved by a

fixed length known as “stride”. In addition, zero padding has been applied to the output to maintain the image size. For an input image with dimension, $W_m \times H_m \times K_m$ where W_m is the width, H_m is the height, and K_m are the number of channels. With K_0 number of kernel filters with size $r \times r$, the output feature map $W_0 \times H_0 \times K_0$ can be written as [49]:

$$\begin{aligned} W_0 &= \frac{W_m - r + 2z}{q} + 1 \\ H_0 &= \frac{H_m - r + 2z}{q} + 1 \end{aligned} \quad (7)$$

In the above equation (7), “ q ” is stride whereas “ z ” is size of zero padding [17]. It is pertinent to mention that convolution operation is combined with activation layer. This activation layer introduces the non-linearity in the network.

- ***Pooling layer:***

After convolution operation, the dimension of convolved features is very large, which may cause excessive computational cost if the convolved features are directly adopted. Considering the fact, the pooling layer (PL) reduces the dimension of convolved feature conserving the features with a high degree of spatial structure [11]. Pooling layer also helps to regulate overfitting. There are two types of pooling methods namely, average and max pooling. Average pooling takes average value of convolved feature map within a pooling window, whereas max pooling selects the feature with maximum value within a pooling window.

- ***Fully connected layer:***

In fully connected layer (FC), the output of CL/PL has been converted into a one-dimension feature vector and the score for each category is calculated. It is noteworthy to mention that fully connected layer is similar to ordinary neural network and each hidden unit in this layer is connected to all activations in the previous layer [25].

- ***Softmax layer:***

Softmax function maps the score obtained from FC into probabilistic value [9]. Based on the probabilistic value, probable class can be predicted.

Combining the above layers, one can build a customizable CNN architecture. The number layer in a customizable CNN architecture is completely empirical and it completely depends on the type of classification task. It is noteworthy to mention that performance of a CNN architecture is governed by various factors such as number and size of kernel, number of CL, type of activation function, type of pooling, number of FC, number of hidden units in FC. In existing literature there are several benchmark CNN models like AlexNet, VGGNet, ResNet etc. have been proposed by various researchers for image classification. A brief overview of different CNN models are shown below.

(1) AlexNet CNN

The AlexNet CNN was proposed by Alex Krizhevsky et al. in 2012 [26] as a winner of ImageNet Large Scale Visual Recognition Challenge (ILSVRC). In the ILSVRC dataset, 1.2 million images are present with 1000 different class labels. Detailed description of AlexNet model has been provided in earlier works in . The basic structure of AlexNet consists of 8 layers. The initial two convolution layers have 96 and 256 filters with size $11 \times 11 \times 3$ and $48 \times 5 \times 5$, respectively followed by local response normalization and two maxpooling layers with filter size 3×3 . The next three convolution layers consists of 384, 384, and 256 numbers of filters, with sizes $256 \times 3 \times 3$, $192 \times 3 \times 3$ and $192 \times 3 \times 3$, respectively. These three convolution layers are followed by another maxpooling layer with filter size 3×3 . Finally, two fully connected layers with 4096 number of neurons and two dropout layers and finally one FC is present at the output. AlexNet is a series connected CNN model with 60 million learnable parameters.

(2) VGGNet CNN

VGGNet is a popularly used CNN architecture originally proposed by the Oxford Visual Geometry Group (VGG) [27]. Like the AlexNet model, training of the VGGNet was also ILSVRC database. The number of layers in VGGNet CNN model varies from 11 to 19 among which in this work author have used 16-layer network known as VGGNet16. The VGGNet16 has 13 convolution layers with 3×3 convolution filters. There are 5 maxpooling layers of size 2×2 with step length of 2 is placed at the output of each convolution layers to reduce the spatial volume of the extracted feature output of the convolution layer. At the output of the final max pooling layer, three FC layers with 4096 number of neurons are connected. A softmax classification layer is connected at the output for the classification. Like AlexNet, VGGNet16 is also a series-connected network with 138 million learnable parameters.

(3) ResNet CNN

Residual networks also known as ResNets are a set of popular CNN networks. ResNets proposed in [28], work on the principle of residual learning which was introduced to take care of the vanishing gradient problem often

encountered in deeper networks. In a ResNet CNN model, a new technique known as the ‘identity mapping’ strategy has been incorporated in its hidden layers. This ‘identity mapping’ can solve the problem of vanishing gradient by providing skip connections i.e. by allowing shortcut paths for gradients to bypass through. Also, the skip connections aid in reducing overfitting issue during extraction of features. Different layers of ResNet like 18, 50, 101 etc. are proposed in existing literature. In this study, ResNet with 50 layers i.e. ResNet 50 has been used to classify PQDEs. The ResNet50 model consists of 5 stages with each stage containing a convolution block and an identity mapping block. The convolution block and identity mapping block contain 3 convolution layers. The total number of learnable parameters in ResNet50 is about 23 million.

D. Proposed CNN model

Although all these pre-trained deep learning models have delivered satisfactory performance in the context of image classification, yet one major limitation of the existing CNN

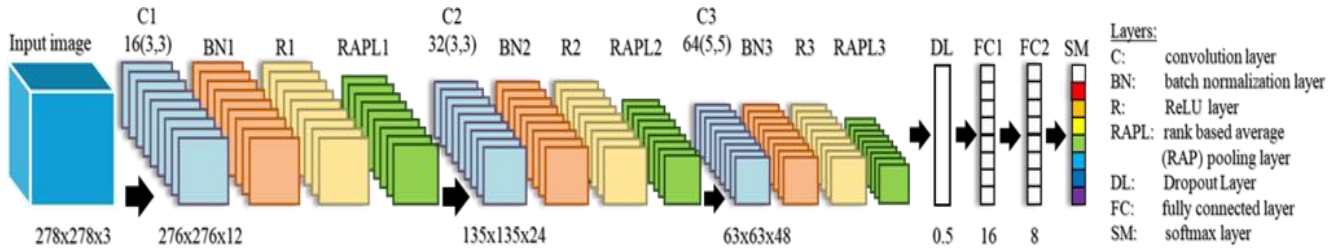


Fig.3.2. Detailed architecture of the designed lightweight CNN model.

delivered satisfactory performance in the context of image classification, yet one major limitation of the existing CNN models is that neither of these aforesaid benchmark models are customized. In other words, the total number of layers used in the above benchmark CNNs are fixed and neither of them can be tuned as per the requirement of the user. Moreover, these CNN models are computationally expensive and require a greater number of learnable parameters. For classification of PQDEs T-F images, it may so happen that a lightweight CNN model with lesser number of learnable parameters may deliver better performance than the existing models and that too at reduced computational burden. This motivates us to design a lightweight CNN model for classification of PQDE images. The detailed architecture of the developed CNN model is given in Fig.3.2.

The proposed CNN structure consists of 12 layers with 3 convolution layers, having filters size 3x3. The number of filters used in each convolution layer was kept fixed at 12, 32 and 64, respectively. Each convolution layer is followed by batch normalization (BN), rectified linear unit (ReLU) activation and rank based average pooling layer (RAP) which were successively placed one after the other. The function of the BN layer is to reduce the feature dimensions at the convolution layer output, without causing any loss of information and at the same time

reducing the training time. It is to be mentioned here that in the proposed CNN model, instead of using other activation functions sigmoid, tanh etc., ReLU activation function has been deployed since it does not suffer from vanishing gradient problem. Moreover, ReLU activation function can reduce learning time and at the same time computation complexity by producing sparse representation during training a CNN model. The RAP layer has been used here because it operates by computing the mean of the weighted feature values, thereby overcoming the loss of information. The output of the final RAP layer, there is a dropout layer with value of 0.5 (chosen empirically) followed by two FC layers in succession. The output of the last FC is added with 22 neurons to classify 22 PQDEs. Finally, a SoftMax layer is connected to the output of the last FC layer for classification. The total number of learnable parameters of the proposed CNN model is roughly 1 million.

3.4 Result and Discussions

A. Analysis of PQ events using ASLT

The time-frequency images of different PQDEs obtained using ALST is discussed in this section. Fig. 3 (a-c) shows a class ‘1’ i.e. single PQDE6 signal (oscillatory transient) and its T-F image obtained using ASLT and conventional ST. Similarly, Fig. 4 (a-c) shows a class ‘2’ i.e. multiple PQDE22

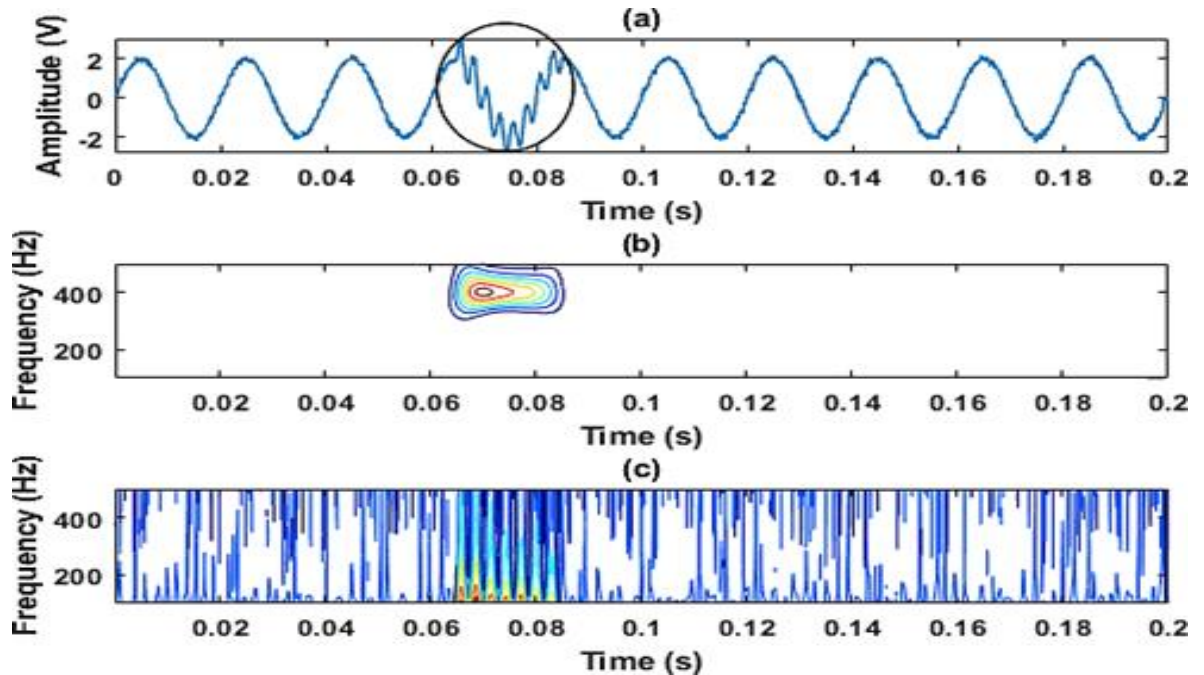


Fig.3.3. PQDE6 and time-frequency representation using (b) ASLT and (c) ST, C1=3 cycles, order:1:30, additive, for ALST.

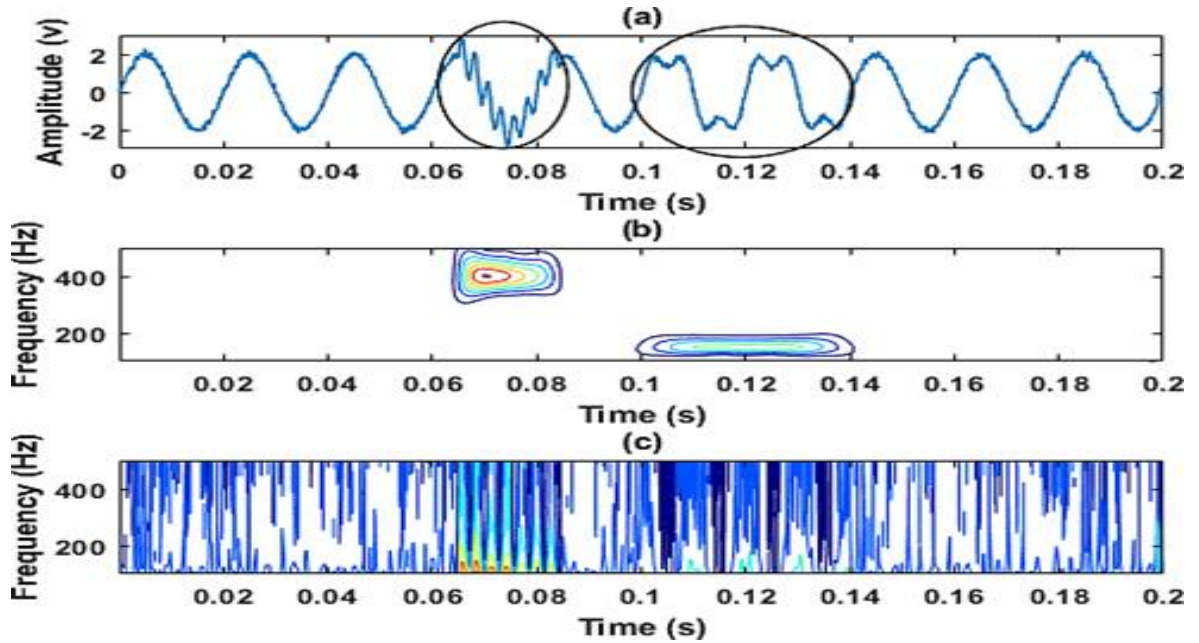


Fig.3.4. PQDE22 and time-frequency representation using (b) ASLT and (c) ST, $C1=3$ cycles, order:1:30, additive, for ALST.

(oscillatory transient with 5th harmonic) signal and its T-F representation obtained using ASLT and ST. The SNR of the sample PQDEs were kept fixed at 20 db. The order of the ALST and the number of cycles used to generate the T-F images are mentioned in the respective Figure captions. It can be seen from Fig. 3.3(a-c) that using ASLT, it is possible to distinguish single as well as multiple PQDEs from the T-F images using ASLT more distinctly than conventional ST. It is evident that for the above signals, ALST has provided better resolution in T-F images compared to ST. It is clearly visible from Fig. 3.3(c) and Fig. 3.4 (c) that the T-F images of

conventional ST are noisy, and it is difficult to discern different PQDEs, whereas by using ASLT clear visibility of different events is obtained. Classification of PQDEs with T-F images obtained using ST will inevitably lead to misclassification as evident from the ST spectrogram. Hence,

ASLT provides better resolution of PQDEs compared to ST.

B. Training of CNN models

The T-F images of different classes of PQDEs obtained using ASLT (described in the earlier section) were at first resized to $278 \times 278 \times 3$ before being fed as inputs to the customized CNN model for automated feature extraction and

classification of PQDEs. Besides, the T-F images of PQDEs were also inputted to the benchmark CNNs namely AlexNet, VGG16 Net and ResNet50 CNN models for comparison. For AlexNet, the size of the PQDE images were altered to $227 \times 227 \times 3$, while for both the VGG16Net and the ResNet50 model, the same was changed to $224 \times 224 \times 3$, respectively. Here, 500 PQDE events were simulated for each class and therefore for 22 class of PQDEs, a total of 11000 signals were generated. Now, the training of the proposed CNN model was done from scratch while in the case of pre-trained models, transfer learning technique (TL) has been adopted. TL is a strategy where a CNN intended to perform one classification task can be used to perform another classification task. In TL, the initial few layers of the benchmark CNNs were kept unchanged while the final few (FC) layers were replaced with the new finetuned layers. The training of the proposed CNN model was done using Adam optimizer. The initial learning rate was kept fixed at 0.001 and mini batch size was kept fixed at 30. For determination of the number of epochs during training phase of the CNN early stopping strategy has been implemented.

The training and testing accuracy graph of the proposed CNN model is given in Fig.5. Using the early stopping strategy, the maximum number of epochs obtained was 50. Another observation from Fig.5 is that as the number of epochs increase the training accuracy and the testing accuracy slowly converges with the latter being slightly less than the former for all epochs. This indicates that the model has performed satisfactorily without overfitting.

