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ISTANBUL AYDIN UNIVERSITY

INSTITUTE OF GRADUATE STUDIES

NEW METHODS FOR POWER QUALITY CONTROL IN HYBRID ELECTRICAL ENERGY SYSTEMS

DOCTORATE'S THESIS

Harun Fecri ASLAN

Department of Electrical and Electronics Engineering

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JUNE, 2025

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THESIS EXAM REPORT

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DECLARATION

I hereby declare with respect that the study “New Methods For Power Quality Control in Hybrid Electrical Energy Systems ”, which I submitted as a PhD thesis, is written without any assistance in violation of scientific ethics and traditions in all the processes from the Project phase to the conclusion of the thesis and that the works I have benefited are from those shown in the References. (11/06/2025)

Harun Fecri ASLAN

FOREWORD

I would like to take this opportunity to thank my thesis supervisor Prof. Dr. Murtaza Farsadi for giving me the opportunity to pursue my PhD studies under his guidance at Istanbul Aydın University (IAU). I am extremely grateful to him for his invaluable guidance, great support and expertise during my PhD journey.

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June, 2025 Harun Fecri ASLAN

NEW METHODS FOR POWER QUALITY CONTROL IN HYBRID ELECTRICAL ENERGY SYSTEMS

ABSTRACT

The increasing integration of renewable energy sources into power grids has led to significant challenges in maintaining power quality, particularly in hybrid electrical energy systems. These systems which combine conventional and renewable energy sources, often suffer from voltage fluctuations, harmonics and frequency instability due to the intermittent nature of renewables. This thesis presents novel control strategies to enhance power quality in hybrid electrical energy systems by mitigating these issues effectively.

The research focuses on developing and implementing advanced control algorithms in MATLAB/Simulink to improve voltage and frequency regulation, reduce harmonics and optimize power flow within hybrid systems. The proposed methods include a combination of adaptive filtering, UPQC, D-STATCOM, PWM and optimization techniques. These approaches ensure real-time dynamic compensation and enhanced system stability under varying load and generation conditions.

Simulation results demonstrate that the developed control strategies significantly improve power quality compared to traditional methods. The application of these controllers reduces total harmonic distortion, minimizes voltage sags and swells and enhances reactive power compensation which is leading to a more stable and efficient hybrid energy system. The results confirm that the proposed methods outperform conventional techniques in terms of response time, robustness and efficiency.

This research contributes to the field by providing a systematic approach to power quality enhancement in hybrid energy systems. The developed control frameworks can be applied to real-world hybrid grids, improving their operational efficiency and sustainability. The findings of this study offer a significant

advancement in power system engineering, ensuring stable and high-quality power delivery in modern energy networks.

Keywords: Power Quality, Hybrid Electrical Systems, Photovoltaic, Wind Power, Control Systems

HİBRİT ENERJİ SİSTEMLERİNDE GÜÇ KALİTE KONTROLÜ İÇİN YENİ METODLAR

ÖZET

Yenilenebilir enerji kaynaklarının elektrik şebekelerine entegrasyonunun artması, özellikle hibrit elektrik enerji sistemlerinde güç kalitesinin korunmasında önemli zorluklar yaratmaktadır. Geleneksel ve yenilenebilir enerji kaynaklarını birleştiren bu sistemler, yenilenebilir enerji kaynaklarının değişken yapısı nedeniyle genellikle gerilim dalgalanmaları, harmonikler ve frekans duzensizligi gibi sorunlarla karşılaşmaktadır. Bu tez, hibrit elektrik enerji sistemlerinde güç kalitesini artırmak için yenilikçi kontrol stratejileri sunarak bu sorunları etkili bir şekilde gidermektedir.

Bu çalışma, MATLAB/Simulink ortamında gelişmiş kontrol algoritmalarının geliştirilmesi ve uygulanmasına odaklanmaktadır. Amaç gerilim ve frekans düzenlemesini iyileştirmek, harmonikleri azaltmak ve hibrit sistemlerde güç akışını optimize etmektir. Önerilen yöntemler; adaptif filtreleme, UPQC, D-STATCOM, PWM ve optimizasyon tekniklerinin bir kombinasyonunu içermektedir. Bu yaklaşımlar, değişken yük ve üretim koşulları altında gerçek zamanlı dinamik dengeleme ve sistem kararlılığının artırılmasını sağlamaktadır.

Simülasyon sonuçları, geliştirilen kontrol stratejilerinin geleneksel yöntemlere kıyasla güç kalitesini önemli ölçüde iyileştirdiğini göstermektedir. Uygulanan kontrolörler, toplam harmonik bozulmaları azaltmakta, gerilim dalgalanmalarını en aza indirmekte ve reaktif güç kompanzasyonunu artırarak daha stabil ve verimli bir hibrit enerji sistemi sağlamaktadır. Sonuçlar, önerilen yöntemlerin tepki süresi, dayanıklılık ve verimlilik açısından geleneksel tekniklerden daha üstün olduğunu doğrulamaktadır.

Bu araştırma, hibrit enerji sistemlerinde güç kalitesini artırmaya yönelik sistematik bir yaklaşım sunarak alana önemli bir katkı sağlamaktadır. Geliştirilen kontrol çerçeveleri, gerçek dünyadaki hibrit şebekelere uygulanabilir ve işletme verimliliğini ve sürdürülebilirliğini artırabilir. Bu çalışmanın bulguları, modern enerji

ağlarında istikrarlı ve yüksek kaliteli güç iletimini güvence altına alarak güç sistemleri mühendisliğinde önemli bir ilerleme sunmaktadır.

Keywords: Güç Kalitesi, Hibrit Elektrik Sistemleri, Fotovoltaik, Rüzgar Enerjisi, Kontrol Sistemleri

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%	**:** Percentage
C_p	:Power Coefficient
I_{Ac}	:AC Current (V)
I_{dc}	:DC Current (A)
I_{mp}	**:**Maximum Power Point Current (A)
I_{peak}	:Peak Current (A)
I_{rms}	:Root Mean Square Current (A)
I_{sc}	:Short-Circuit Current (A)
I_{thd}	**:**Current Total Harmonic Distortion (%)
K_d	**:** Derivative Gain
K_i	**:** Integral Gain
K_p	**:** Proportional Gain
P_{pv}	:PV Output Power (W)
P_{ref}	**:** Active Power Reference
P_{wind}	:Wind Power Output (W)
Q_{ref}	**:** Reactive Power Reference
$R_{turbine}$	**:**Turbine Blade Radius (m**)**
V_{ac}	:AC Voltage (V)
V_{dc}	:DC Voltage (V)
V_{mp}	:Maximum Power Point Voltage (V)
V_{oc}	:Open-Circuit Voltage (V)

V_{peak} :Peak Voltage (V)

V_{rms} :Root Mean Square Voltage (V)

V_{thd} **:**Voltage Total Harmonic Distortion (%)

f_s :Switching Frequency (Hz)

$i_d, i_q, v_d,, v_q$ **:**Current and Voltage in d-q reference frame

v_f **:** Voltage Frequency Control

λ_{tip} :Tip Speed Ratio

^{0} **:** Degree

^{0}**C** **:** Celsius

AC : Alternating Current

AI : Artificial Intelligence

ANN : Artificial Neural Network

APF : Active Power Filter

BESS : Battery Energy Storage System

BMS : Battery Management System

CAES : Compressed Air Energy Storage

D :Duty Cycle (%)

DC : Direct Current

DFT : Discrete Fourier Transform

dI/dt :Rate of Change of Current (A/s)

DSP : Digital Signal Processors

D-STATCOM: Distribution Static Synchronous Compensator

DVR : Dynamic Voltage Restorer

E :Energy (J)

EMI : Electromagnetic Interference

ESS : Energy Storage Systems

EV : Electric Vehicles

FACTS : Flexible AC Transmission Systems

FFT : Fast Fourier Transform

FIT : Feed-in Tariffs

FLC : Fuzzy Logic Control

G **:**Solar Irradiance (W/m²)

H *:*Harmonic Order

HAPF : Hybrid Active Power Filter

HES : Hybrid Electrical Systems

I :Current

IEC : International Electrotechnical Commission

IEEE : Institute of Electrical and Electronics Engineers

IGBT : Insulated-Gate Bipolar Transistors

LCL :Inductor-Capacitor-Inductor

ML : Machine Learning

MPC : Model Predictive Control

MPPT : Maximum Power Point Tracking

MRAC : Model Reference Adaptive Control

NIST : National Institute of Standards and Technology

PCC : Point of Common Coupling

PCS : Power Conversion System

PHF : Passive Harmonic Filters

PI : Proportional-Integral

PID : Proportional-Integral-Derivative

PLL : Phase-Locked Loop

PPC : Power Plant Controller

PQ	:Power Quality
PV	: Photovoltaic
PWM	: Pulse Width Modulation
RES	: Renewable Energy Sources
S	: Apparent Power (VA)
SCADA	: Supervisory Control and Data Acquisition
SMC	: Sliding Mode Control
SVC	: Static Var Compensators
T	:Temperature (°C)
THD	: Total Harmonic Distortion
UPQC	: Unified Power Quality Conditioner
UPS	: Uninterruptable Power Supplies
VCO	: Voltage Controlled Oscillator
VSC	: Voltage Source Converters
η	:Efficiency (%)
λ	:Wavelength (m)
ρ	:Air Density (kg/m^3)
Ω	: Ohm
P	: Active Power(W)
PQ	: Active and Reactive Power
Q	: Reactive Power(VAR)
V	: System Voltage
dV/dt	:Rate of Change of Voltage (V/s)
f	: Frequency

I. INTRODUCTION

A. Definition of Power Quality

Power quality is defined as a set of electrical features and attributes that pertain to the quality, stability, efficiency, and dependability of electrical power supply systems. This is with regard to waveform of voltage and current supplied to electrical devices and systems. High power quality means that the electrical power is made available in definite voltage and frequency values with little fluctuations or deviations (H. Wang et al., 2021).

Power quality is known to have several important factors that dictate it. Voltage stability is a condition in which voltage is held constant to acceptable levels and there are prevented sudden changes in voltage that can upset the performance of electrical equipment. Fluctuations or lack of stability in the supply frequency may cause the failure of important equipment which rely on electric supply. Non-sinusoidal current distortions, called harmonics, need to be controlled to reduce their impact on the power systems and prevent overheating and inefficiency. Power quality is one of the significant factors in hybrid energy systems, which connect renewable energy sources to conventional power grid (Mohanty et al., 2024). These systems experience fluctuation and volatility in the available power supply, therefore calls for power quality management in order to allow full compatibility and utilization. Low power quality is inconvenience as it causes equipment malfunctions, decreased efficiency and increased costs.

Power quality can be classified as Short-term, Mid-term and Long-term power variations. While short term variations is considered waveforms of seconds or milliseconds in the electrical systems, Mid-term variations is usually scale of minutes to hours. However, long term power variations may take hours or days or even weeks to months (Zhang and Yan, 2020).

Power quality refers to the features of voltage and current signals, which guarantee efficiency, stability and controllability of power systems. Generally, it is essential to keep high power quality at the grid to support modern electrical power systems, especially for systems with integrated hybrid energy sources and storage systems.

B. Importance of Power Quality in Hybrid Energy Systems

Power quality plays a crucial role in hybrid energy systems, which are particularly sensitive to fluctuations and disturbances. The efficiency, reliability, and longevity of these systems depend heavily on the consistency and stability of the electrical power supplied. Power quality will deliver a stabale results for hybrid systems. (Deepak et al., 2024). Maintenance of high-power quality in Hybrid Energy Systems having renewable energy sources such as Solar, Wind, battery storage etc. along with conventional synergetic power sources guarantees good interfacing and efficiency.

It is important here to note that power quality involves several parameters, one of which is voltage stability. The integration of renewable sources may pose challenges since such systems are always likely to fluctuate at some point of time. Fluctuations in voltage supply are not favourable because they contribute to energy wastage and can cause damage on most appliances that require a constant and steady supply of power (Bravo-Rodríguez et al., 2020).

The risks associated with these fluctuations are mitigated when the voltage levels are kept constant in order to improve system reliability. Another important factor is the harmonic distortion, which is caused by the nonlinear loading and switching operations in the power converters. If the harmonic distortion is extremely high, then the efficiency with which energy is converted and distributed would decline, making the overall operational costs high and the life of the elements in the system short. One of the major challenges of operating hybrid energy systems is harmonic distortion; proper management of which is crucial for the envisioned functioning. Frequency stability is equally as important, especially given the need to interface renewable resources with more traditional power networks (Zhou et al., 2022). Variations of frequency can cause desynchronization of the system and lead to operational problems, power0sensitive applications and failures where it is used (Veeranjaneyulu, et al., 2024).

In summary, high-power quality in HESs is significant in determining the energy system's capabilities in terms of efficiency, stability, and longevity. It facilitates the coordination and connectivity of various power systems, provides necessary risk mitigation, and empowers the robustness of the energy systems.

C. Overview of Traditional Power Quality Control Methods

Conventional power quality control strategies used in the HESs have always been primitive in maintaining the stability of power supply. These methods mainly rely on employing standard techniques and equipment to control and correct adverse power quality qualities such as voltage dips, harmonics, and frequency fluctuations (Bousnoubra et al., 2024). The most common compensation technique is the shunt compensation by using the capacitive and inductive elements which helps to regulate the voltage magnitudes. Further to this, the synchronous condensers, which are actually synchronous motors without mechanical workload, are used to supply the reactive power and for voltage regulation.

Another conventional method is the usage of Uninterruptable Power Supplies (UPS) and Dynamic Voltage Restorers (DVR). UPS systems provide power back- up and voltage regulation for a short period of time when such disturbances occur. DVR on the other hand counters voltage sags by putting in the ideal voltage to ensure the load voltage remains stable.

In addition, passive and active harmonic filters is employed to suppress the effect of harmonic distortions. Low pass and bandpass passive filters are made of inductors, capacitors, and resistors that are adjusted to specific frequencies, which are suppressed in the system. They are adaptive to harmonic content in the system; they offer a higher degree of harmonic suppression with fast changing harmonics. However, these conventional strategies may prove costly in terms of infrastructure and maintenance costs (Qasim et al., 2024). This makes the integration of new techniques in hybrid energy systems important as the control problem becomes more complex and, in the future, will most likely be solved by state-of-the-art techniques such as machine learning and AI-based adaptive control systems.

D. Objectives of New Control Methods for Power Quality

As for objectives of new control methods for power quality in Hybrid Electrical Systems (HES) in the years 2020–present, they are such: improvement of efficiency, reliability, as well as sustainability. Key goals include:

- **Optimization of Energy Management**: Introducing superior level models like Model Predictive Control (MPC) and Reinforcment Learning to perform dynamic power distribution and achieving optimum energy sharing between sources while minimizing power loss.
- **Integration of Renewable Sources**: Enabling the incorporation of renewable power sources such as solar, wind and BESS utilizing pertinent control approaches (Nkambule et al., 2024). These are Maximum Power Point Tracking (MPPT) and ANN for real time tuning of variable power feed.
- **Enhanced Stability and Reliability**: Applying Situations control methods such as Fuzzy Logic Control (FLC) and Sliding Mode Control (SMC) to ensure control stability and system reliability in response to varying energy demand and generation.
- **Harmonic Mitigation and Voltage Regulation**: Using various technologies consisting Active Power Filters (APF) and Dynamic Voltage Restorers (DVR) including the management of harmonics and voltage control for power quality to maintain constant operation.
- **Predictive Maintenance and Fault Detection**: Applying AI and machine learning solutions for prognosis and early signs of faults in systems used for hybrid energy storage and decreasing the time of system stops in the long run.
- **Adaptive Load Management**: Exploring the use of AI techniques to implement intelligent load management that can adapt loads based on data received from the smart grid to enhance general system effectiveness.