C. Performance analysis of CNN models

In this study, the performance of the proposed CNN model as well as for benchmark CNN models, was assessed using a 5-fold cross validation (CV) strategy. In a 5-fold CV method, the input PQDE images were divided randomly in the ratio of 4:1, for training and validation/testing purposes, respectively. The training and validation/testing data were then interchanged iteratively in a progressive manner (keeping the ratio fixed) and for each runtime the following performance parameters namely Accuracy (Acc), Sensitivity (Sen), Specificity (Spe) etc. were computed from the confusion matrix. Finally, the mean and standard deviation of the aforesaid statistical parameters was calculated, and the performance parameters are tabulated in Table II for the proposed CNN model as well as for the benchmark CNN models. The equations describing the performance parameters are as follows [23]:

$$Acc = \frac{True\ Positive + True\ Negative}{True\ Positive + False\ Positive + True\ Negative + False\ Negative} \quad (8)$$

$$Sen = \frac{True\ Positive}{True\ Positive + False\ Negative} \quad (9)$$

$$Spe = \frac{True\ Negative}{True\ Negative + False\ Positive} \quad (10)$$

For computing the above statistical parameters, the value of true positives cases, false positives cases, true negatives cases and false negatives cases were obtained from the PQDE classification confusion matrix. From the variation of the accuracy, specificity, sensitivity and F1 score, shown in Table 3.2, it is evident that the performance parameters obtained for all the CNN models are reasonably satisfactory. The proposed

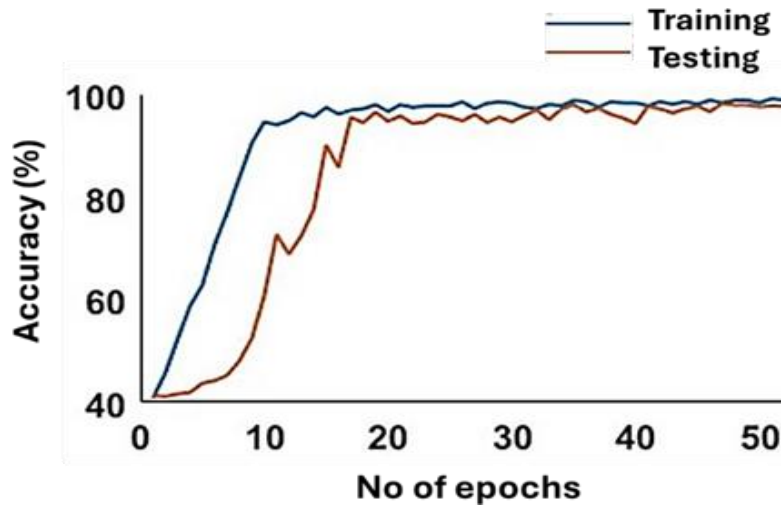


Fig.3.5. Training and Testing accuracy of the designed lightweight CNN model

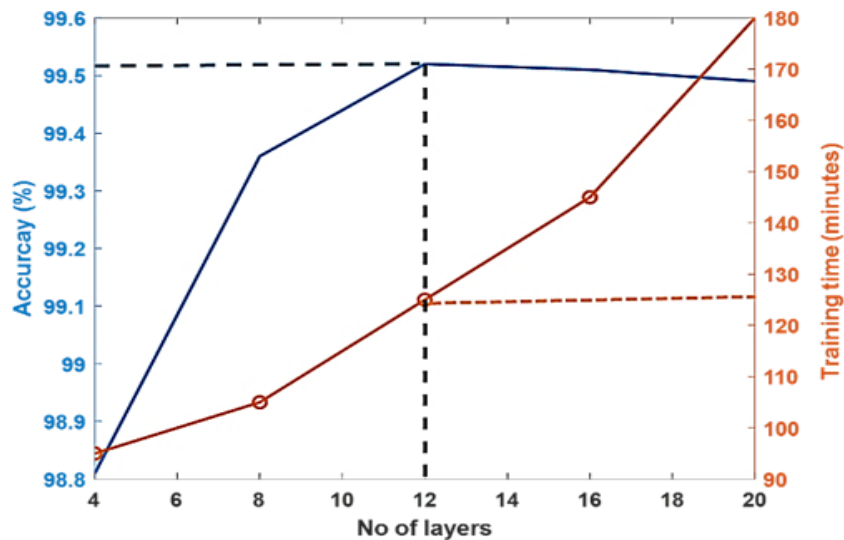


Fig.3.6. Variation of accuracy and training time with number of layers

Table 3.2. Classification Performance of different CNN models

CNN model	Accu (%)	Sen(%)	Spe(%)	Total Learnable parameters
AlexNet	99.14±0.40	98.13±1.27	99.64±0.17	60 million
VGGNet16	99.01±0.35	99.21±0.45	97.46±1.85	138 million
ResNet50	98.92±0.60	98.35±1.01	100±0	23 million
Proposed CNN model	99.52±0.28	100±0	99.10±0.46	1 million

CNN model has delivered marginally better performance than the benchmark CNN models. Among the benchmark CNN models, the performance of AlexNet is close to the proposed CNN model followed by the VGGNet16 and ResNet50. In addition, it can be observed that for all CNN models, the standard deviation is minimum for all CNN models. Further, the Tukey Kramer post hoc analysis have been done to evaluate the classification performance of different CNN models. Tukey-Kramer post-hoc analysis revealed no significant difference in performance between the different CNN models indicating the performance of the proposed model is robust

D. Performance of the proposed CNN model by alteration of different parameters

In this section, the performance of the proposed CNN model has been verified by varying different design parameters namely (i) the number of layers and (ii) Kernel size. For each case, the classification accuracies and computational (training time) have been computed. This

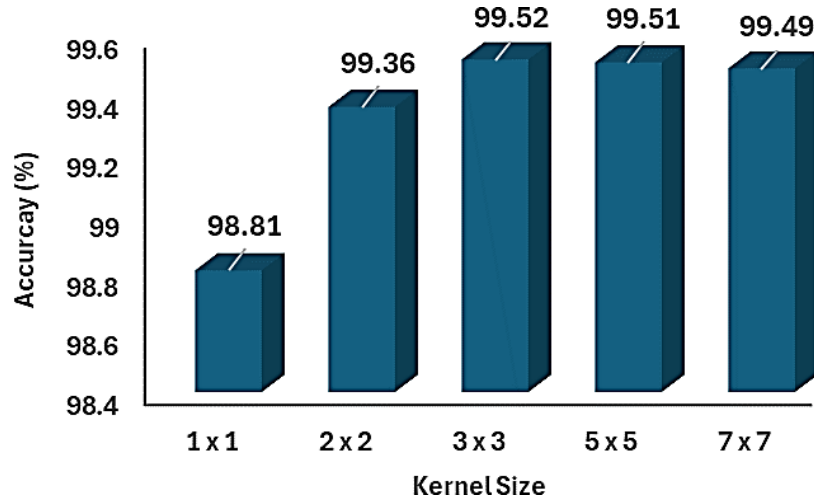


Fig.3.7. Variation of accuracy with kernel size.

analysis is done to justify the design of the customized CNN model. The variation of the classification accuracies with number of CNN layers and corresponding training time is shown in Fig.6. It can be observed that as the number of layers increases, the accuracy of the proposed CNN model increases, but after 12th layer, no appreciable increment in accuracy is noticed. On the contrary, the training time (plotted in secondary y axis) gradually increases with increasing the number of layers. Therefore, the proposed CNN model is designed with 12 layers where the maximum accuracy has been achieved and training time is also less than the other layers. Now, in Fig.3.7, the effect of varying the kernel size has been investigated. It can be seen from Fig.3.7 that the kernel size also has a direct influence on the accuracy of PD detection. In this study, the kernel sizes of the proposed CNN model were increased progressively from 1×1 to 7×7 and it has been observed that for the kernel size 3×3, maximum recognition accuracy has been achieved. So, in this work, a 12-layer CNN model with kernel size 3×3 has been chosen that delivered the optimum performance.

E. Computational cost

The computational complexity of the proposed model is discussed in this section. The extraction of time-frequency (T- F) images of PQDEs using ALST required approximately 1206 seconds. Using the proposed CNN model, classification of 22 classes of PQDEs required approximately 125 minutes. The classification time required by the AlexNet, VGGNet16 and ResNet50 models are approximately 140 minutes, 294 minutes and 192 minutes, respectively. Thus, in comparison with the AlexNet, VGGNet16 and ResNet50, the overall training time has been reduced by 10.71%, 57.48% and 34.89% respectively. This reduction in computational time is mainly due to the reduced number of learnable parameters present in the proposed

CNN model compared to the benchmark models. Hence, it can be inferred that the proposed CNN model is lightweight and has less computational burden compared to the benchmark models.

F. Analysis of PQ events using ASLT in presence of noise

In real life, PQDEs are often contaminated with high background noise which can lead to error in detection. Therefore, a reliable PQD monitoring framework should be able to detect the PQDE correctly in a noisy background

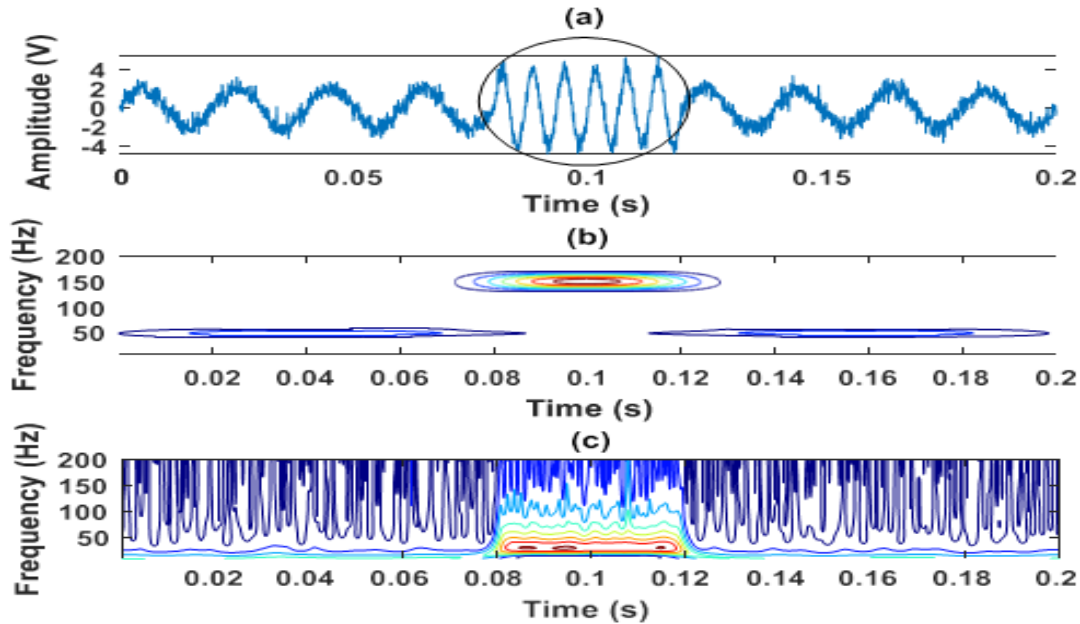


Fig.3.8. PQDE4 with SNR=5 dB and time-frequency representation using (b) ASLT and (c) ST, $C_1=3$ cycles, order:1:30, additive, for ASLT.

Considering the aforesaid issue, performance of proposed framework was investigated for different background noise. For this purpose, white gaussian noise of signal to noise (SNR) value “5 dB”, “10 dB”, “20 dB” and “25 dB” was added to generated PQDEs. The time-frequency representation of a sample PQDE4 (swell signal) obtained using ASLT in the presence of high noise level SNR= 5 dB is shown in Fig.3.8 (b). In Fig.3.8(c), time-frequency representation obtained using conventional ST is also shown along with. It is imperative from Fig.3.8(a-c), that when the SNR is very low, the different frequency components present in PQDEs can be distinctly identified in time-frequency plane using ASLT, while the time-frequency image obtained using ST is very noisy and difficult to identify the events correctly. Thus, ASLT is more robust against noise compared to ST.

In Table. 3.3, the performance of proposed CNN model under a noisy background is reported for ALST, CWT and ST for different signal-to-noise ratios. Based on the result, it can be stated that the performance of both ST and CWT is inferior compared to ASLT especially when the SNR is very low. However, as the SNR increases, the performance of CWT and ST becomes comparable with ASLT. This indicates that ASLT can be used to detect

PQDEs accurately even in the presence of high background noise.

Table 3.3. Performance of proposed framework under noisy background for ASLT, CWT and ST

SNR value(dB)	ASLT	CWT	ST
	Accuracy(%)	Accuracy(%)	Accuracy(%)
5	98.47	94.45	91.50
10	99.01	97.51	92.56
20	99.35	98.65	97.42
30	99.52	99.25	99.10

H. Performance analysis with real-life PQDE data

To establish the effectiveness of proposed framework, the performance of the framework was validated with real-life PQDE signals. For this purpose, the real life PQDEs were procured from several online available datasets [53-55]. In

Table 3.4. Information of collected real-life PQDE

Class	PQDE Description	Source of collected PQDE data
1	Sag	IEEE Dataport [53]
2	Harmonics	Kaggle [54]
3	Interruption	Kaggle [54]
4	Transient	IEEE Dataport [55]
5	Notch	Kaggle [54]

Table 3.5. Validation Performance using real-life PQD datas

Accuracy (%)	Sensitivity (%)	Specificity (%)
98.18	99.0	98.05

True Class	1	99	1	0	0	0
	2	1	96	2	1	0
	3	0	2	97	1	0
	4	0	0	0	99	1
	5	0	0	0	0	100
		1	2	3	4	5
		Predicted Class				

Fig.3.9 Confusion matrix of the validation data

Table 3.4, the description of real-life PQDEs along with their sources are mentioned. The collected PQD signals were transformed into RGB T-F images using ALST. Finally, the PQDE images were fed to the proposed CNN model for diagnosis of PQDEs. The classification performance of proposed framework on real life PQDE is reported in Table 3.5. It is evident from Table 3.5, that the performance of proposed framework with real life data has been found to be little lower than the simulation data. This may be due to the dearth of availability of large real-life PQDE signal dataset. Nevertheless, the performance of the proposed CNN model is reasonably satisfactory and hence can be used for accurate real-life power quality monitoring. To obtain better insight into the classification results, confusion matrix of the validation data for real life PQDE classification is shown in Fig.3.9. It can be seen from the confusion matrix shown in Fig.3.9 that the proposed framework can classify most of the events accurately with some misclassifications indicating the performance of the proposed model is satisfactory while classifying real-life PQDEs.

1. Comparative analysis with state-of-the-art techniques

The comparative study of proposed framework with some state-of-the-art PQDE detection techniques and the results are displayed in Table 3.6. It may be observed from Table 3.6 that the proposed framework based on ASLT and CNN provided almost comparable and even better than some of the existing methodologies. In [56-61], manual feature extraction method was implemented for classification of PQDEs. The disadvantage of the above methods is that manual feature extraction always impose the risk of selecting redundant features, which directly influence the detection accuracy. Also, the manual feature extraction method cannot be used for

automated detection of PQDEs in real-time applications. In [62], automated feature extraction based on ST has been proposed, but the problem of ST is that it cannot be used in noisy environment as depicted in Fig.3.3-3.4. Moreover, in the existing methods, the number of PQDE events chosen are also less compared to the

present study. The distinct advantage of the proposed framework is that it can classify single, as well as double class PQDE event automatically with no dependency on manual feature extraction. The entire framework is automated and is therefore suitable for power quality monitoring in real-time environment.