They elucidate the developments in control methods targeting enhanced performance, reliability, and integration of hybrid electrical systems in the current energy sector.

II. BACKGROUND

The hybrid electrical systems are a great step forward in the field of electrical engineering that will change the way energy is produced, stored and used. These integrated systems come with various energy sources such as solar, wind, hydro, and conventional fossil fuel sources as well as storage technologies, such as batteries, and supercapacitors to obtain a more robust, efficient, and dependable energy grid (Chawda et al., 2020). It should come as no surprise that the idea of hybrid power systems has gathered momentum in the recent past, being that clean energy solutions are gaining popularity, climate change mitigation is becoming a major problem and limitations of traditional power generation systems are being realized.

The history of hybrid energy systems can be traced back to the early days of renewable energy integration and the hybridization of power sources. The different energy sources tap out the potential of scientists and technology experts. This happens; however, not as the ultimate ends but to complement the deficient flow of renewable sources which are solar and wind (Pinsky et al., 2020). It is clear that the first application of a hybrid energy system, which simply meant combining the renewable sources with the conventional ones so as to avoid discontinuous power supply is in the off-grid systems or the remote ones. Nonetheless, with the emergence of renewable energy technologies and energy storage systems, the capacity and abilities of hybrid energy systems have increased a lot.

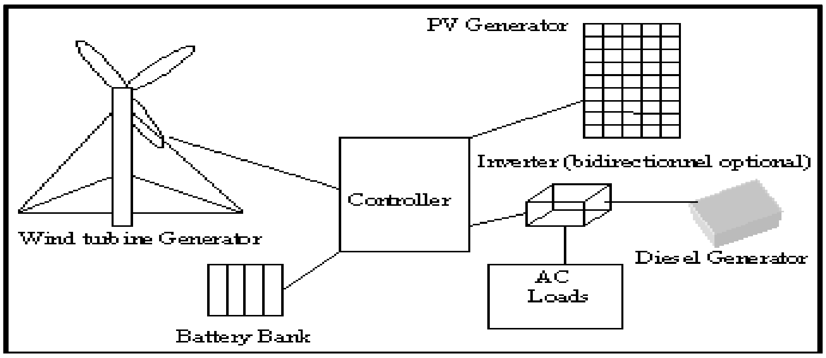

Figure1 Schematic diagram of the hybrid energy system

(Source: researchgate.net, 2024)

The integration of renewable energy sources as demonstrated in Figure 1 has main issues that the hybrid energy systems created to the grid that needs to be addressed. The producing of solar and wind energy, although abundant and pollution free, is intrinsically intermittent and they are depend on factors such as weather conditions and time of day. Such insufficiency is the reason why grid is unstable which means that solution should be found in order to keep supply of the power steady. A hybrid energy system is a viable mechanism to the challenge through combining multiple energies and utilizing electro-static units configured to enable real time balancing of supply and demand (Olabi et al., 2020). The increasing realization of the necessity of decarbonization and sustainability has resulted in the popularization of hybrid energy systems which is a way to lessen greenhouse gas emissions and dependence on fossil fuels. The integrated systems consisting of renewable power sources, batteries for storage and smart management systems can be brought into use to improve the efficiency of the clean energy utilization as well as lessening the existing environmental problems. This ties up with the global theme of a low carbon economy which mean the creation of an environment-friendly economy and adverse effects of climate change are to be mitigated (Jako et al., 2014).

A. Hybrid Energy Systems Overview

Hybrid energy system is employing two or more power sources for efficiency and reliability with electricity as the main source of power. Mostly, it is the combination of renewables, which include solar and wind energy, with traditional sources that comprise diesel generators, grid or storage systems (Alkahtani et al., 2020). An overview of Hybrid Energy System (HES) is demonstrated in Figure 2 that is combine of above energy types. In recent years batteries start involving in many hybrid systems to offer better power performance (Lata-García and Astudillo, 2022). These systems are based on energy generation optimization factors such as weather conditions, demand fluctuations, and fuel availability to get the best results.

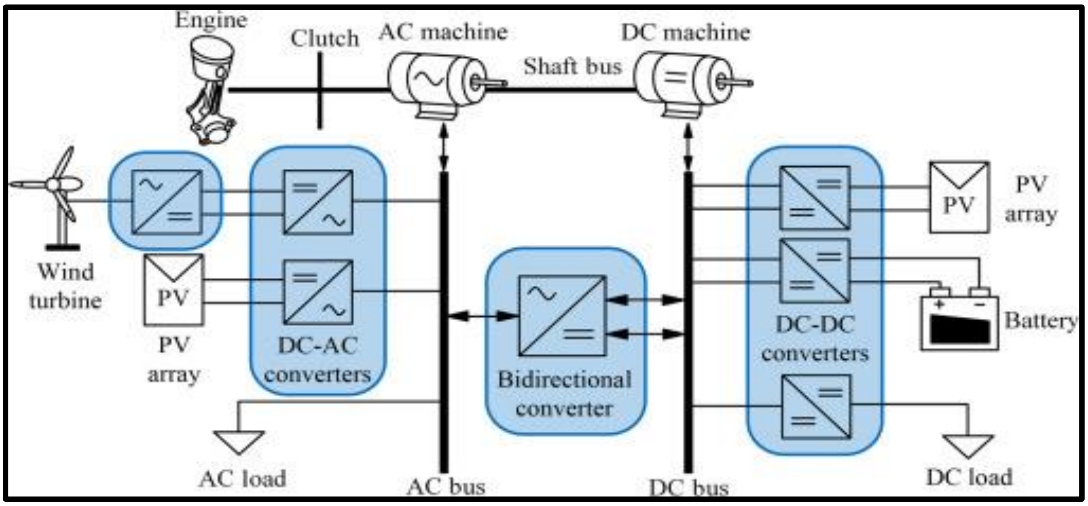

Figure 2 Overview of Hybrid Energy System

(Source: sciencedirect.com, 2024)

Diverse energy sources not only build reliability but also resilience, reduce costs and damage to the environment and produce clean energy. Hybrid energy systems are widely used in remote areas, off-grid locations, and industries that require a continuous power supply, for example telecommunications and mining that may need to have a microgrid system (Jiao and Mansson, 2020).

1. Main Components of Power Quality

Various energy sources are being used in the systems due to their adoption of functionalities that meet different needs. These roles are done in a combined manner, and different elements integrate to ensure atonement and general high performance. In this study, the main parts and the way they are incorporated into the hybrid energy systems will be discussed.

a. Energy sources

The fundamental attributes of the power system that incorporates a mix of renewable energy with conventional energy sources are the diverse sources of renewable energy that also include the conventional energy sources such as diesel generators and grid electric (Xu et al., 2024). Each energy source is an integral component of the entire system, and collectively make the system more robust and sustainable.

b. Energy conversion devices

Energy conversion devices are the crucial parts of the system which convert energy from various sources into usable forms. Correctly choosing the devices such as inverters, converters and controllers depend on the supplies of energy and the device itself. Such measure will make possible to establish the path in various types of responses and types of energy.

c. Energy storage systems

In hybrid power systems, energy storage components are used extensively to tackle the issue of variability of renewable sources that occur in the system. These systems are aimed at keeping the excess energy generated during times of low demand or high production and releasing it when needed, so that the power supply is always on. The main energy storage media that are used in wind and solar energy systems are batteries (Chamandoust et al., 2020). They produce electricity from chemical fuel that is stored and discharged only when there is excess electricity demand. Lithium-ion batteries are usually the choice because of their high energy density and efficiency. The other technological means used is flywheels which store kinetic energy in a rotor spinning. The energy from the rotor goes back into the circuit when required and is converted back into electricity. Flywheel systems are very fast to respond and are good for applications that need to charge and discharge frequently.

Integration of energy storage systems enhances the reliability and stability of hybrid energy systems because they can reserve power when renewable energy production is on the low side or when grid outages occur. On top of this, they help with grid balancing through better dealing with the supply and demand variations, managers.

d. Power management and control systems

Integration and control systems, which are the “brain” of hybrid energy infrastructures, provide decision making for any components that contribute to the improvement of operation and efficiency by controlling operations. Via cutting-edge algorithms and sophisticated control techniques these systems precisely run a live show by appropriately combining energy generation, storage, and distribution while taking into account weather conditions, demand patterns and trends market dynamics. In other words, these systems are a combination of sensors that are used to get real-time data about energy production, consumption, and environmental parameters. Such data is put through exotic algorithms in order to properly determine the right system parameters for power distribution, charging/discharging rates, and operational modalities. Through this approach, these variables get adjusted continuously (Ren et al., 2022). Therefore, the resulting system ensures the highest efficiency, reliability, and resilience in conditions that change with time. In addition, these systems usually combine predictive modelling and machine learning algorithms to anticipate future energy demands and allocate resources in advance.

The predictive nature, in essence, enables the anticipation of developing problems and taps on new opportunities to boost the system's overall resilience and hence the performance. To put it all in a nutshell, power management and control systems are undoubtedly the most crucial elements within hybrid energy systems as they are instrumental in maintaining the delicate balance of disparate components and delivering the unmatched performance, efficiency and reliability that lies within the very operations.

e. Auxiliary components

Moreover, in addition to the basic elements listed above, hybrid energy systems may include various auxiliary components to improve the operation and safety of the system. These may also comprise of monitoring and diagnostic systems and protective devices like circuit breakers and surge suppressors and communication interfaces for remote monitoring and control.

Integration of those components of a hybrid energy system is something which requires engineering and design carefully to ensure compatibility, steadiness, and effectiveness. The interdisciplinary collaboration of experts in electrical engineering, renewable energy, control systems and energy economics is usually required to solve the technical challenges that come with integration and optimization (Gilvaei et al., 2020). Moreover, research and development efforts are advancing in terms of increasing system efficiency, flexibility, and adaptability with the changing energy needs of current energy systems. Hybrid energy systems have the opportunity to take a prominent position in the shift towards renewable and secure energy future. This will be possible if improved technology and novel design approaches are employed.

2. Power Generation and Storage Technologies

In the context of hybrid energy systems there is a quite wide range of power generation and the storage ones that are used. Sustainable and reliable sources use of the variety of energy sources, which is the function of these systems, greatly contribute to the solutions of energy-related problems in modern energy infrastructure. The renewable sources such as solar and wind to the conventional fuels as natural gas and diesel, hybrid energy systems combine various resources to generate the optimal power. Because of that, solar photovoltaic (PV) panels appear a usual element of many hybrid power plants, changing sun light into electricity. For these kinds of systems, semiconductors are used for capturing the photons and generating an electron flow that turns into the electric current. Besides, energy storage options like lithium-ion batteries or flow batteries, solar PV arrays facilitate the continuous power supply even when the sun is not visible, thus ensuring the reliability of energy delivery.

Likewise, wind turbines are a critical part of a hybrid energy system as the fast-moving wind is converted into kinetic energy which makes the blades rotate and thus the generator rotates to produce electricity. To realize the potential of wind energy, need to develop effective energy storage methods that can compensate the fluctuations in supply and demand (Ho et al., 2021). The technologies like pumped hydro storage or compressed air energy storage are the viable options for storing the excess wind energy during the high generation periods for later use. Thus, they enhance the system reliability and grid stability. Using conventional generation methods like natural gas or diesel fueled internal combustion engines is another way to achieve this goal. These generators can provide an additional generation capacity required for meeting different demand levels and can serve as reserve sources during periods of low renewable availability. The advanced control systems are responsible for the coordination of the operation of different generation assets in hybrid systems, thus, the fuel consumption is being optimized and the environmental impacts are reduced.

Hydropower, another significant element of the hybrid energy system, is a technology involving the conversion of the gravitational potential energy of water to generate electricity. Large dams are inevitably put in the picture as well as small-scale run-of-river systems for renewable energy portfolios with reliable base-load power.

3. Standards and Regulations for power quality

The provision of high-quality power delivery is an essential key aspect for the smooth and efficient function of hybrid energy systems. The standards and regulations do have the biggest role in putting out guidelines and requisites for power quality, including voltage regulation, frequency stability, harmonic mitigation and compatibility of the grid (Kavadias and Triantafyllou, 2021). In this in-depth study, the attention will be on the standards and the regulations that deal with power quality in the hybrid energy systems, emphasizing their importance, implementation difficulties, and the consequences for the system design and the operation.

a. Voltage regulation and stability

Voltage regulation criteria cover the tolerance bands for variations of voltage from nominal ones, that complies with electrical equipment and appliances. Dynamic fluctuations in voltage might occur in the hybrid power systems because of changes in the renewable energy generation rates, load fluctuations or grid disturbances. The standards like IEEE 1547 and IEC 61727 specify the voltage regulation requirements for the grid-tied renewable energy systems, including the limits of voltage deviations and response times. There is a need to follow up these regulations by virtue of the implementation of voltage control mechanisms, which include, grid-tied inverters with voltage regulation and voltage support by energy storage systems (Gabbar et al., 2020). Leads to the dynamical response to changing operation conditions, and the coordination of multi-voltage control devices as well as grid disturbances.

b. Frequency regulation and synchronization

The frequency regulation standards are the ones that control the stability and synchronization of AC power systems, making them produce the same frequency within the specified limits. Hybrid energy systems require frequency control given the importance of grid stability and harmony with connected power networks. As specified by standards like IEEE 1547 and IEC 61000-3-6, requirements for frequency response are given together with frequency deviation limits and frequency synchronization protocols (Hu et al., 2023). Implementation of these standards requires grid-tied inverters with frequency control capabilities, synchronized operation of renewable energy sources, and coordination with grid frequency regulation mechanisms. Issues with frequency regulation include quick response to a load change, frequency droop control for an islanding operation and cooperation of distributed energy resources to compensate frequency.

c. Harmonics and interharmonics mitigation

Harmonics, interharmonics are unwanted distortions of AC power waveforms which arise due to significant nonlinear loads, power electronics and switching. Harmonics can reduce power quality, make equipment malfunction, and disturb communication and control systems and alter the system impedance (Francois and Johan, 2022). The IEEE 519 and IEC 61000-2-2 standards specify the limits on the harmonic's distortion levels and the techniques of mitigation for generating harmonics emissions. These standards can only be satisfactorily achieved by the use of harmonic filters, active power filters, and other power conditioning devices which are used for suppressing harmonic currents, and voltage (Teixeira *et al.,* 2021). The challenges in the harmonics mitigation process are the identification of the sources of the harmonics, the selection of the appropriate mitigation measures, and the compatibility of the system components and control algorithms.

d. Grid interconnection and grid codes compliance

Grid interconnection standards and grid codes provide the technical specifications, which renewable projects should comply with while being connected to the grid, providing the backbone of the power system. Grid codes are the requirements for voltage and frequency regulation, active and reactive power control, fault ride-through capability, and anti-islanding protection. The grid codes compliance is key to grid-connected hybrid energy systems to remain stable on the grid, prevent any grid operation problems and enhance interoperability with the utility grid. Challenges in grid codes compliance includes but not limited to compliance to specific technical requirements, testing and certification procedures, and proper coordination between grid operators and regulatory bodies.

e. Power quality monitoring and reporting

The power quality monitoring standards describe the rules of calculation, analysis and reporting of the power quality parameters in the electric energy systems. The listed instruments under IEEE 1159 and IEC 61000-4-30 standards provide precise measuring methods, the need of instruments for measurement, and data analysis techniques as means to detect power quality indicators like voltage sag, swell, harmonics and inter-harmonics (Park et al., 2020). The conformity with these rules helps the entities to identify power quality problems, diagnose system faults, and take the needed measures to enhance performance and reliability. The main areas of the monitoring of power quality are basically the selection of measurement points, the data integrity preservation, and the meaning of complex power quality phenomena.