Table. 3.6 Comparisons of the proposed technique with other state-of-art techniques

Reference no.	PQDE classes	Feature extraction mode	Accuracy (%)
[56]	11	Manual	97.10
[57]	22	Manual	99.09
[58]	14	Manual	99.46
[44]	10	Manual	99.67
[28]	14	Manual	97.29
[59]	13	Manual	99.37
[60]	16	Manual	99.38
[61]	14	Manual	99.46
[62]	13	Automated	99.46
This work (Simulated PQDEs)	22	Automated	99.52
This work (Real-life)	5	Automated	98.18

3.5 Conclusions

In this contribution, an automated, accurate and robust framework based on ASLT and CNN has been presented for diagnosis of single, double and triple class PQDEs. For this purpose, the different PQDEs were analyzed in T-F frame utilizing ASLT based signal processing technique. It has been observed that ASLT can provide better resolution with improved visibility of different events in T-F plane even when the SNR is very low. Unlike ST, no optimization of Gaussian window is necessary to improve time-frequency resolution for analysis of noisy PQDEs. Thus, ASLT can distinguish different PQDEs in noisy environment which conventional ST cannot. To classify the PQ events, a customized lightweight CNN architecture was designed

to classify the PQDE signal encoded T-F images. In addition, several benchmark CNN models were trained for the purpose of comparison. The proposed CNN architecture achieved mean recognition accuracy of 99.52%, which is best among other benchmark CNN configurations. Moreover, the proposed CNN model is fast and computationally efficient. Thus, it can be concluded that the proposed CNN architecture can effectively be utilized power distribution network. The limitation of the proposed framework is that here only 22 classes of PQDEs consisting of single and double classes have been considered. In future, investigation will be carried out on triple class of PQDEs to examine the performance of the proposed PQDE detection framework. Moreover, the number of real-life PQDEs in this study are restricted to 5 only. In future, more classes of real-life PQDEs will be incorporated so that the proposed model can classify different types of real-life PQDEs accurately. Also, advanced deep learning models like attention-based vision transformer will be implemented in future to investigate the performance of the proposed model. Finally, as a part of the future work, hardware implementation of the proposed CNN model will be done using raspberry-pi or low-cost microcontroller module to develop a PQDE detection device.

3.6 References

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Chapter:4

Implementation of hybrid harmonics mitigation Techniques to improve Power Quality in grid-connected PV system

4.1 Introduction

The global solar photovoltaic (PV) market has seen continuous growth since 2000, reaching 1,177 GW in 2022. China and the United States lead the market with 307 and 122 GW of installed PV capacity, respectively. Chile and Honduras have the highest share of photovoltaic energy in total energy produced in 2022. This growth reflects a global shift towards renewable and sustainable energy technologies. [1-2]. This study highlights the significance of studying solar cells as they are the ideal partner for renewable and traditional energies in hybrid energy systems, which are widely used worldwide due to their reliability and stability in producing energy from individual systems like PV with Grid, PV with Wind, PV with Diesel, PV with CSP, PV with Wind and Diesel, and PV with Wind and Battery. [3-12]. In today's power system scenario, reliability and quality are paramount. Power quality deals with the measurement of the degree up to which the voltage, frequency, and waveform match the required standards. A power system with good quality ensures a supply voltage staying within the specified range having a frequency in proximity with the rated value and a smooth waveform of the voltage (a sine wave). These parameters of a good quality power system suffer greatly due to the presence of harmonics. Mitigation of harmonics is a step of utmost importance toward improving the quality of the power system.

India's government is implementing renewable energy systems, particularly solar and wind, under the Jawaharlal Nehru National Solar Mission (JNNSM), aiming to deploy 97,000 MW of grid-connected solar power by 2022. [13-17].

A hybrid renewable energy system (HRES) is a system that combines various types of renewable energy, such as wind, solar, biomass, etc. In this Chapter, the author study a grid-connected PV system. Basically, there are three main types of PV systems used (a) Off-grid system, (b) Grid-tied system, and (c) Hybrid system. In a PV system, the inverter is one of the essential devices which convert DC to AC power. This inverter is the main source of harmonics generation during the conversion of power, it uses power electronics switching which generates a number of odd-order harmonics [18]. Also, the nonlinear loads are the other source of harmonics. [19] In recent years the pattern of the load changed with advanced technology. Basically, loads are attached with different power electronic devices which generate different types of non-sinusoidal shape that corresponds to the combination of different sine waves. The magnitudes and phase angles of the different frequencies of those waves are multiples of the system frequency. Power quality and harmonics are closely related as harmonics are one of the factors that can affect power quality in electrical systems. Power quality refers to the characteristics of the electrical power supply, including parameters such as voltage level, frequency, waveform distortion, and stability. Harmonics can significantly impact power quality by introducing various issues and disturbances.

Literature Review: Researchers [13-17] explain generation of Active and Reactive power from a generating

station is non-sinusoidal. The power quality of the system is weakening because of a different sequence component of current and Voltage harmonics, also voltage swell, voltage sag, flicker, voltage interruption of voltage, etc. [20] Total harmonic Distortion directly depends on an interface with the size of the PV plant and utility system. The author [21] analyzed PV inverters' harmonic emissions with the different values of solar irradiance levels and matched the results with field measurements. The nature-inspired optimization algorithms were developed for the optimal design of passive filters to reduce harmonics in the Power system network [22]. A Genetic Algorithm is used to minimize the Total Harmonic Distortion (THD) of current which helps to a reduction in total cost [23].

The Design method of a single-tuned Passive Filter was described which helps to minimize the voltage THD using Particle Swarm Optimization (PSO) [24 -25]. A continuous and discrete, neural-network-based design of this single-tuned Passive Filter contains a single weighted objective function for the multi-objective problem [26]. Single- and double-tuned Passive Filters were also designed by BCO (Bee Colony Optimization) [27].

A problem is indicated regarding resonance after the implementation of a filter in the power system network for compensation [28-31].

4.2 Comparison between Active and passive filter

I. Passive Harmonic Filters

Passive filters use passive components such as resistors, inductors, and capacitors to mitigate harmonics. They are designed to block specific harmonic frequencies and allow the fundamental frequency to pass through.

Characteristics:

Design: Designed to trap or absorb certain harmonics. Typically tuned to specific harmonic orders (e.g., 5th, 7th, 11th).

Components: Composed of inductors (L) and capacitors (C) to form series or parallel resonant circuits.

Cost: Generally less expensive than active filters.

Operation: Works automatically without external control, but its performance is dependent on the system load and impedance.

Efficiency: Can be effective at specific harmonic frequencies but may not handle a wide range of harmonic orders.

Load Dependency: Performance can degrade if system conditions change, such as a shift in load, making it less flexible.

Use Cases: Typically used in fixed-frequency applications with predictable harmonic profiles, such as in industrial settings.

Advantages: Cost-effective for single harmonic issues. Simple design and low maintenance.

Proven technology with a long operational history.

Disadvantages: Fixed design, not adaptable to changes in harmonic spectrum. Risk of resonance with system

impedance, which can amplify other harmonics. Cannot adapt to dynamic harmonic changes.

II. Active Harmonic Filters

Active filters use power electronics to actively monitor and cancel out harmonic distortions by injecting counteracting signals in real time.

Characteristics: Design: Monitors the system harmonics continuously and generates compensating signals (opposite phase) to cancel them out.

Components: Uses power electronics like insulated-gate bipolar transistors (IGBTs), microcontrollers, and sensors.

Cost: More expensive due to the use of sophisticated electronics and control systems.

Operation: Dynamic, can adjust to varying system loads and harmonic conditions.

Efficiency: Capable of mitigating a wide range of harmonic orders, making it suitable for systems with complex and changing harmonic profiles

Load Dependency: Independent of load, meaning it can adapt to load changes in real time.

Use Cases: Ideal for dynamic environments with varying loads and harmonics, such as commercial buildings, data centers, or industries with highly variable equipment usage.

Advantages: Can address a wide range of harmonic frequencies. Highly adaptable to system changes, providing real-time correction risk of resonance issues. Can also provide additional functionalities like power factor correction and voltage stabilization.

Disadvantages: Higher initial and maintenance costs compared to passive filters. Requires complex control systems and power electronics. All the previous related literature reviewed mainly focused on the harmonics mitigation process of the grid-connected PV system. However, in this Chapter, the author find that STPF [Single tuned Passive Filter] can generate harmonics on the other bus when installed on a particular bus. To decrease this problem present author introduce a hybrid arrangement of phase-shifting transformers with STPF [Single tuned Passive Filter] to mitigate the odd-order harmonics. This study also compares the effectiveness of the hybrid combination over STPF [Single tuned Passive Filter].

Nowadays, integrating photovoltaic (PV) generation into the conventional grid system has become a significant concern. As a consequence, the analysis of the impact of the PV system on the existing grid and the application of preventive methods to maintain the power quality of the system has joined paramount importance. In this Chapter, the author have proposed a grid-connected PV ETAP Simulation Model to analyze the harmonics' effect on the system in the presence of nonlinear loads. After analyzing, it is observed that different odd-order harmonics are generated in the system which can have a negative impact on the system. To take care of these odd-order harmonics the author compare two basic mitigation techniques; one being the Single Tune Passive Filter (STPF) mitigation which is not applicable for

multiple harmonics order reduction with system power loss and the other being the Phase shifting transform mitigation. As compared to the passive filter method, the phase-shifting transformer bears the advantage of minimal power loss and voltage fluctuations. However, the phase-shifting transformer method is effective for multiple harmonic order reduction but not applicable for higher odd harmonics. To overcome this problem author introduced a hybrid concept of mitigation which reduces power loss by up to 52% and mitigates harmonics up to 85-90%.

4.3 Model Description

The main objective of this research work is to design a grid-connected PV system and compare the different mitigation methods by ETAP simulation software. In this Chapter, a simulation model is designed using ETAP for a 762.102 MVA grid connected with a 156 kW PV system coupled with a 3600 kW inverter. Both these sources contribute power for two 2MVA nonlinear loads by two 5MVA transformers. The X/R ratio of the proposed simulation model is 14. Fig.01 shows the proposed ETAP simulation model for a Grid-connected PV system.

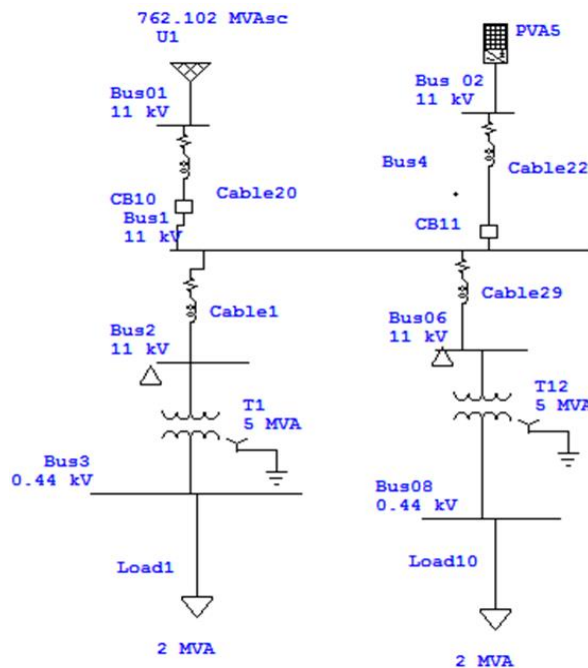


Fig 4.1. Proposed ETAP simulation model for Grid-connected PV system.

4.4 Mitigation of Harmonics

I. Using Single Tune Passive Filter [STPF]:

Harmonics can introduce distortions in voltage and current waveforms, leading to irregular waveforms. They can also contribute to imbalances in three-phase power systems, causing inefficiencies, increased

losses, and reduced equipment lifespan. High levels of harmonics can cause voltage fluctuations, flicker, overheating, losses, and resonance issues in electrical systems. These issues can result in equipment malfunctions, disruptions, and potential damage. Therefore, it is crucial to address harmonics to maintain power quality. Harmonics mitigation is the process of controlling unwanted frequencies in an electrical power system, which can cause issues like equipment malfunction, overheating, increased losses, and interference with communication systems. Common methods include passive harmonic filters, active filters, harmonic traps, variable frequency drives (VFDs), transformer design, and harmonic filters.[32] Passive filters create impedance at specific harmonic frequencies, while active filters detect and cancel out harmonics using power electronics. Tuned filters provide a low-impedance path to specific harmonic frequencies while maintaining high impedance for other frequencies. Transformers with lower impedance can also help mitigate harmonics. The selection of a method depends on the system's requirements, harmonic magnitude and frequency, and budget constraints.

In this Chapter, author implement single-tune passive filters (STPF) to reduce the effect of the harmonic in the system. A single-tuned passive filter, also known as a single-tuned harmonic filter, is used for harmonics mitigation in electrical power systems. It is designed to mitigate a specific harmonic frequency or a narrow band of harmonic frequencies. The single-tuned filter consists of a series LC circuit (inductor and capacitor) that creates a high impedance at the desired harmonic frequency, allowing it to divert the harmonic currents away from sensitive equipment. The LC circuit is typically tuned to the frequency of the targeted harmonics.

$$Z=R+j(\omega L_n-1/(\omega C_n)) \quad (1)$$

The impedance, Z of the filter can be expressed in equation (i), where R is resistance, L is inductance, and C is capacitance, of the filter, respectively. Also, the filter's resonant frequency is ω . At the resonance frequency, ωL_n

$= 1/\omega C_n$ [33-35], that gives, $Z_n = R_n$. The Q factor or quality factor determines the sharpness of tuning of the filter. The Q factor is the ratio of X/R where X is the reactance. The filter with low Q is sharply tuned to one of the lower harmonic frequencies [36] a typical value is between 30 and 60. The filter with a high Q is typically in the region between 0.5-5.5.

Another important parameter for STPF design is the relation of tuning factor [37] δ with Q is shown in the following equation (ii).

$$Z = \left\{ 1 + jQ\delta \frac{(2+\delta)}{(1+\delta)} \right\} \quad (2)$$

Single-tuned passive filters are effective in mitigating of specific harmonic frequencies but have limitations such as limited range, resonance issues, lack of adaptability, impact on power factor, size, and space requirements, and parallel resonance between the system and filter. These filters are designed to mitigate a specific frequency or narrow band. If multiple filters are used, they may require multiple numbers of filters, increasing complexity and cost. Additionally, they can amplify voltages and currents, leading to potential equipment damage. Upgrading or reconfiguring the filter may be necessary to accommodate system changes. The design and implementation process should consider adequate space and suitable installation locations. Power quality experts or electrical engineers can help select the most suitable harmonic mitigation solution for a given application.

I. Using Phase shifting Transformer:

Three-phase non-linear loads currents generate 3rd, 5th, 7th, 9th, 11th, 13th, 17th, 19th, odd order harmonics. A harmonic mitigating phase-shifting transformer can use dual secondary windings or pairs of transformers to reduce these harmonics. In this proposed model two transformers with a 30° phase shift between them can be used to eliminate odd-order harmonics. The degree of phase shift is chosen to ensure that the harmonic components of one secondary are out of phase with those of another. Pairs of delta Star transformers with a 30° phase shift can be applied to mitigate the 3rd, 5th, and 7th order harmonics. [38-39]

Here author consider two non-linear Load1 and Load2 connected with two 2MVA transformers. The nonlinear loads generate 3rd, 5th, 7th, and 11th-order harmonics which is injected in the main bus (bus1). Bus number 1 is the bus where the grid and PV generation are interconnected to supply the loads. In this Chapter, the author introduce harmonics mitigation through a phase-shifting transformer. In this method, the phase angle shifting can be used to further of combination sine waves providing for more harmonics mitigation. The theory of combining single wave describe two way of harmonic mitigation (i) by using the inherent phase angle displacement of the electrical wave shapes within the transformer, it is then combined at the nodes or connection points of the windings within the transformer, (ii) by combining the sine waves at the common bus feeding two transformers of different phase shift. With the help of equations (iii) to (v) the sequence of odd-order harmonics has been obtained.

$$I_R = I_R \sin n\theta \dots\dots\dots (3)$$

$$I_Y = I_Y \sin(\theta - 120^\circ) \quad (4)$$

$$I_B = I_B \sin(\theta - 240^\circ) \quad (5)$$

Where, n is the order of harmonics, n =3, 5, 7, 9, 11..... odd harmonics. If 3rd harmonic is present in the system according to equation no (iii) to (v), only zero sequence current has been injected into the system as explained below.

Let, the interphase current under balance condition be;

$$I_R = I_R \sin 3\theta$$

$$I_Y = I_R \sin 3(\theta - 120^\circ) = I_R \sin(3\theta - 360^\circ) = I_R \sin \theta$$

$$I_B = I_R \sin 3(\theta - 240^\circ) = I_R \sin(3\theta - 720^\circ) = I_R \sin \theta$$

Table. 01 indicates the different order harmonics and sequence of current.

Table4.1. Phase shifts for harmonic mitigation or Cancellation for 3-ph.nonlinear loads

Harmonics Order	Sequence	Phase Shift	Solution
3 rd	zero	60 ^o 180 ^o	Cancellation Cancellation
5 th	-ve	30 ^o 180 ^o	Mitigation Cancellation
7 th	+ve	30 ^o 180 ^o	Mitigation Cancellation
9 th	zero	60 ^o 180 ^o	Cancellation Cancellation
11 th	-ve	15 ^o 180 ^o	Mitigation Mitigation
13 th	+ve	15 ^o 180 ^o	Mitigation Cancellation

From the above table 01, it is observed that each harmonic is either canceled or mitigated by different phase shifting of the transformer. The 3rd and 9th orders can be canceled properly by the phase shifting of 60^o and 180^o whereas the 5th, 7th, 11th, and 13th odd orders are only mitigated by this phase shifting method.