f. Cybersecurity and resilience

Cybersecurity standards build security measures used to guard hybrid energy systems from cyber hazards, intrusions and malware attacks on data and communication networks. Standards such as NIST SP 800-82 and IEC 62443 are clear rules for the security measures, risk assessment methodologies and control mechanisms to safeguard the critical infrastructure and ensure system resilience. Cybersecurity standards compliance is a key part of the safety of hybrid energy systems from cyber-attacks, data breaches, and operational disruptions that may result in low voltage and power supply quality. Cybersecurity problems systematize where the changing nature of threat is involved, security measures are integrated into the product architecture, or the trade-off among security needs, system usability, and performance needs to be considered (Liaquat et al., 2020).

g. Safety and environmental regulations

The safety and environmental regulations designed by the government control the planning, installation, and operation of the hybrid systems such that people, environment and incidental hazardous materials and practices are protected from harm. The codes such as NFPA 70 (National Electrical Code) and IEC 61882 are the foundations for the establishment of the principles of electric safety, equipment protection, and hazard area classification in power production and transmission systems. Implementation of safety regulations which may include but not limited to implementation of safety procedures, conducting risk assessments and also the best practice for handling, storing and disposal of hazardous material. These are safety and the environment related issues which include: adherence to the regulatory requirements, personnel training on safety procedures and documentation and record keeping for regulatory audits and inspections.

h. Market and policy considerations

The regulatory regimes, incentive schemes, and market structures are all essential components that influence the process of development and action of hybrid energy systems. Renewable Portfolio Standards, Feed-in Tariffs (FIT) and required Net-Metering are among the policy measures that exhibit an array of financial incentives to integrate renewable sources and modernize grids. The market and policy compliance is a process that includes the analysis of the sophisticated regulatory layers, the sorting out of the eligibility criteria, and the use of financial incentives and supports on the hybrid energy systems' adoption. There are several important issues in the field of market and policy compliance such as political uncertainty, regulatory complexity, and matching broader energy strategy goals and priorities.

Regulating performance and design criteria and an adequate regulatory framework which focus on the power quality is an unavoidable measure for maintaining the reliable and economic operation of hybrid energy systems (Thirunavukkarasu and Sawle, 2020). These standards define the criteria and standards for voltage regulation, frequency stability, harmonic attenuation, grid feed-in, power quality monitoring, cyber-security, safety and environmental compliance and thus the design, implementation and operation of hybrid energy systems depend on them. Compliance with standards and regulations allows the power operators, manufacturers and regulators to maintain the high quality of power, minimize the risks and promote the wide-spread use of the energy hybrid as a sustainable and reliable alternative to fossil fuels in order to address the world's energy needs. Therefore, policies play a vital role for hybrid energy systems planning to have a more stable and reliable centralized and decentralized system in the overall grid infrastructure. (Schnidrig et al., 2024).

B. Types of Main Hybrid Energy Systems

The hybrid energy systems are a concept of combining two or more energy sources in system in order gain higher overall efficiency and availability of system. In the field of electrical engineering, this is the core of the solution to the energy problems with the least environmental impact. The details of the main hybrid energy system types and their main component for PV, Wind, Storage and generator will be addressed.

1. Photovoltaic (PV)

PV technology is the predominant form of renewable energy. The photovoltaic effect is the process through which generates electricity from the sun. This process is achieved by creation of voltage and current when the semiconductor stuff is illuminated from the light, mostly the sunlight (Alghamdi *et al.* 2023). PV modules or solar panels, are the most fundamental components of PV as it is main source of this energy as shown below Figure 3.

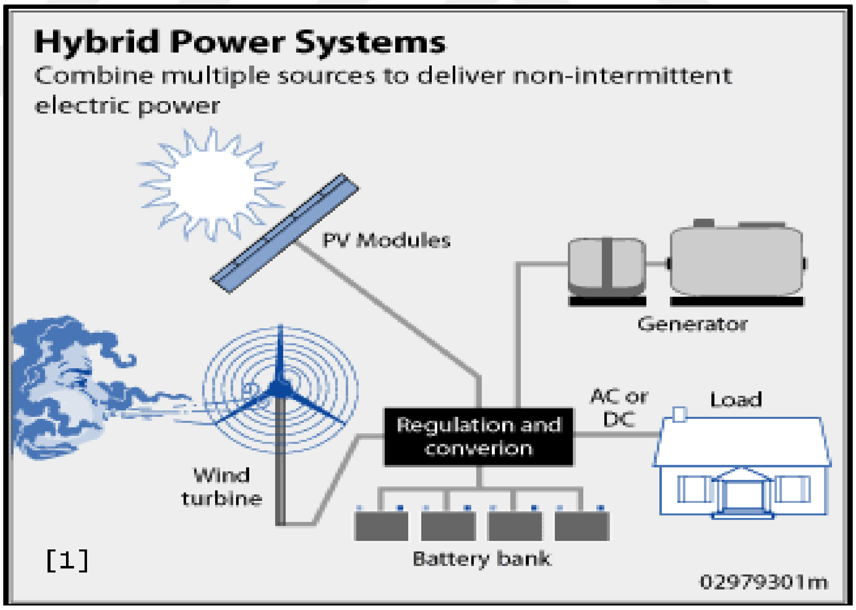

Figure 3 Overview of Photovoltaics

(Source: esru.strath.ac.uk, 2024)

PV energy includes a row of connected PV cells which are in series and parallel to each other and are used for producing the desired current and voltage values respectively. Either silicon or some other semiconductor material is the constituent element of photovoltaic cells and they turn the sun's photons into electric current when the photons encounter the surface of the cells (Adak et al., 2021). These photoelectric cells go through the photovoltaic effect as the absorbed photons bring about the excitation of electrons in the semiconductor material which results in the formation of an electron-hole pair.

The electric field formed is the one that propels opposite charges in the cell. This streaming charge causes a potential difference, or voltage, across the cell, and the electric current happens when a circuit is added to the setup. This system is made to increase the efficiency of a PV system with the help of different other components such as inverters, mounting structures, wiring and connectors, controllers and monitoring systems.

a. Inverters

Through inverters, PV systems are converted to AC from the DC generated by solar panels, which then satisfies all the requirements of electric grids. This transformation is the key to the successful integration of solar power into residential, utility or grid-based electrical systems. To achieve this, inverters utilize semiconductor devices such as power transistors as their modulators. These devices modulate the DC input into a waveform that mimics the features of an AC signal. The mentioned process contains most control algorithms to control voltage, frequency and waveform quality in order to keep the compatibility with the connected electrical grid or appliances (Huang et al., 2021). Also, the inverters have features like maximum power point tracking (MPPT) that will help to extract energy from the solar array in different conditions such as shading or temperature changes. Besides, inverters of high capacity and quality they also have grid capability allowing excess power to be exported to the grid or system switching between grid and off-grid modes to be smooth as well as support grid via Power Plant Controller (PPC) and Supervisory Control and Data Acquisition (SCADA). Inverter are used in Hybrid systems especially in PV and Wind power have a great support to the grid power references P_{ref} and Q_{ref} at the power transferred to the grid at PPC point(Mirmohammad and Azad, 2024).

b. Charge controllers

In the case of off-grid and battery-based PV systems, a charge controller acts as a vital medium that governs the power exchange between the PV array and the battery bank. These controllers are in charge of the charging and discharging process, making sure that the battery works in the best possible way and that it lasts long. All charging controllers utilize some advanced circuits and algorithms to regulate the voltage and current parameters for the PV array and the battery bank. The charge controller is responsible to limit the charging current when the PV array is in operation. If not limited, overcharging will cause batteries degradation and short lifespan. On the contrary, during the period of low sunlight or high energy demand, the charge controller helps to discharge the stored energy from the batteries while preventing it from deep discharging, which can also damage the battery health. Moreover, charge controllers are equipped with highly innovative functionality like temperature compensation, which accounts for variations in climate, thereby improving the performance and lifespan of the batteries and support harmonics too (Arranz-Gimon et al., 2021).

c. Mounting structures

Mounting structures have a very important function of maintaining functionality of PV panels through proper mounting so that they can be faced to the direction of maximum sunlight. These structures, usually in the form of racks or frames, are the basis of the panels and at the same time they can be adjusted to optimal angles for the reception of sunlight. They can be either fixed system structure or tracking system to maximize the energy output by following the Sun. The main purpose of mounting structures is to fix PV panels in place so as to protect them from the impact of weather elements (such as strong winds, precipitation and seismic effects). This consequently guarantees the long-term quality of the solar array as well as the resilience of the panels to damage or dislodgement. Besides, the mounting structures make it possible to change the tilt angles to have the panels directed to the sun's position at the best possible orientation. Using mounting structures at the right tilt angles allows gathering sunlight throughout the day and across seasons. This is determined mostly by the latitude and seasons dimensions.

The orientation adjustment functionality is instrumental to maximizing energy harvest and improving the general efficiency of the photovoltaic systems (Memon and Patel, 2021). Besides, the mounting structures help in spacing and arrangement of PV panels adequately to prevent shading and make full use of the available space. It is through the mechanical design of this strategic layout optimization that uniform distribution of sunlight is achieved across the solar array, thus contributing to the enhancement of energy generation performance. Mounting systems are one of the key elements that define PV systems as stable, adjustable and best positioned for maximum capture of solar rays and energy.

d. Wiring and connectors

Connecting and connectors are the key elements for the efficient transmission of electricity within photovoltaic (PV) systems, while at the same time reducing the losses due to the electrical resistance. The use of durable cables and the connecting elements is crucial to provide the system with the superior performance and safety. In a PV system, the electric current travels from solar panels toward different components like inverters, AC or DC boxes, Monitoring units, charge controllers and batteries before arriving at the load or grid connection point. On the way, the electrical conductors including cables and connectors must have a low resistance to minimize the power losses. Resistance in the conductors gives rise to heat dissipation, which reduces the system's efficiency and in some cases, can create a safety hazard if proper management is not considered (Elmelegi et al. 2021). High-quality cables are most commonly made using materials with superior conductivity features like copper or aluminium and engineered to withstand challenging natural conditions in exterior installations. Besides, these have suitable sizes to deal with the expected current loads without too much voltage drop.

While connectors, in comparison, work as the conduits between various components of the PV system, paving the way for smooth flow of electrical current. Weather and dust proof connectors are designed in a way so they maintain system integrity even in the presence of humidity, dust and temperature fluctuations.

e. Monitoring and control systems

Monitoring and control systems are the key elements that are aimed at the observing the energy production, detecting of abnormal situations and enhancing the system efficiency from the distance. These systems provide the platform for planned maintenance and fault detection, after which the reliability of the PV system is bolstered and the operational performance of the system is extended. Above all, the monitoring and control systems are a network of sensors, devices and analysers that are spread throughout the PV array and collect the necessary data on energy generation, environmental conditions and system health parameters. The data received is then relayed to the control unit, which does the processing by employing powerful algorithms and diagnostic machines to create reports or alarms to take action on the plants.

Real-time monitoring makes these systems react very quickly to any deviations from the expected performance or faulty process, as it can start appropriate actions like alerts or automated responses. The actual identification of problems in advance enables prompt response, thus reducing downtime and averting the possible collapse of the PV system (Abdalla et al., 2021). Same way, monitoring and control systems usually allow for the operators to have access to remote functions making it possible to change the settings, solve the troubles, and enhance the performance through a centralized place. This remote functional boost efficiency of operation and enables timely reaction to threats or emergence of opportunities. The monitoring and control systems and smart applications or power electronic devices (D-STATCOM etc.) are the key to the reliability and efficiency of the advanced PV installations (Myneni et al., 2020). They provide the comprehensive view, the proactive maintenance capability, and the remote access to optimize the system performance and to ensure the long-term viability of the installation.

People and organizations can use these elements in a carefully devised PV system so that they can efficiently use the solar power, thus making fewer use of the fossil fuels and lowering the environmental effects. PV technology development while enhancing its effectiveness and lowering the costs, which lead to greater expansion across the globe as one of the main solutions to the environmental change.

2. Wind Power

Wind power is a major part of many hybrid energy systems which are the systems that combine different sources of energy together to make the energy more reliable and efficient. A variety of hybrid wind power systems can be found below which have their own characteristics suitable for different applications.

a. Wind-diesel hybrid systems

Wind-diesel co-systems which integrate wind turbines and diesel generators aim at electricity provision in inaccessible grid areas. Below Figure 4 clearly demonstrates a combination wind-diesel power generation system.

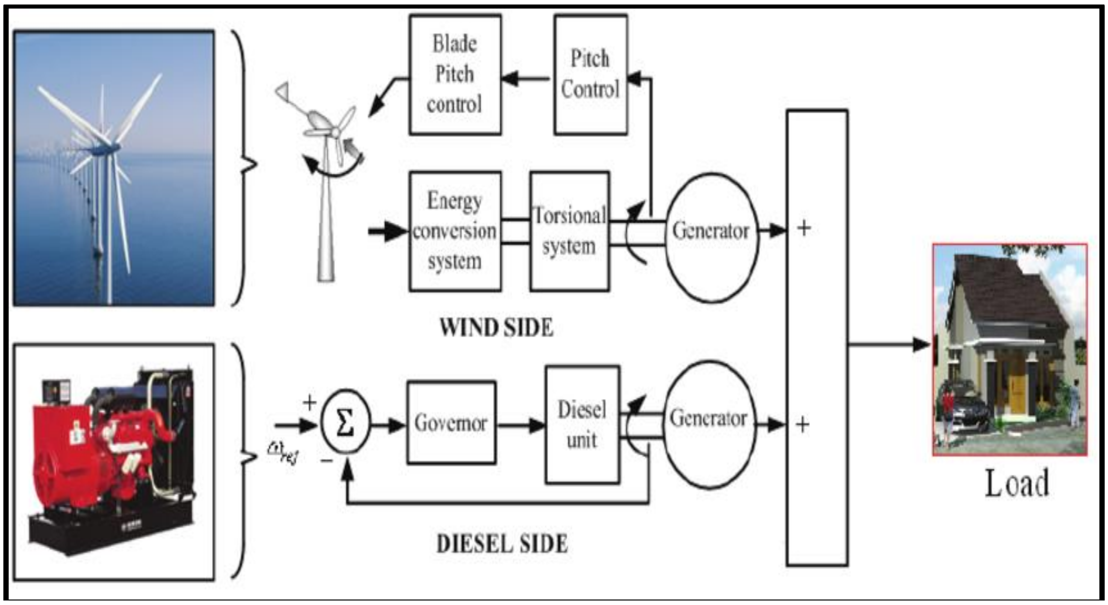

Figure 4 Basic configuration of a hybrid wind-diesel power generation system

(Source: researchgate.net, 2024)

Such control systems usually entail a management mechanism which governs the equilibrium between wind and diesel power generation in terms of factors such as wind speed, load demand, fuel availability and EV (Brenna et al., 2020). The blending of wind power and the use of diesel fuel less reduces reliance on the fossil, leading to economic and environmentally positive results.

b. Wind-PV hybrid systems

Wind-PV hybrid systems combine wind turbines and photovoltaic (PV) solar panels to take advantage of the synergies between wind and solar resources. Meanwhile, this combination makes a more consistent power delivery across variable weather. Moreover, it decreases storage systems dependence because off peak time of one source can be balanced by the peak of the other (Bullich-Massagué et al., 2020). From a technical point of view, these systems are equipped with the so-called controllers that are designed to regulate the power generation from both wind and solar sources. These controllers optimize available resource allocation using current wind speeds, solar irradiance, and energy demand in real time. Via smart algorithms, the system automatically switches the output from different sources with the aim of obtaining optimum effectiveness and stability (Kulkarni et al., 2023).

c. Wind-hydro hybrid systems

Wind-hydro hybrid systems unite wind turbines with hydroelectric power generation facilities to take advantage of both wind and water energy resources. Generally, such schemes utilize pumped-storage hydroelectricity technologies with excess wind turbine power being used to pump water into the reservoir during off-peak hours. In a similar way, at peak electricity demand, the stored water in the reservoir is discharged, powering hydroelectric generators to produce electricity, resulting in storage and use of the wind energy produced during high-demand periods. The combination of wind and hydro resources increases the system reliability and flexibility by diversifying the energy sources and thus the problems of intermittency of wind power are reduced (Quawi et al., 2023). Wind turbines provide to the generation of variable renewable, but hydroelectric power plants enable a dispatchable and controllable supply of energy. This hybrid resource helps to solve the problem of fluctuating energy demand by making the grid more stable and the use of fossil fuels is therefore greatly reduced. Furthermore, wind-hydro hybrid systems can use the existing hydro infrastructure, which in turn reduces the construction costs and environmental impacts when compared to standalone wind or hydro projects.