4.5 Methodology

To analyze the performance of the different Harmonics methods author, perform five case studies.

Case Study: I Analyzed the Load flow and the effect of the harmonic when only the grid is present in the system.

Case Study: II Analyze the Load flow and the effect of the harmonic when the grid and PV generation both are present in the system.

Case study: III Single tune passive filter (STPF) design and implementation for mitigating 5th, 7th, and 11th order harmonics.

Case Study: IV The phase-shifting transformer implementation to eliminate 5th, 7th, and 11th order harmonics.

Case Study: V Single tune passive filter (STPF) and the phase-shifting transformer combination to mitigate 5th, 7th, and 11th-order harmonics.

Case Study I: In the first Case study author implement Harmonic analysis of a grid-connected system. The output data of the harmonic analysis is shown in Figure 02.

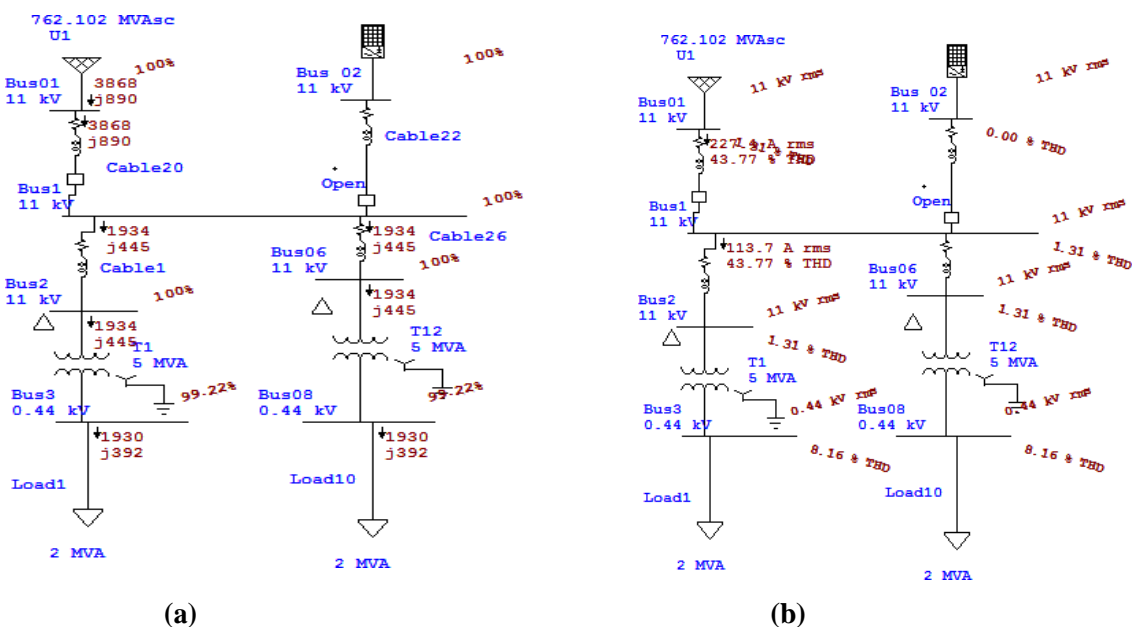


Fig4.2. (a) Load Flow output of ETAP simulated model when PV generation is not connected with the system.

(b) Harmonic analysis output of ETAP simulated hybrid model when PV generation is not connected with the system

Case Study II:

In the second Case study author implement a Harmonic analysis of a grid connected with a PV system the output data of the harmonic analysis is shown in Fig. 03.

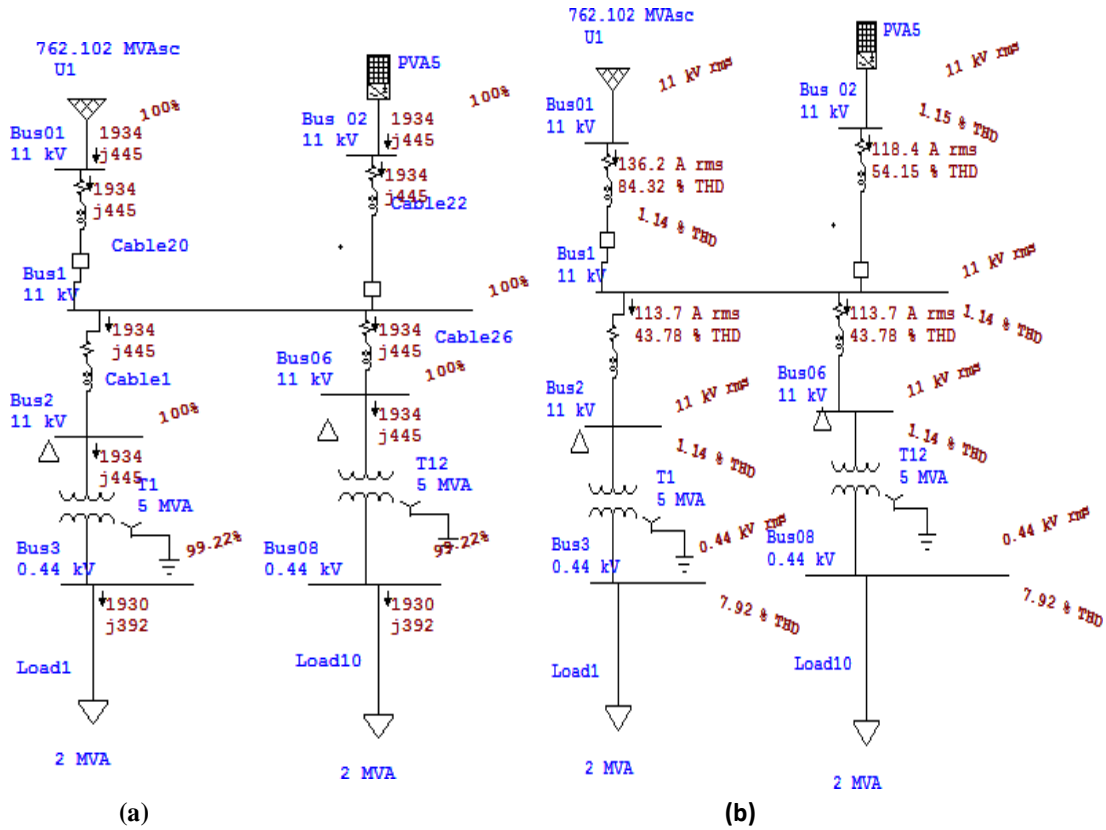


Fig4.3. (a) Load Flow output of ETAP simulated hybrid model when PV generation connected with the system. (b) Harmonic analysis output of ETAP simulated hybrid model when PV generation connected with the system

Table 4.2. The calculation for different odd-order Harmonics in Bus.1

Harmonics order	%I _h	Z Ω	V _h	V _h ²	I _h ²
3 rd	50	0.476377	42.874015	1838.1812	8100
5 th	20	0.793963	28.582677	816.96943	1296
7 th	5	1.111548	10.003937	100.07875	81
9 th	2.5	1.429133	6.6883464	44.733978	21.901
11 th	1.3	1.129122	2.577774	21.23356	11.202

From, the calculation, it is found that %VTH is 1.145% and %ITH is 43.20% which is very close to the simulation output.

Case Study III: Harmonic Mitigation technique implementation: to mitigate the 5th, 7th, and 11th odd-order harmonics three STPF [Single Tune Passive Filter] is implemented on Bus no 3 and 08. The details of the design parameter of the three Passive filters are given in Table 03.

Table 4. 3. Design parameter of Single Tune Passive Filter (STPF)

Bus Number	Harmonic sorder	Harmonics Current	1 phase [KVAR]	Capacitive Value [μF]	X _L [Ohm/Phase]	Q factor
Bus no.03&08	5th	120	872	13430	0.0079	40
Bus no.03&08	7th	120	872	13429	0.0045	40
Bus no.03&08	11th	120	872	13427	0.0016	40

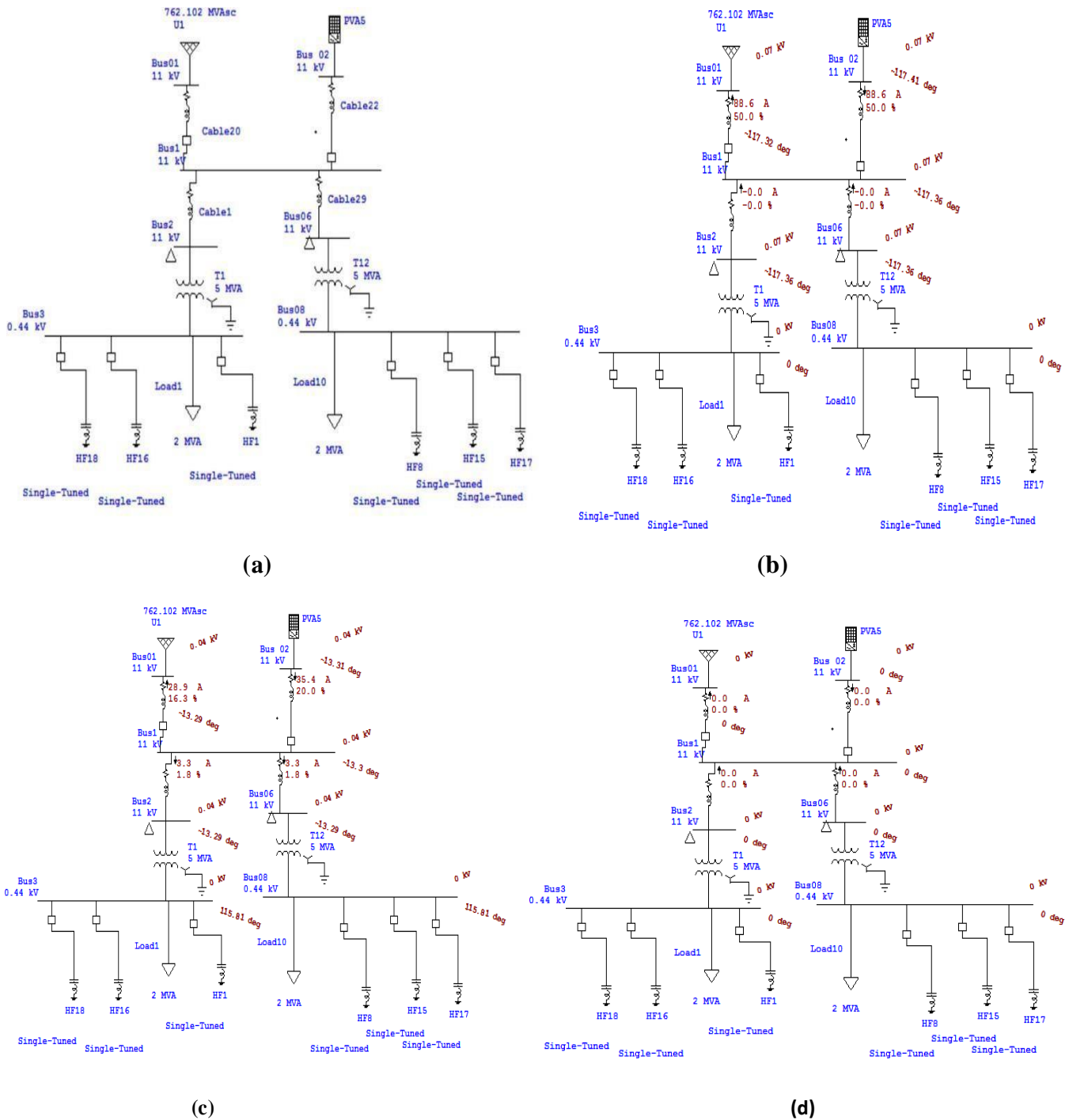


Fig4.4. (a) ETAP simulated a grid-connected PV system when single-tune passive filters (STPF) are connected with the system.(b), (c) and (d) Etap simulation results after 5th, 7th, and 11th order harmonics mitigation respectively of the grid-connected PV system by single-tune passive filters (STPF).

Case Study IV:

The Phase Sifting Transformers are implemented to mitigate 5th, 7th, and 11th-order harmonics from the grid-connected PV system shown in Fig. 05.

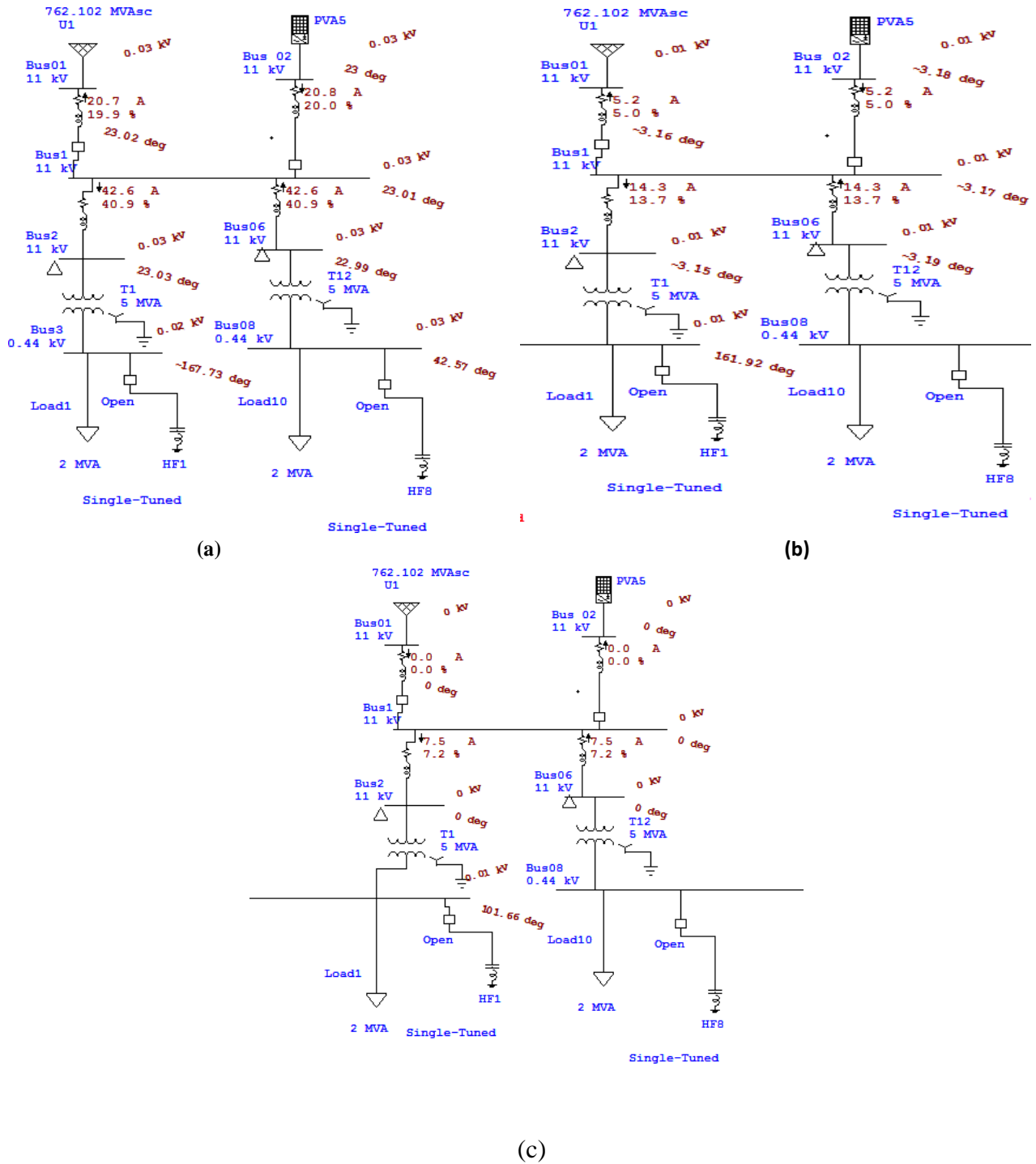
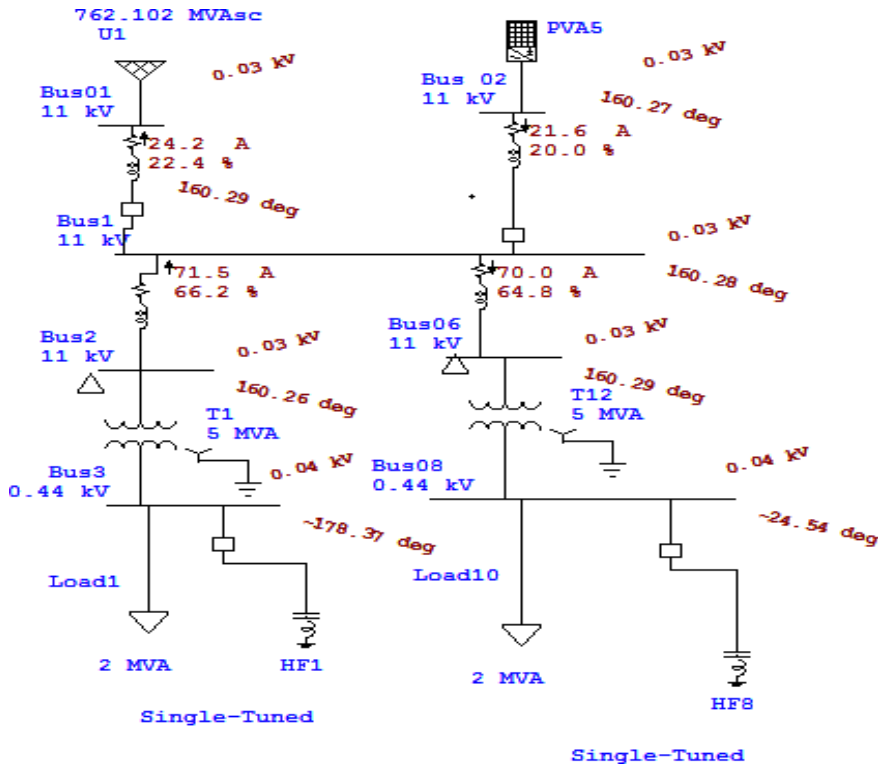


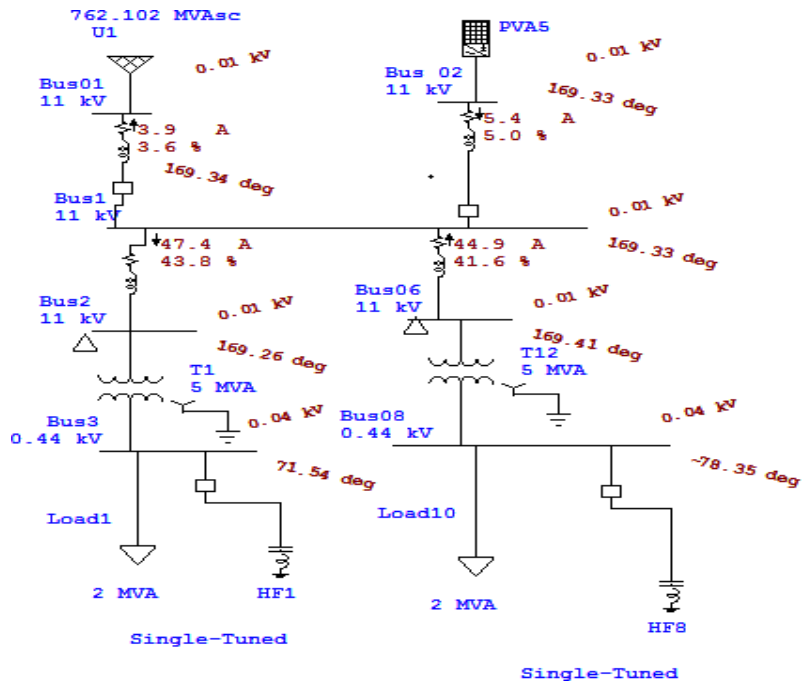
Fig 4.5. (a), (b) and (c) Etap simulation results after 5th,7th, and 11th order harmonics mitigation of the grid-connected PV system, respectively by phase sifting method implementation on transformers.

In figure.05 (a) it is observed that the 5th odd-order harmonic current cancels each other in Bus.1. Similarly, the other harmonics like the 7th and 11th odder canceled from Bus.1 as in Fig. 05(b) and (c) in this present phase sifting method of the transformer.

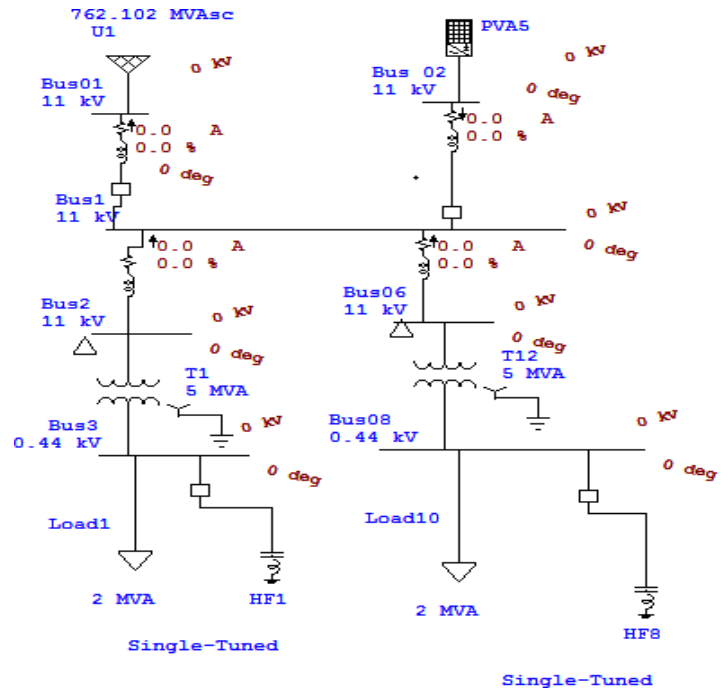
Case Study V: To analyze the performance of the proposed hybrid mitigation process where STPF and Phase sifting transformers jointly reduce the odd-order harmonic generation. From cases III and IV, it is observed that STPF can eliminate all odd-order harmonics, but the phase shifting transformer can eliminate the harmonics of 5th and 7th orders by the vector group changing method. In this proposed network, a single-tune passive filter has been used for 11th-order harmonic mitigation. Design parameters for the Single-tune passive filter STPF are described in Table 2. In case study V a combination of a shifting transformer with the single-tuned passive filter (STPF) was implemented to mitigate the odd-order harmonics. The outcomes of the simulation results are shown in Fig. 06. From cases II and III it is observed that active power loss increased up to twice the normal value whenever the Single tuned passive filter (STPF) was implemented for the 5th, 7th, and 11th order harmonics but in case III whenever the phase shifting transformer the overall active power loss slightly changed with normal value.



(a)



(b)



(c)

Fig 4.6. (a), (b) and (c) Etap simulation output for 3rd, 5th, 7th, and 11th order harmonics mitigation of the grid-connected PV system respectively by a combination of Phase Sifting Transformer and Single Tune Passive Filter

4.6 Results and Discussion

In this present work, a hybrid combination has been proposed which is able to mitigate the different order harmonics in the proposed system. From case II it is observed that 3rd, 5th, 7th and 11th-order harmonics are present in the proposed system. Table 02 indicates the theoretical calculation of the harmonics current (I_h) and Voltage (V_h) of Bus 1 in the system. After calculating the percentage of Voltage Total Harmonics (VTH) and Current Total Harmonics (ITH), the accuracy level of ETAP simulation output data is 98% and found to be mitigating.

The design parameters of STPF used for mitigating % of 5th, &7th and 11th order harmonics are described in Table 03. Figure 04 (b) to (d) shows the output results after implementing the single-tuned passive filter (STPF) for each harmonics order.

In case study IV, the phase-sifting method using a transformer has been implemented to mitigate the odd-order harmonics. According to Table 01 to mitigate 5th order harmonics, -Ve sequence current provides phase shifting of 30° for mitigating employing Dy1 Connection, similarly to mitigate 7th harmonics +ve sequence current providing a shifting of 30° is required. From Figure 05 (a) it is observed that at Bus1 the injected harmonics current (I_h) 42.6 A cancels out by the same magnitude but different directional current in that similar way it also mitigates the 7th and 11th order harmonics [fig. 05 (b) and (c)].

From The above case studies, some drawbacks are found in both case studies III and IV, in Case III the single-tune passive filters increase the system's current absorption, which leads to double active power loss in the system. Table 04 indicates that case study III generates more power loss than others. In case study IV, the transformer phase sifting angle is the same for 5th and 7th harmonicas but in the case of 11th harmonics, it's different so in the same operating time different phase shifting arrangement is not applicable, but active and reactive power loss in this method is comparatively acceptable.

To overcome this drawback a combination of phase-sifting transformers was used to mitigate 5th and 7th harmonics and the single-tuned passive filter (STPF) was used to mitigate 11th-order harmonics [Fig.06]. With this combination, it was observed that active and reactive power loss is within the acceptable range. The performance of this harmonics mitigation method is also within satisfactory limits.

Table 4.4 Active and reactive power loss comparison

Total loss	KW	KVAR
Case Study: III	34.1	412.6
Case Study: IV	17.5	211.9
Case Study: V	18.2	220.0

From the above table 04, it is observed that each harmonic is either canceled or mitigated by

different phase shifting of the transformer, 3rd and 9th order can be canceled properly by the phase shifting 60° and 180° but the 5th, 7th, 11th, and 13th these odd orders are only mitigated by this phase sifting method.

4.7 Conclusion

In the present scenario, the percentage of use of Renewable sources with nonlinear loads is increasing gradually, which generates a negative impact on the power quality of existing power systems. The Single-tune passive filter can mitigate a specific harmonic order at a time. So each harmonic order requires a separate single-tune passive filter, which increases the system power loss and the operational cost. The phase-shifting transformer can mitigate multiple harmonics but is not applicable for higher odd-order harmonics, Also, it has some limitations for a specific phase-sifting angle, which is applicable for the 5th and 7th harmonics which is not for the 11th order. The proposed hybrid system efficiently overcomes these two drawbacks, where power loss is reduced by up to 52%, and all odd-order harmonics mitigation can be achieved up to 85-95%. After analysis of the performance of the proposed hybrid harmonic mitigation system, it can be concluded that it can improve the overall power quality of a Grid-connected PV system.

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Chapter:5

Investigation of Harmonics Mitigation Technique for PV Connected Standard Bus System and its Effects

5.1 Introduction

At present, power quality is an important aspect of the PV-integrated hybrid power system. To improve power quality, different compensation techniques are implemented in the power system. In this Chapter, the author analyze the effect of a single-tune passive filter [STPF] on the overall PV-connected power system. The study is conducted using ETAP software, using one of the IEEE bus systems. The single-tuned passive filter [STPF] has been designed to mitigate different order harmonics in the proposed IEEE system. To achieve a complete harmonic-free system and maintain decent power quality, the author analyzed the effect of a single-tuned filter [STPF] on the other buses in the system that are not connected to a single-tuned filter [STPF]. After detailed analysis, the author found that a single-tuned filter [STPF] can cause harmonic generation for other buses in the same system. The main cause behind this harmonic generation is the parallel resonance between the source and the passive filter. Due to parallel resonance, a large harmonic current can be generated at the Point of Common Coupling (PCC). In this Chapter, the author implement a counter-filter implementation method to solve that problem.

Now a days India is one of the most expeditious powers authoritatively mandating countries in the world It's authentically challenging for Engineers to meet ultimate demand. The power crisis is a prevalent quandary. The conventional source is not ample enough to meet the present power and demand. In India, over 300 million people have to be integrated to access electrical energy in the coming year consequently

The Gov. of India has taken the initiative towards the immensely colossal installation of renewable predicated energy systems, especially solar and wind energy systems. Under JNNSM (on the 11th of January 2010 the Jawaharlal Nehru National Solar Mission was launched by our former Prime Minister, Dr. Manmohan Singh. The Mission has set the obsessive target of deploying 97,000 MW of grid-connected solar power by 2022 and aims at minimizing the cost of solar Power generation in the country) scheme [1].

Nowadays, everybody must consider the environmental aspect and should ascertain a better environment before installing any kind of puissance engendering station on a sizably voluminous scale renewable source is the only solution. Solar energy is one of the greatest Renewable sources among the other sources. PV solar system is one of the best ways to utilize this great puissance. Renewable power generation systems can be wired in different configurations depending upon the authoritative ordinance and

circumstances of an area. Three main configurations are (a) off-grid system, (b) Grid-tied system, and (c) Hybrid system. The term off-grid refers to the generation system not being connected to a national transmission grid. Off-grid electrification withal kened as a Stand-Alone System is an approach in places with little possibility of electrification via utility grid. Grid-tied is a photovoltaic generation system connected to the grid without any battery backup. The puissance engendered during daytime is directly supplied to load requisites and the excess power being engendered may be given to the grid.

During the nighttime, since there is no generation by the photovoltaic system load is supplied by grid electricity. A hybrid system may be termed as a grid-tied system with battery back-up, implicatively insinuates it combines energy storage in the form of a battery to keep “critical load” circuits in the house operational during a utility outage. During the nighttime, even if an outage occurs during the nighttime, even if an outage occurs the unit disconnects from the utility and powers categorical circuits in the abode via the battery bank [2]. Photo Voltaic in the grid-connected distribution system reiterated change of irradiance can lead to an undesirable variation of Power quality which might even exceed acceptable limits that are set out by the respective grid. The inverter is one of the essential contrivances to convert. DC to AC power for the grid continually regulates desired output from frequent change input it’s a prodigiously and sizably voluminous challenge to design an inverter to maintain congruous quality output for the grid, so power quality is distorted during this DC to AC conversion. In addition, it meant, that astronomically immense quantities of photovoltaic inverters can give ascend to power quality quandaries on low voltage networks, even when inverters comply with standards [3]. Such deportment, considered by low power quality, is often onerous because it averts reliable equipment operation and causes failure of sensitive electronic contrivances [4]-[5].

5.2 Literature Review

The author of [6]-[9] explain Generation of Active and Reactive power from a generating station is sinusoidal. The power quality of the system is weakening because of a different sequence component of current and Voltage harmonics, also voltage swell, voltage sag, flicker, voltage interruption of voltage, etc. [10] Total harmonic Distortion directly depends on an interface with the size of the PV plant and utility system. The author of [11] analyzed PV inverters' harmonic emissions with the different values of solar irradiance levels and matched the results with field measurements. [12] The nature-inspired optimization algorithms were developed for the optimal design of passive filters to reduce harmonics in the Power system network. The author of [13] used a Genetic Algorithm to minimize the Total Harmonic Distortion (THD) of current which helps to a reduction in total cost. In Ref. [14] The Design method of a single-tuned Passive Filter was described which helps minimize the voltage THD using Particle Swarm Optimization (PSO). A continuous and discrete, neural-network-based design, this single-tuned Passive Filter contains a single weighted objective function for the multi-objective problem Refs. Suggested in [15]-[16]. Single- and double-tuned Passive Filters were also designed by BOC (Bee Colony Optimization) in Ref.[17]. The Author [18]-[20],[21]- [30] indicate a problem regarding resonance after the implementation of a filter in the power system network for compensation.

5.3 ETAP [Electrical Transient and Analysis Program] Simulation Software

ETAP is a progressive Load Flow module that can easily make and authenticate your system model and obtain correct and reliable results [21]. Automatic device assessment, summary alarms/warnings, outcome analyzer, and intelligent graphics make it the most effective Load Flow program available today. With help of the ETAP software we can analyze different parameters like bus voltages, currents, power factors for different branches, and power flows throughout the electrical system, voltage-regulated and accepting power sources with several types of power grids and conventional generator connections. It is accomplished by performing analysis on both loop and radial systems. ETAP authorizes you to choose different procedures to achieve the best calculation efficiency and accuracy. In this present work Load flow study on the IEEE-9 bus system with a PV module has been carried out using the ETAP simulation method and analyzing the output data.

5.4 The Proposed Method

The following two cases are very important in designing a Harmonics Mitigation Filter for a PV-connected system. In this Chapter, the author choose the standard IEEE 9 bus system. Figure 1 shows standard input data, which is given in the table. 5.1 to 5.3 to analyze the harmonic effect on a standard Bus system.