It is also common to have the pumped-storage mechanism adds storage element capability for short to medium term durations. It provides grid balancing services as well as the integration of more intermittent renewables into the power system. Mainly, wind-hydro hybrid systems are based on the additive nature of wind and hydro technologies, defining the best way of joint action that enhances the system in terms of overall efficiency, reliability and sustainability. In addition, usage of pumped storage units with wind energy generation have supported improving of dispatch ability of wind power to the grid too (Nigam and Sharma, 2023).A basic modelling of Wind-Hydro Hybrid Energy System can be found as below in Figure 5.

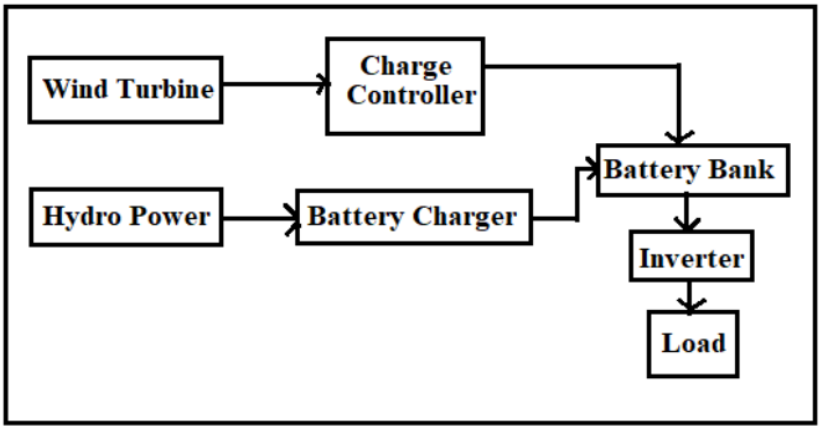

Figure 5 Modeling of Wind-Hydro Hybrid Energy System

(Nigam and Sharma, 2023)

d. Wind-battery hybrid systems

Wind-battery hybrid systems unite wind turbines with energy storage mechanisms such as batteries to mitigate the intermittency associated with wind power generation. Batteries work as depots storing energy that is generated by the turbines during the peak wind more than 20 mph and releasing it at times of wind strength less than 10 mph. Grid support benefits from the integration of renewable energy sources which enhances supply stability in times of unpredictable wind patterns and guarantees a constant supply of power. In a nutshell, these systems have sophisticated control algorithms that control the charging and discharging of batteries in accordance with the real-time wind speed data and energy demand forecasts (Rafiei et al., 2020). While during times of surplus, storage batteries utilize the surplus energy by employing advanced technique of charging to maximize the storage of energy. However, when wind speeds reduce, stored energy is tapped on, being able to optimally discharged through precision systems in dealing with demand fluctuations. Besides, these systems have sophisticated monitoring and predictive analysis functions that help to predict wind patterns and to optimize energy storage and distribution accordingly.

3. Storage systems

Hybrid energy systems are a rising phenomenon in the world's energy systems, devising a way to merge several sources to maximize efficiency and reliability. While storage systems are not the only ones that contribute to the stability of energy systems, they are probably the most important one in maintaining the balance between energy production and use. Here's an overview of the types of storage systems commonly integrated into hybrid energy setups.

a. Battery energy storage systems

Battery Energy Storage Systems (BESS) are the most widely used and extensively studied part of hybrid systems. Mainly utilizing either lithium-ion or lead-acid and flow cells, BESS performs its function of storing the electrical energy perfectly. As they have been highly responsive to large energy storage capacity and scalable basis, these systems are the foundation of the supply and demand dynamics balancing. BESS systems are one of the greatest hybrid energy type in the world when it comes to the ability of absorbing the surplus energy during the periods of low demand and discharge it when the demand is high, which in turn improves the grid stability and makes it more reliable (Kulkarni et al., 2021). BESS with other hybrid systems can combine other renewable energy source such a battery bank, flywheel, super capacitors, or a fuel cells (Kulakarni et al., 2023) This rapid flexibility in varying needs of energy demand is one of their main strengths, making them indispensable, especially for the tolerance of renewable energy source intermittency like solar and wind power. Pertaining BESS, there are sophisticated control systems that regulate the charging/discharging cycles to achieve optimal conditions and lifetime. The advanced monitoring systems are used for the precise control of the battery health and performance metrics, which are the key factors in the effective usage and maintenance of the system in the energy efficiency and reliability (Duchesne et al., 2020). With increase of more renewable energy technologies, BESS will also become more important part of this hybrid systems (Rakib et al., 2020).

b. Pumped hydro storage

The popularity of pumped hydro storage has grown tremendously and the technology stands as a well-established and efficient part of hybrid energy schemes. Storing energy in the form of gravitational potential energy is the economic principle working on this process at its core. Majority of pumped hydro systems are installed in river valleys but there is a huge potential also for off-river (closed loop) pumped hydro (Blakers et al., 2018). low-demand phases water is elevated to reservoirs and then through turbines when high-demand periods arrive the water is released for the purpose of generating electricity These systems are well-known for their large storage capacity and long discharge time, which are possible only in the presence of the suitable geographical conditions, including water bodies at different elevations. Technically, these systems are a pair of reservoirs placed at different elevations, generally connected by pipes, turbines, and pumps. The concept is, the power is generated from the lower and upper reservoir’s pumping and use it when necessary (Legacy et al., 2024). In times of low demand, electric power produced excessively is used to pump water from the lower reservoir to the upper one. Contrary to this, during the peak demand hours, water from the upper reservoir is released and it goes back down through the turbines to generate electricity.

In spite of their efficiency, hydro pump storage projects require thorough assessment of environmental implications as well as the granting of the required licensing permits as the water flow patterns will be altered and an ecosystem will be disrupted. However, with good architecture and execution, pumped hydropower storage remains an important technology for large-scale energy storage which can be used for grid stability and the integration of renewable energy.

c. Compressed air energy storage

Compressed Air Energy Storage (CAES) systems have been developed as a way of storage by compressing air that is subsequently stored in underground caverns or tanks. In some cases, the energy is used for compression air and afterwards is stored in pressurized forms. As more energy is needed, the compressed air is released and expanded through turbines to generate electricity. Tailoring the scale of deployed CAES systems is another benefit of these systems because different storage needs can be met this way. Moreover, CAES systems are often considered as cost-efficient solutions in contrast with other energy storage service by the reason of its utilization of underground storage facilities, which is mining pits or caverns. In addition, CAES systems have a long cycle life, which means they are reliable and durable in the long run. A Schematic diagram of a CAES is illustrated in below Figure 6 for its working pribciple.