TABLE 5.1
PV Panel details which are simulated by ETAP software

No of Panels.	Power	V_{mp}	V_{oc}	%eff	I_{mp}	I_{sc}	Fill factor
10	200W	25.34V	32.94V	14.5	7.83A	8.5A	70.86%

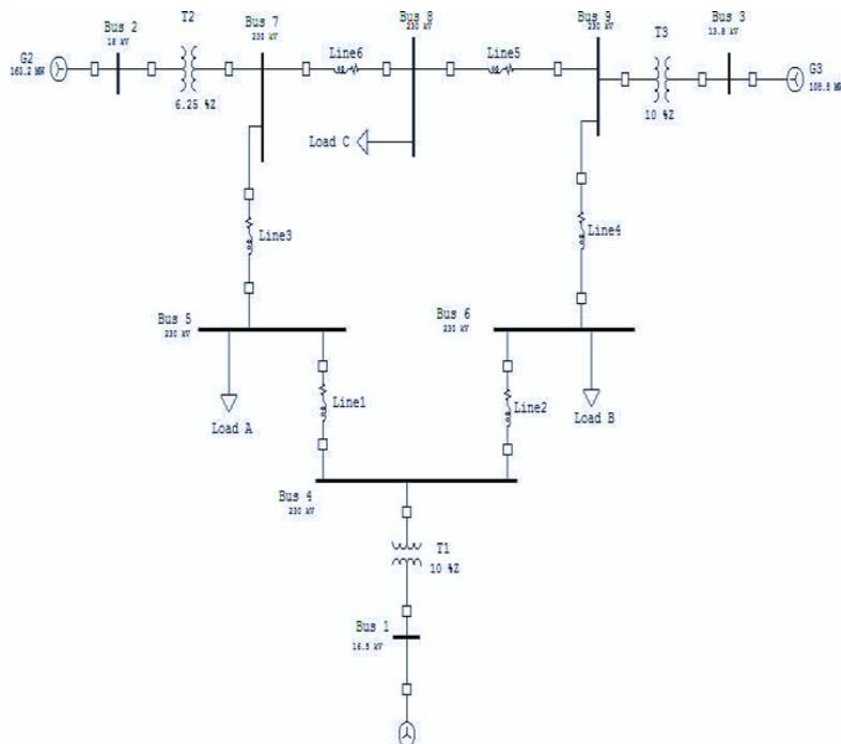


Fig.5.1 Proposed IEEE-9 bus system simulation model in ETAP without PV

TABLE 5.2
Inverter Details, which is simulated by the ETAP software

DC Power.	DC Voltage	%eff of DC	AC Power	Ac Voltage	%eff of AC
7KW	8KV	90%	7KW	25KV	85%

TABLE 5.3
Input data of the Proposed IEEE-9 bus system without PV module

	Power	Voltage
Generator 1	247 MW	16.5KV
Generator 2	163.4MW	18KV
Generator3	108.8MW	14KV
Load A	125.84MW+j 0.5MVAR	230KV
Load B	87.7MW+j29.23 MVAR	230KV
Load C	96.8MW+j33.90MVAR	230KV

A. Case study 01. To analyze the characteristics and change of the Harmonics generation between a PV-connected hybrid IEEE system and without a PV IEEE bus system perform harmonic analysis with the help of ETAP simulation. Fig. 1. to 3 indicate the complete Harmonic analysis data of the IEEE-9 bus system without PV also Table 5.4 specifies the VIHD and VTHD report

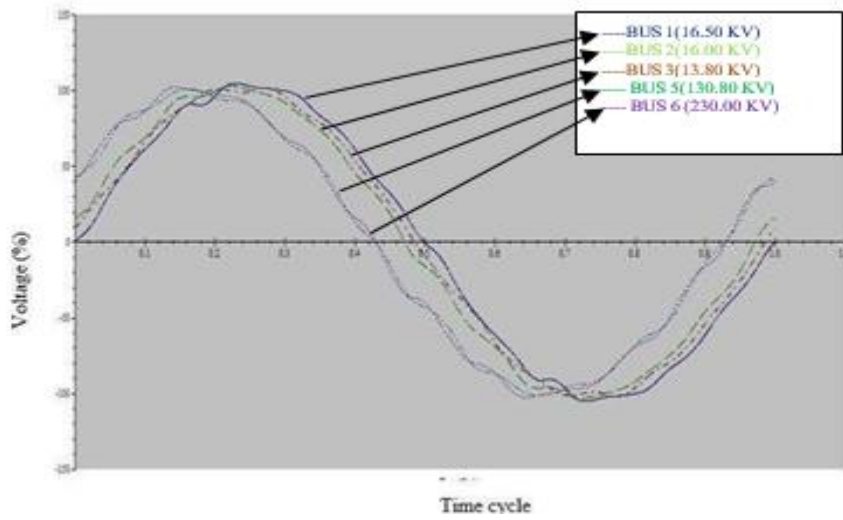


Fig. 5.2. Load Bus [5 and 6] voltages vs. harmonics order without PV. Spectrum

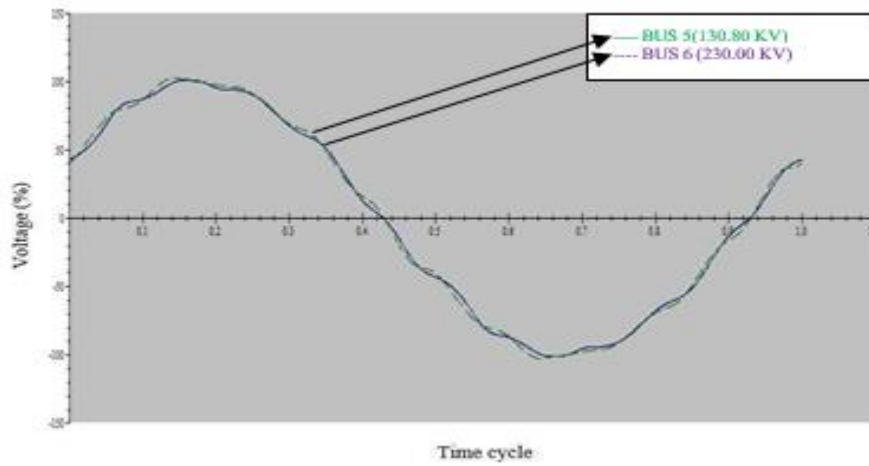


Fig. 5.3. Load Bus [5 and 6] voltages vs. harmonics order without PV. Spectrum

TABLE 5.4
Output data VIHD

Bus ID	KV	Found%	%VIHD	Harmonics order
Bus 5	230	99.35	3.16	11
Bus 6	230	100.7	3.33	11

Output data VTHD

Bus ID	KV	Found%	% VTHD
Bus 2	18	102.5	2.73
Bus 4	230	102.09	3.92
Bus 5	230	99.35	3.82
Bus 6	230	100.7	3.95
Bus 7	230	102.32	3.05
Bus 8	230	101.32	3.47
Bus 9	230	102.85	3.21

From this output Table 5.4, it is observed that only 11th-order harmonics are present in this standard Bus system.

B. Case study 02. Study the impact of the Harmonic character of a PV-connected hybrid system for different irradiation values of the sun Fig 4 and 5 with Table 5.5 indicate the output data of harmonic analysis for 191.

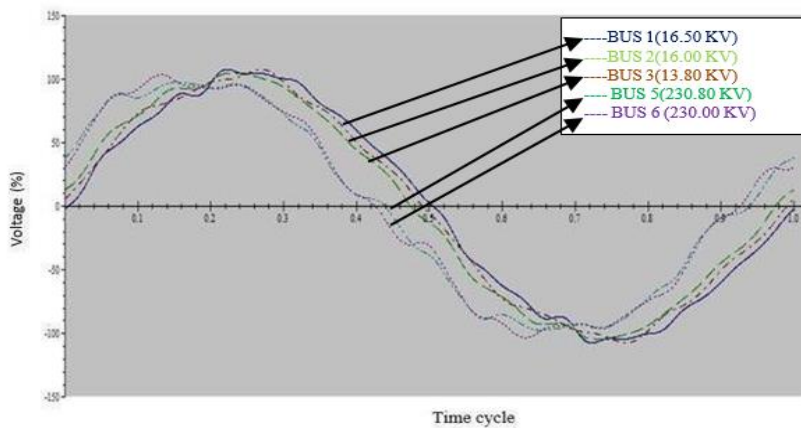


Fig. 5.4 Bus voltage vs. harmonics order with PV. Spectrum [DNI191]

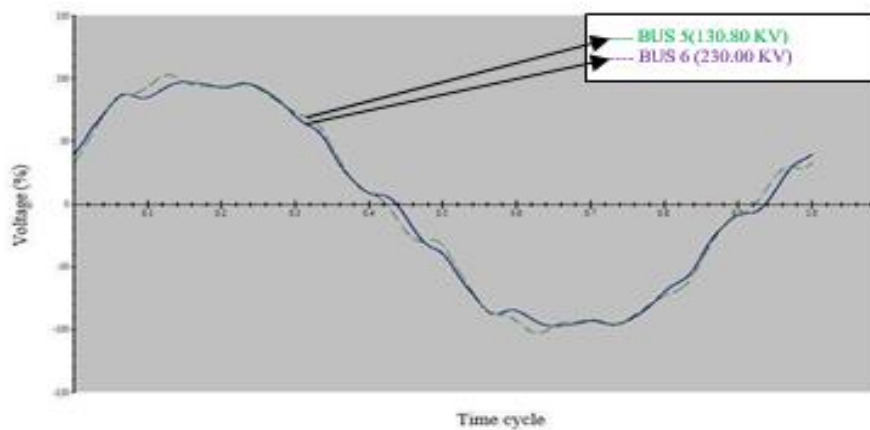


Fig. 5.5 Load Bus voltages vs. harmonics order with PV. Spectrum [DNI191]

TABLE 5.5
Output data VIHD report with PV [DNI191]

Bus ID	KV	% Found	% VIHD	Harmonics Order
Bus 5	230	99.35	5.18	11
Bus 6	230	100.7	6.48	11
Bus 9	230	102.85	5.65	5
Bus 12	230	100.7	6.08	5
Bus 3	230	102.5	3.74	5
Bus 11	230	99.35	5.23	5
Bus 6	230	100.7	4.15	5

5.5 Harmonic Mitigation Techniques Implementation

The data ETAP harmonics analysis on the IEEE with and without PV bus system indicates that without PV system generate 11th order harmonics. PV-connected IEEE systems generate 5th and 11th-order harmonics. Most of the cases connected are loads affected by the system harmonics to prevent the harmonics a mitigation technique must be required. In this Chapter, the author implements a Single-element Filter Mitigation Technique. Fig 6 shows the simulation diagram after

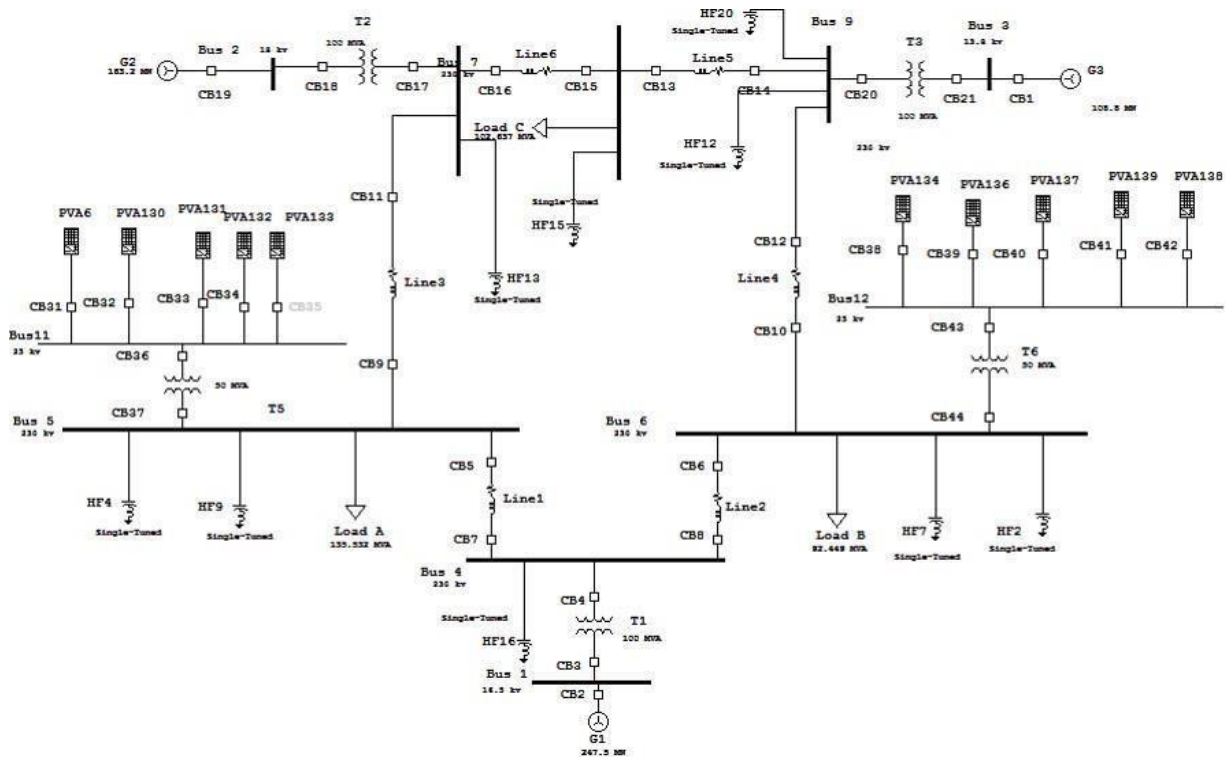


Fig.5. 6. IEEE-9 Bus system simulation with STPF [Single tuned Passive Filter]

TABLE 5.6
Filter design parameter for load buses with DNI191, two Irradiance values 191 and 641.

Bus No	Harmonics Order	Harmonics Current	1 Phase [KVAR]	V _C [KV]	X _L [ohm/phase]	I _L [Amp]
5	11	8.3	16086	331.339	26.17	74.24
6	11	7.4	12084	332.144	36.17	53.87
6	5	14.3	16804	351.466	125.92	77.92

We are implementing the STPF after the identification of the specific order of harmonics STPR was designed by specific parameters. Tables 5.6 and 5.7. Shows the design parameters for harmonic order.

TABLE 5.7
Filter design parameter for other Buses [bus No.4,7,8,9,] with DNI 191

Bus No	Harmonics Order	Harmonics Current	1 Phase [KVAR]	V _C [KV]	X _L [ohm/phase]	I _L [Amp]
4	5	18.3	16804	335.028	125.92	78.25
5	5	18.3	12064	361.702	175.05	57.72
7	5	13.8	16804	350.932	125.92	77.31
8	5	12.2	16804	350	125.92	77.24
9	5	13.6	16804	350.662	125.92	77.26

In this Chapter author analyzes After implementing STPF on buses 6 and 5, harmonics were observed on buses 4, 5, 7, 8, and 3. To reduce the overall harmonics counter, an STPF design was implemented.

Output Figure 7 and 8 show the final result after implementing the counter STPF for the tested system

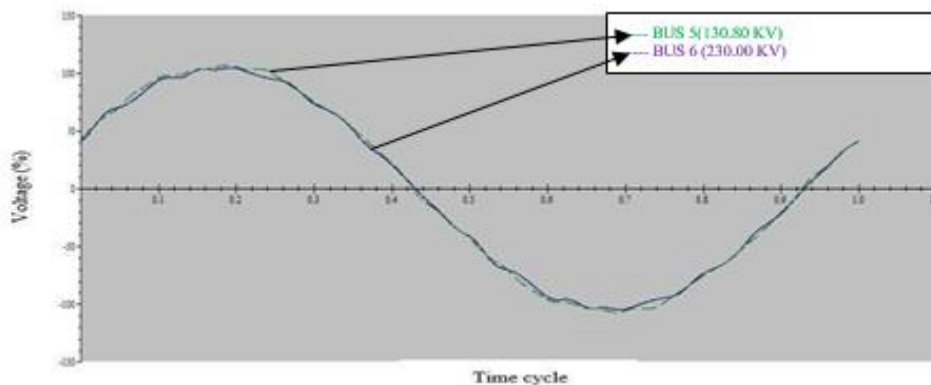


Fig. 5.7. All Bus voltages vs. harmonics order with PV. Spectrum

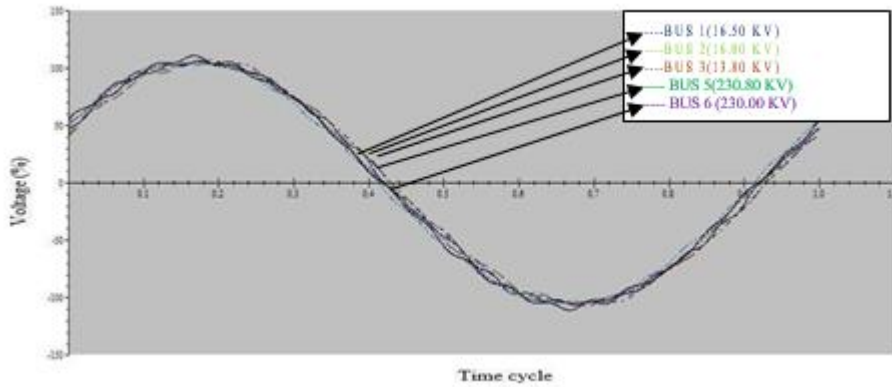


Fig. 5.8. Load Bus voltage vs. harmonics order with PV. Spectrum

TABLE 5.8
Filter design parameter for Load buses with PV [DNI 641]

Bus No	Harmonics Order	Harmonics Current	1 Phase [KVAR]	V _C [KV]	X _L [ohm/phase]	I _L [Amp]
5	11	5.2	12086	330	175.25	53.24
5	5	19.29	12068	362.702	175.25	58.04
6	11	5.4	16804	330	26.02	73.87
6	5	14.3	16804	351.466	125.92	77.92

Similarly, after implementing the passive filter on bus no 5,6 the harmonics will appear on other Buses 4,7,8,9 and which are not connected with a filter.

TABLE 5.9
Filter design parameter for other buses [bus no.4,7,8,9] with DNI 641

Bus No	Harmonics Order	Harmonics Current	1 Phase [KVAR]	V _C [KV]	X _L [ohm/phase]	I _L [Amp]
4	5	18.3	16804	335.028	125.92	78.25
7	5	13.8	16804	350.932	125.92	77.31
8	5	13.2	16804	350	125.92	77.24
9	5	13.3	16804	350.662	125.92	77.26

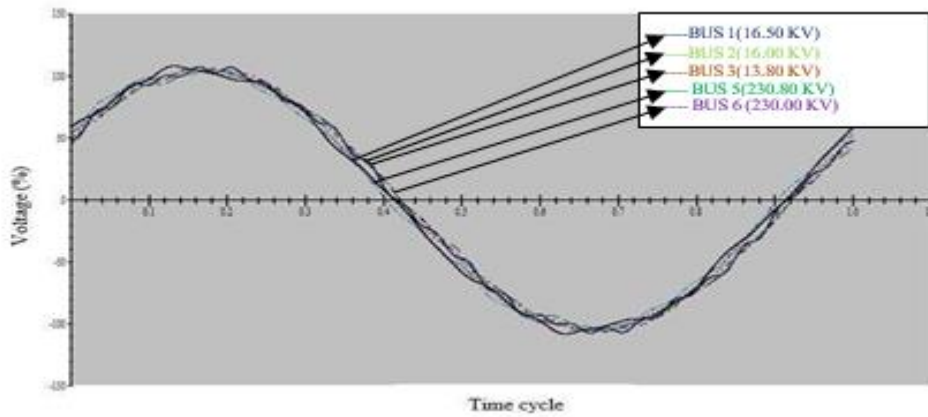


Fig. 5.9. Load Bus voltages vs. harmonics order with PV Waveform

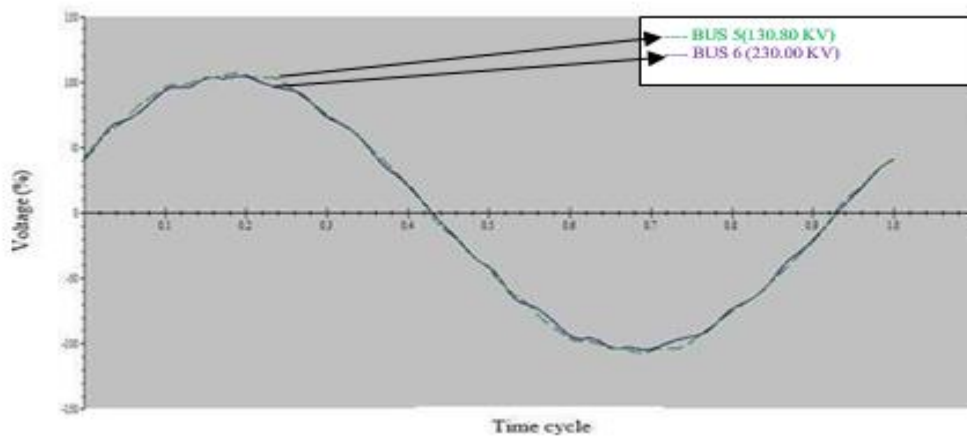


Fig. 5.10. Load Bus voltage vs. harmonics order with PV. Spectrum

5.6 Results and Discussion

Case studies 01 and 02 compare the harmonic characteristics of a with and without PV-connected IEEE-9 bussystem. In the first case study, the values of the VIHD and VTHD percentages in Table 5.1 are within the limit according to the IEEE519-199 standard limits of voltage distortion—observation of Case 2. PV-connected solar inverter injects different order harmonics into the system, which generates different VIHD and VTHD percentage values Table 5.4 According to the voltage distortion limit IEEE519-1992, the output results of the ETAP harmonic analysis also cross the maximum limits.

In this Chapter, the harmonic filter technique has to be implemented to maintain the system's power quality. Table 5.6 [16] [20] indicates the single-tuned passive filter parameter for DNI 191. Which is implemented to reduce the harmonics on bus numbers 05 and 06. after implementation, it is been observed that the 5th and 7th harmonics are generated on other Buses like 04,07,08,09. To achieve an ultimate harmonics-free system, the counter STPF Table 5.7 [16] [20] design is implemented on

the affected Buses, and the order of the harmonics each STPF has been designed. Comparing Figures 04 and 05 with 07 and 08 shows that the generated odd harmonic is reduced after the implementation of the counter, Single-tuned passive filters for each affected bus. The same methodology has been implemented for different DNI 641.

Tables 5.8 and 5.9 indicate input data for the filter, and Figures 09 and 10 indicate the output waveform of ETAP harmonic analysis. This technique generates promising results. In this Chapter, the author test the given IEEE system with different DNI values to identify whether this problem was generated from different irradiation values or not.

5.7 Conclusion

This Chapter deals with the IEEE bus system's power quality and harmonics mitigation techniques. The load flow analysis is organized to determine the different orders of harmonic levels of harmonic distortion using ETAP software. The output results of the ETAP simulation indicate that after the implementation of the STPF [Single tuned Passive Filter] on a specific bus, other buses are affected due to the presence of parallel resonance. To mitigate all order harmonics, a counter STPF [Single tuned Passive Filter] has been applied for those specific buses to maintain the power quality of the system. This Chapter shows the drawbacks of STPF [Single tuned Passive Filter] and describes how to overcome that problem using the counter filter implementation technique.

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Chapter:6
Summary, Discussion and Concluding Remarks

6.1 Summary

The primary objective of this thesis is to identify the impacts of renewable energy on existing networks. This identification aids in understanding the behavior of the current network when it receives power from non-conventional sources. In the future, this study can inform the development of strategies to address unknown power quality disturbance events (PQDE). The main challenge in the global power sector in the coming years will be to manage power quality, as the increasing percentage of renewable energy will alter the behavior of the connected grids.

In **Chapter 2**, the power factor of a PV-connected hybrid system varies with PV generation, with 20%, 30%, and 40% of PV generation being considered. Simulation results show that more PV generation decreases the power factor, and the magnitude of capacitor banks with respect to DNI is crucial for maintaining a constant bandwidth. This work addresses problems related to large-scale solar energy integration into conventional grids. A short circuit analysis is conducted to determine protective equipment ratings, and a single line diagram of an IEEE 9-bus PV connected system is considered. Simulations are performed using ETAP software, and the short circuit characteristics are analyzed at different buses at different fault conditions. The relay operating sequence with and without PV is identified, and steps are specified corresponding to faults occurring at different buses in the network. The simulation results show that a PV-connected bus has a low fault current rating, requiring a low C.T. ratio. The system generates non-stationary signals with multiple classes, creating power quality disturbance events (PQDE) similar to conventional source-based systems. Differentiating the actual cause of disturbance is a challenge, and specific identification methods are important for modern-day networks.

In **Chapter 3**, this contribution presents an automated, accurate, and robust framework based on ASLT and CNN for diagnosing single, double, and triple class PQDEs. The framework uses ASLT-based signal processing techniques to analyze PQDEs in T-F frames, providing better resolution and visibility even in low SNR environments. ASLT can distinguish different PQDEs in noisy environments, unlike conventional ST. A customized lightweight CNN architecture is designed to classify PQDE signal encoded T-F images, with a mean recognition accuracy of 99.52%. The proposed CNN model is fast and computationally efficient, making it effective for power distribution networks. However, the framework has limitations, including only considering 22 classes of PQDEs, limiting the number of real-life PQDEs to 5. Future research will investigate the performance of the proposed PQDE detection framework on triple classes and incorporate more real-life PQDEs. Advanced deep learning models, such as attention-based vision transformers, will also be implemented to further investigate the model's performance. The proposed CNN model will be hardware-implemented using Raspberry Pi or low-cost microcontroller modules for PQDE detection devices.

In **Chapter 4**, harmonic mitigation of different orders in a particular system by a single tune passive filter is quite challenging. A single-tune passive filter is not a suitable strategy for mitigating odd order harmonics

due to its high loss and cost. Similarly, using phase-shifting transformer for mitigation is another option, but it can only mitigate two odd orders at a time and leads to loss gain in the system.

The proposed hybrid mitigation technique with a single-tune passive filter and phase-shifting transformer can reduce power loss by up to 52% and achieve all odd order harmonics mitigation up to 85-95%. This system can improve the overall power quality of a Grid-connected PV system by overcoming limitations in specific phase-shifting angles and higher odd-order harmonics. The proposed hybrid harmonic mitigation system can significantly improve the overall power quality of a grid-connected PV system.

In **Chapter 5**, this study focuses on the IEEE bus system's power quality and harmonics reduction strategies. The load flow analysis is designed to identify the various orders of harmonic distortion levels using ETAP software. The ETAP simulation results show that after implementing the STPF [Single tuned Passive Filter] on a single bus, additional buses are impacted owing to parallel resonance. A counter STPF [Single tuned Passive Filter] has been deployed for those specific buses to attenuate all order harmonics and maintain the system's power quality. This Chapter demonstrates the disadvantages of STPF [Single tuned Passive Filter] and illustrates how to overcome them using the counter filter implementation approach.

6.2 Discussion and Concluding Remarks

The study analyzes the challenges and solutions of integrating large-scale photovoltaic systems into IEEE bus-based power networks using ETAP-based simulations. It reveals how increased PV penetration impacts system parameters like power factor, fault current ratings, and harmonic distortion.

Power Factor Sensitivity: PV integration leads to a declining power factor when a large amount of RE is injected, necessitating dynamic reactive power compensation using appropriately sized capacitor banks based on Direct Normal Irradiance (DNI). As it generates non-stationary signals like Time-varying Harmonics, Transient Disturbances, Voltage Flicker, and Interharmonics.

Protection Coordination: real coordination of PV-connected hybrid system change compared with without PV, also the backup protection relay sequence change. It also generates non-stationary signals like Voltage Sags/Swells, Current Transients, Harmonic Distortion, and Intermittent Fault Signatures.

Power Quality Disturbance Events (PQDEs): The system produces complex non-stationary signals with single and multiple overlapping classes. A novel detection framework using Adaptive Stockwell Transform (ASLT) and a custom lightweight CNN achieves high classification accuracy up to 99.52% compared with other methods of PQDEs, even under noisy conditions. This sets a foundation for real-time, low-cost PQDE monitoring using embedded systems.

Harmonic Mitigation: While single-tune passive filters (STPFs) are cost-effective, they struggle with higher-odd-order harmonics. A hybrid mitigation system combining STPFs and phase-shifting transformers

improves harmonic suppression efficiency by up to 95% and reduces system losses it also generates reliable outcomes.

Counter Filter Strategy: Using the single-tune passive filter in a particular bus in a network generates resonance effects and odd-order harmonics on other buses. The study proposes a counter-filter approach that ensures harmonic attenuation across all buses, preserving system-wide power quality.

6.3 The feasibility of implementation and the future scalability of the hybrid mitigation system.

The proposed hybrid harmonic mitigation system demonstrates strong feasibility for real-time deployment in grid-connected photovoltaic (PV) systems, owing to its utilization of industry-standard components, including the Single-Tuned Passive Filter (STPF) and Phase-Shifting Transformer (PST). These components are already widely used in distribution networks, ensuring ease of integration and cost-effectiveness. The system can be effectively tested on IEEE 9-bus and 14-bus networks and later scaled to field-level PV installations using simulation-based optimisation and hardware-in-loop methods.

Research evidence further supports the system's practicality. Study demonstrated that hybrid filters combining STPF and PST can reduce overall power losses by nearly 52% and mitigate dominant odd harmonics (5th–11th) by 85–95%, outperforming conventional filtering techniques. Similarly, it was shown that hybrid compensators using synchronous machines and switched capacitors offer reliable reactive power compensation in renewable-based grids.

The modular nature of the proposed system enhances scalability, allowing adaptation to varying renewable penetration levels and nonlinear load profiles. The integration of AI-based disturbance identification and adaptive tuning further strengthens this flexibility. The design is suitable for university microgrids, industrial feeders, PV-based hybrid systems, and can be expanded to large smart-grid architectures, aligning with findings in that highlight the benefits of AI-enabled hybrid mitigation frameworks.

6.4 Comparison with Existing Benchmark Techniques: Cost–Benefit Analysis and Scalability

The comparative evaluation of existing benchmark techniques shows that the proposed STPF–PST hybrid system offers the most balanced and industry-ready solution for harmonic mitigation in PV-integrated and industrial-scale networks. While passive filters (STPF) remain the lowest-cost option, their performance is limited to fixed-load conditions with moderate harmonic reduction (60–70%). Active Power Filters (APFs) deliver the highest harmonic suppression (90–95%) but come with significantly higher capital expenditure (₹9,000/kVA), high operational cost, and shorter system life.

Hybrid compensators using motors and capacitors provide better power loss reduction and reliability than standalone filters but still fall short in adaptability and payback efficiency. In contrast, the proposed STPF with PST hybrid demonstrates superior cost-effectiveness, offering high harmonic reduction (85–95%) and the highest power loss reduction ($\approx 52\%$) at a moderate capital cost (₹3,000/kVA). Its low annual O&M

cost, extended lifespan (12–15 years), and the shortest payback period (2.5–3 years) make it financially favourable for industrial applications.

The system's scalability and suitability for PV-integrated grids, MSMEs, and smart microgrids further enhance its industrial relevance, positioning it as a practical and future-ready alternative to conventional benchmark techniques.

6.5 Quantitative validation of the proposed hybrid mitigation system under various operating conditions

To establish the scientific rigour and reproducibility of the proposed hybrid harmonic mitigation system (STPF integrated with PST), an extensive quantitative validation was conducted across diverse operating conditions relevant to Indian grid-connected PV networks. The methodology combined analytical modelling, ETAP-based harmonic studies, Etap/Simulink dynamic simulations, and economic evaluation, ensuring a holistic assessment of technical, financial, and reliability parameters.

Validation Methodology

- I. **Simulation Environment:** The proposed system was modelled on the IEEE 9-bus and 14-bus test networks using ETAP's Harmonic Load Flow and Frequency Scan tools to examine harmonic propagation, resonance behaviour, and mitigation efficiency. The grid parameters were calibrated according to Indian industrial feeders (415 V, 50 Hz, short-circuit capacity \approx 250 MVA).
- II. **Operating Conditions Tested:** PV penetration levels are analysed at 10%, 30%, 50%, and 70% of system load, considering load variability, including balanced/unbalanced and nonlinear industrial loads. Disturbances such as capacitor bank switching, random PV generation ramps, and faults (single-line or three-phase) are examined. Network impedance variations ranging from 0.5 to 2.0 p.u. represent both weak and strong grid conditions.
- III. **Performance Metrics:** Key considerations include Electrical parameters such as Total Harmonic Distortion (THD) of voltage and current, harmonic order amplitudes (5th, 7th, 11th), the power factor, and K-factor of transformers. Economic factors address power-loss reduction, annual energy savings, capital expenditures, operational expenditures, payback periods, and net present value (NPV) over 10 years at an 8% discount rate. Reliability focuses on relay coordination checks, resonance avoidance, and system stability indices.

Chapter:7
Avenue of the Future Work

7.1 Future Works

To enhance power quality, the regular development of different techniques is the only solution. In this thesis, the impact of renewable energy on the existing power system has been identified in terms of power quality. The methods proposed in this thesis can be extended in the future in different directions, some of which are mentioned below

1. There are PQDEs with different classes of non-stationary signals analyzed by the deep learning method. In the future, a hardware setup for PQDE generation will be fabricated for the study of different types of non-stationary signals. Signals may contain multiple classes of those signals by the Deep learning method.
2. Non-linear loads are becoming increasingly important in industrial and commercial applications due to technological advancements. Hybrid power production systems have an impact on transformer efficiency and losses. Harmonics lead to excessive heat generation in distribution transformers, but they also add to capitalization expenses while running for an extended duration. This research estimates the K-factor to reduce harmonics in grid-connected PV systems and proposes a hybrid approach using a single-tune passive filter to obtain a lower-order K-factor with increased loads.
3. In a PV System, the Inverter is a major component that performs the conversion process. Due to this conversion, it contributes a large number of odd-order harmonics, which affect the power quality of the system. The cost and different types of inverter topology make it more difficult for the consumer to choose. It is being observed that the Static Inverter performance is also different for different environmental zones. In place of a static Inverter, a rotary inverter has been implemented with an advanced controller circuit. It can be a solution for harmonic generation in the static Inverter can also operate at any temperature without depending on the environment. Controlling the power output of the rotary inverter is so important because, without a proper control strategy, it is very difficult to achieve the desired amount of quality output from the system. So this method can be an alternative to the static inverter to overcome all drawbacks and change the scenario of DC to AC conversion.

Appendix

Comparison of Harmonics Mitigation Techniques for Grid-Connected PV System and Introduction of a Concept of Hybrid Filter

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Abstract—Nowadays, integrating photovoltaic (PV) generation into the conventional grid system has become a significant concern. As a consequence, the analysis of the impact of the PV system on the existing grid and the application of preventive methods to maintain the power quality of the system has joined paramount importance. In this paper, the authors have proposed a grid-connected PV ETAP Simulation Model to analyze the harmonics' effect on the system in the presence of nonlinear loads. After analyzing, it is observed that different odd-order harmonics are generated in the system which can have a negative impact on the system. To take care of these odd-order harmonics the authors compare two basic mitigation techniques; one being the Single Tune Passive Filter (STPF) mitigation which is not applicable for multiple harmonics order reduction with system power loss and the other being the Phase sifting transform mitigation. As compared to the passive filter method, the phase-shifting transformer bears the advantage of minimal power loss and voltage fluctuations. However, the phase-shifting transformer method is effective for multiple harmonic order reduction but not applicable for higher odd harmonics. To overcome this problem authors introduced a hybrid concept of mitigation which reduces power loss by up to 52% and mitigates harmonics up to 85–90%.

Keywords: DNI (Direct Normal Irradiation), Harmonics Mitigation, Power Quality, STPF Single Tuned Passive Filter, Phase Sifting Transformer

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INTRODUCTION

The global solar photovoltaic (PV) market has seen continuous growth since 2000, reaching 1177 GW in 2022. China and the United States lead the market with 307 and 122 GW of installed PV capacity, respectively. Chile and Honduras have the highest share of photovoltaic energy in total energy produced in 2022. This growth reflects a global shift towards renewable and sustainable energy technologies [1, 2].

This study highlights the significance of studying solar cells as they are the ideal partner for renewable and traditional energies in hybrid energy systems, which are widely used worldwide due to their reliability and stability in producing energy from individual systems like PV with Grid, PV with Wind, PV with Diesel, PV with CSP, PV with Wind and Diesel, and PV with Wind and Battery [3–12].

In today's power system scenario, reliability and quality are of paramount importance. Power quality deals with the measurement of the degree up to which the voltage, frequency, and waveform match with the required standards. A power system with good quality ensures a supply voltage staying within the specified

range having a frequency in proximity with the rated value and a smooth waveform of the voltage (a sine wave).

These parameters of a good quality power system suffer to a great extent due to the presence of harmonics. Mitigation of harmonics is a step of utmost importance toward improving the quality of the power system.

India's government is implementing renewable energy systems, particularly solar and wind, under the Jawaharlal Nehru National Solar Mission (JNNSM), aiming to deploy 97000 MW of grid-connected solar power by 2022 [13–17]. A hybrid renewable energy system (HRES) is a system that combines various types of renewable energy, such as wind, solar, biomass, etc. In this paper, the authors study a grid-connected PV system. Basically, there are three main types of PV systems used (a) Off-grid system, (b) Grid-tied system, and (c) Hybrid system. In a PV system, the inverter is one of the essential devices which convert DC to AC power. This inverter is the main source of harmonics generation during the conversion of power, it uses power electronics switching which generates a number of odd-order harmonics [18].



Deep learning aided power quality disturbance detection with improved time–frequency resolution employing adaptive superlet transform

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Abstract

Accurate identification of power quality disturbances is important for reliable operation of power system network as it may lead to unwanted and premature failure of power system components. Considering the above said fact, in this paper, a novel technique for detection and classification of power quality disturbance events (PQDE) is proposed employing adaptive superlet transform (ALST)-based time–frequency analysis and deep learning technique. ALST is a powerful signal processing tool for analysis of non-stationary signals in time–frequency frame. To this end, synthetic PQDEs were initially generated following IEEE std. 1159–2009. The generated 1D PQDEs were transformed to 2-D time–frequency RGB images using ASLT. The transformed time–frequency images of 1D PQDEs employing ALST showed enhanced resolution in time–frequency frame and showed distinct representations of different events even in the presence of very high noise level. The obtained PQDEs obtained using ASLT were finally fed as inputs to a designed lightweight customized convolutional neural network (CNN) architecture for automated feature extraction and classification. In addition, the performance of the proposed model was further evaluated using benchmark CNN models and also on real-life PQDE signals. It has been found that the proposed method returned 99.52% and 98.18% accuracies for classification of simulated PQDEs and real-life PQDEs, respectively. The performance of the proposed CNN aided ASLT is superior compared to other time–frequency representation methods and requires less computational time and memory compared to existing CNN models. Besides, the proposed framework is capable of diagnosis of power quality disturbance events in both noise-free and strong noisy environment.

Keywords Classification · Deep learning · Machine learning · Power quality · Signals and time–frequency analysis

Abbreviations

PQDE	Power quality disturbances
DG	Distributed generation
RE	Renewable energy
PV	Photovoltaic
CWT	Continuous wavelet transform
CNN	Convolutional neural network
T–F	Time–frequency

ST	Stockwell transform
SLT	Superlet transform
ASLT	Adaptive superlet transform
SNR	Signal-to-noise ratio
ACC	Accuracy
SPE	Specificity
SEN	Sensitivity
RNN	Recurrent neural networks
SVM	Support vector machines
DWT	Discrete wavelet transform
DFA	Detrended fluctuation analysis
RELU	Rectified linear unit
PL	Pooling layer
BN	Batch normalization
RAP	Rank base average pooling
GM	Geometric mean
TFR	Time frequency representation

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Analysis on Relay Coordination in IEEE 9 bus PV integrated Hybrid Power System using ETAP software: A case study

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Abstract. The modern power system of the country like India, there is an important need to design an uninterrupted electrical power system network having adequate security, stability and reliability. In this present paper an IEEE 9-Bus hybrid system is considered for a short circuit analysis and protection relaying coordination for designing of overcurrent relaying scheme to operate the relay efficiently and disconnect the fault section from healthy section instantly. It also compares the differences between existing systems with PV connected hybrid system. Now days, when Electrical Power System adopts the Renewable Energy source with existing power source of the network, the main challenge is to design a protection scheme to protect the hybrid system where different intermittent sources make a great impact. To design such a power system the behavior of the existing protection scheme need to be analyzed. In this paper authors simulate an IEEE 9-Bus system using ETAP simulation and analysis is made through Load Flow Study and Short Circuit Analysis. The study reveals that the behavior of the protection system changes with variation of the renewable energy sources integrated with in the bus system. Also set point of the protection relays varies with percentage sharing of the load by PV sources compared to the existing scheme. Observation of the behavior of existing protection system with PV connected hybrid system generates a road map to design an accurate protection scheme for hybrid system.

Keywords - ETAP; Photo voltaic generation; Direct Normal Irradiance (DNI); Short Circuit Analysis.

1. INTRODUCTION

In abnormal condition, it includes an electrical failure of power system equipment operating at one of the primary voltage within the system that causes a fault in a power system network. Under balanced load condition, when disturbed by a fault due to either flashover, insulation failure, physical damage or human error creates excessive high currents flow through the system that causes the system to operate in the abnormal state which is not desired. Classification of the short circuit faults in the system as: (i) symmetrical fault, (ii) asymmetrical fault. Symmetrical faults can be as follows; (i) the three phase are short-circuited to each other *i.e.*, L-L-L, (ii) the three phase are grounded *i.e.*, L-L-L-G. The three phases are equally affected and can be called balanced fault. But these faults occur irregularly. Whereas, Asymmetrical faults can be, (i) single phase to ground *i.e.*, L-G, (ii) double phase to ground *i.e.*, L-L-G, (iii) phase to phase faults *i.e.*, L-L, in which the single phase to ground fault occurs frequently [1, 2]. In the present work, a short circuit analysis is carried out to ensure the stability of the power system network and to confirm the safety of the general public also it will help to determine the ratings of protective equipment. Here, the minimum device rating is determined considering the maximum steady-state short circuit current and the relay coordination is analyzed based on the minimum steady-state short circuit value of the power system network. In this case the circuit breaker can safely isolate the faulty circuit but proper protection scheme with proper selection and settings of protective devices *i.e.*, fuse, circuit breaker and relays are needed [3]. In this paper, a single line diagram of IEEE 9-bus PV connected system based on actual data is considered and simulated in ETAP software for analysis purpose. The short circuit characteristic has been analyzed at different bus at different fault conditions using IEC standard in ETAP platform.

1.1. ABOUT ETAP

Electrical Transient Analyzer Program (ETAP) is the foremost integrated database for electrical systems having multiple representations of a power system for design, analysis, simulation, monitoring, control, and optimization and automation purpose. This software offers the most comprehensive and integrated suite of power system network that spans from modeling to operation. ETAP is the best Electrical Transient analysis software for performing rigorous analysis on electrical network. The objective of this paper to provide the basic understanding of the load flow studies and use of Electrical Transient Analyzer Program (ETAP) application software as a successful and accurate tool to conduct load flow study and short circuit analysis of complex electrical power systems within minimum time period [4, 5]. Short circuit current can be calculated using ETAP through the 'Short Circuit Analysis' module [6, 7, 8]. This module allows the C37 Series of the ANSI/IEEE standard calculation of fault duties and other modes of options and preferences within ETAP.

1.2 RELAY SETTING

The protective relay is used for detecting the fault current that send the trip signal to the circuit breaker. In every zone of the power system network a primary relay installed to protect the system. If the primary relay does not operate then the fault is cleared by backup relay. If the relay has quick response to identify the fault at suitable time and send the signal to the auxiliary devices then only it can implement relay coordination [10]. Therefore, a suitable relay setting is required for any particular network. The protective relay has two types of settings: (i) plug setting for deciding the time of relay operation, (ii) plug setting for deciding the current required to pick up for the relay [11]. After the main relay operation, an adequate time has to be given to operate the backup relay *i.e.*, relay coordination. In this paper, authors show the over current relay coordination of IEEE 9-bus system using ETAP's star view. The star view feature in ETAP presents relays with their associated characteristic curves, and circuit breaker with their actions and opening times.

A. **Overcurrent Relay Setting.** The actual current flowing in the relay expressed as a multiple of current setting *i.e.*, pickup current is known as the plug setting multiplier (PSM) [12]. To find the PSM, it is given by in equation 1 as follows:



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Study of Power Factor Correction Technique for a grid connected Hybrid System

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Abstract—In recent years injection of renewable energy in existing system is a new challenge for faster growing country like India. In hybrid generation fossil fuel based and renewable based source are involved. The effect of the renewable energy on every parameters of the system is very important to study for maintaining proper stability of the system. Direct Normal Irradiance (DNI) is one of the major parameter which regulates the solar generation. This frequent change of solar generation makes a great impact on the power factor of a hybrid system. To compensate the power factor with compensation device for a PV connected system must consider a relation between power factors with PV generation. In this paper author established a relation between Direct Normal Irradiance which regulate the PV generation with power factor of the system to make system more stable and economical. In this paper authors uses an ETAP simulation model to investigate the effect of the PV generation on power factor and correction technique.

Keywords—ETAP, Reactive power, Active power, Capacitor bank, Photovoltaic generation, Direct Normal Irradiance(DNI)

I. INTRODUCTION

In India, the core energy provider is conventional sources which are universal economy. Last 10 years the energy demand increasing exponentially which create an issue for power distributors in India. It is the only way to solve this problem is to introduce the renewable energy in the power sector as because most part of the country includes a high number of sunny days and daily irradiance PV (Photo voltaic) generation system can make a better option for the power compensation in India.^[1]

The leading aim of this work is to study the performance of the grid connected photo voltaic generation with respect to Direct Normal Irradiance (DNI). The analysis includes active power analysis, power factor by load flow technique at the grid side of the solar farm. In this paper authors implementing ETAP simulation model for suitable operation. The overview of photo voltaic generation was simulated in ETAP-12.6 as a single line diagram. The photo voltaic panel rating increases with 20%, 30% and 40% of the total load.^[2]

II. LOAD FLOW USING ELECTRICAL TRANSIENT ANALYZER PROGRAM (ETAP)

Load flow in ETAP software performs power flow analysis and voltage difference calculations with approximately correct and reliable results. Incorporated options like equipment analysis, alerts load flow result analyzer when a mismatch or

fault occur in the network and automatic and symbolic graphics which give a complete idea about the electrical system.

ETAP load flow calculation program calculates different parameter like bus voltage, branch power factors, line currents and power flows of overall electrical network. The features in ETAP for swing, both option for voltage regulated, and unregulated power sources with unlimited power grids and generator connections. This load flow tools is also capable of performing analysis on both radial and loop systems.

III. PHOTOVOLTAIC GENERATION SYSTEM

Sunlight to Direct Current (DC) electricity (*i.e.* light energy to electrical energy) converts using PV cells. Charge controller work as control the power from solar panel which reverses back to solar panel get cause of panel damage. When sunlight not available (*i.e.* night) then storage of electric power is used from battery system. To convert Direct Current into Alternating Current, from this system connected to an inverter^[3].

To make a solar module, the numbers of solar cells connected electrically with series and parallel combination and to make a solar array. To produce high amount of electric energy this configuration is required^[4].

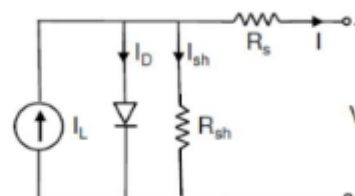


Fig.1: Equivalent circuit of solar cell

Fig.1 shows equivalent circuit of solar cell, where Current Source = I_{ph} , Shunt Resistance = R_{sh} and Series Resistance = R_s . The value series resistance (R_s) is less than the value of shunt resistance (R_{sh}), so we can neglected for simplification. Boltzmann constant = K , Diode ideality factor = N and cell temperature = T . Load current equation is shown below^[5]

$$[e \text{ ————— } 1] - \text{—————}$$



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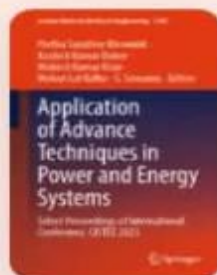
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