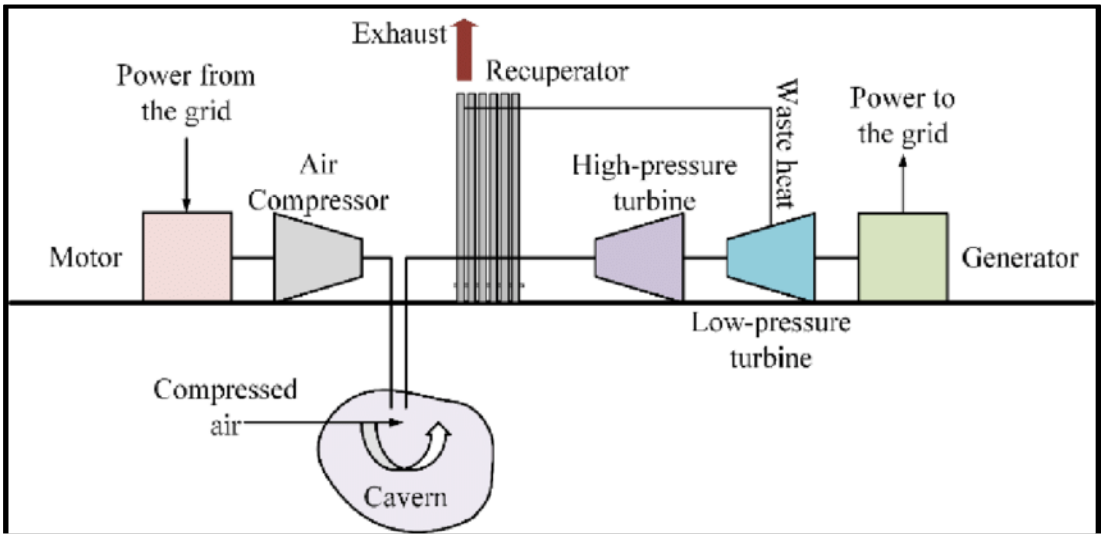

Figure 6 Schematic diagram of a Compressed Air Energy Storage (CAES)

(Source: researchgate.net, 2024)

Although in the case of a CAES system it may be a bit less efficient than some other storage techniques. The major reason for the difference in efficiency is the energy losses that occur during the compression and expansion processes (Ahilan, 2023). However, as a trade off, CAES also retains its validity and importance, being the most cost-effective and scalable solution for those who are in need of long-term reliability.

d. Flywheel energy storage

Kinetic energy storage systems based on flywheels accrue energy by means of rotating rotors at a high speed under a vacuum or inert gas conditions. In the time of higher energy level, the rotor is accelerated thus the energy is stored in its rotational motion. When cycling is needed, the rotor's kinetic energy is converted into electrical energy (Faraji et al., 2021). Flywheels are valued largely because of their relatively quick response times, high efficiency and long time that operation can be performed (Zhai et al., 2023). They are particularly applicable in the cases where the charge-discharge cycles are frequent and rapid, for instance, grid stabilization and frequency regulation.

4. Diesel Generator

Hybrid energy systems combine two or more types of renewable and non-renewable energy sources in order to develop energy systems which are effective as well as sustainable. From different hybrid energy systems, generators running on diesel take an important position, especially in the regions where the access to the grid network is limited or instable (Liu et al., 2023). This section will discuss the diesel generator element inside the hybrid energy systems. Here's an explanation of the diesel generator component within hybrid energy systems

a. Functionality

The diesel generator works as an intrinsic combustion engine, converting the diesel fuel combustion into electrical power. In the hybrid energy setups, they act as standby or complementary power sources to renewable energy generation from sources such as solar or wind. In cases where renewable sources are not enough, for example, during unfavourable weather conditions or low energy output, diesel generators come in to provide a reliable energy supply to meet the demand. Such generators work in a way diesel combustion chamber burns the fuel and the following generated energy is converted physically into mechanical energy by means of pistons and crankshaft (Zhu et al., 2024).

The integration of hybrid systems involves the smooth communication with renewable energy sources and power management systems. Automated control systems allow for the transition between different power sources to become smooth, prioritizing renewable energy source when it is available and switching to diesel generation when necessary is done in a seamless fashion.

b. Integration

The introduction of diesel generators into hybrid energy systems is made easier by advanced control and monitoring systems. These systems are the key components that control the distribution of power and they are able to respond quickly to the changes in the demand and the availability of the renewable energy sources. At times, when renewable sources are overabundant, the excess energy is transmitted by the control system to other parts in order to be efficiently used (Tang et al., 2021). Excess electricity possibly can be stored in batteries for later consumption or simultaneously fed to loads, optimizing the amount of energy used and improving the whole system performance. On the contrary, when the renewable energy production is not enough to satisfy the need, the control system automatically starts the diesel generators. Below in Figure 7 an example of off-grid system based diesel generator with integration of PV and BESS is demonstrated (Rezkallah et al., 2020). This kind of hybrid system configuration are linked to the main grid through an automatic interface, always ready to compensate for temporary shortages and satisfy the operational needs of the organization.

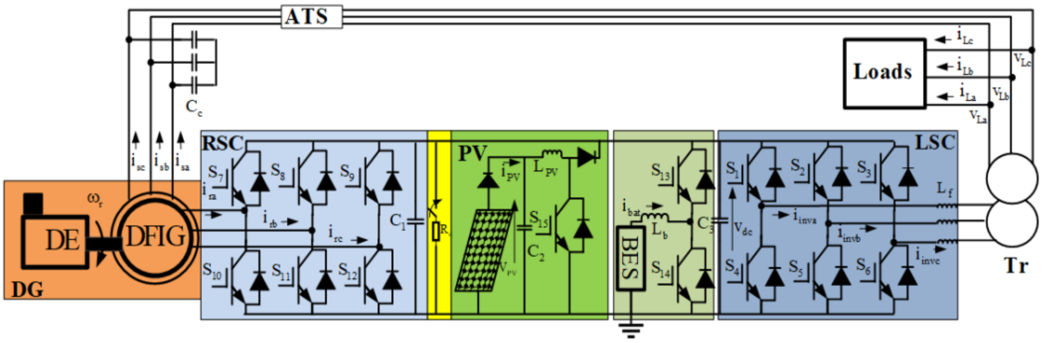

Figure 7 Configuration of Off-Grid System based on Diesel-PV power generators

c. Efficiency and environmental impact

The diesel generators in hybrid systems are favoured for their reliability and flexibility but can be energy ineffective and cause environmental pollution. In contrast to renewable ones, diesel generators pollute the air and contribute to the carbon footprint through the consumption of fossil fuels. To cope with these problems, hybrid systems utilize diverse technologies. Emissions control systems with modern features are crucial. These systems use catalytic converters and diesel particulate filters to decrease the air pollution emissions coming out of the exhaust pipe.

d. Sizing and scalability

The sizing of diesel generators in hybrid energy systems is dictated by the factors like the size of the load, the availability of renewable resources and the desired level of autonomy from the grid. It is varying from the residential and remote sector to the commercial and industrial utilities, depending on the requirements and size. Moreover, hybrid renewable systems can be gradually up-scaled and be able to incorporate new sources of renewable energy or energy storage so that reliance on diesel generators can be achieved in the long run. The capacity of diesel generators should be able to meet the maximum required power need and usually system design of the diesel generators have some reserve capacity for the generators to deal with the uncertainties or prediction errors of renewable energy (Xiao et al., 2014). The sizing formula of the generators can be formulated as below.

$$CD = \max\{\, |P_D(i)|\} \, (1 + R)$$

where CD is the capacity of the diesel generators and R is the capacity reserve rate.

e. Cost considerations

The cost of diesel generators, fuel, maintenance and emissions compliance should be considered together with the benefits of reliability and energy independence in hybrid energy systems (Zhang et al,. 2020). Diesel generators at first are more costly and they also consume more fuel compared to renewable electricity technologies. These generators are good for hybrid systems that help to ensure uninterrupted supply of power in off-grid and unreliable grid environments.

Valuing the clear role of diesel generators for hybrid energy systems is as a backup supply of power for renewable energy resources. Their integration requires highly developed control and monitoring systems to reach the best performance, efficiency, and environmental impact. Even though these systems are subject to some problems with emissions and fuel consumption, diesel generators are essential for the operation of the hybrid energy system wherever they are applied.

C. Power Quality Issues in Hybrid Energy Systems

Voltage fluctuations, a usual problem in hybrid energy systems are due to the varying loads and the intermittent renewable energy sources. This can bring about either the creation or the destruction of some systems. The subject of harmonic distortion that is another issue occurs due to the non-linear loads producing harmonics that were not the originals in the fundamental waveform which interfere with efficiency and equipment damages. As it is presented in Figure 8, power quality is created due to below power generations at a glance.

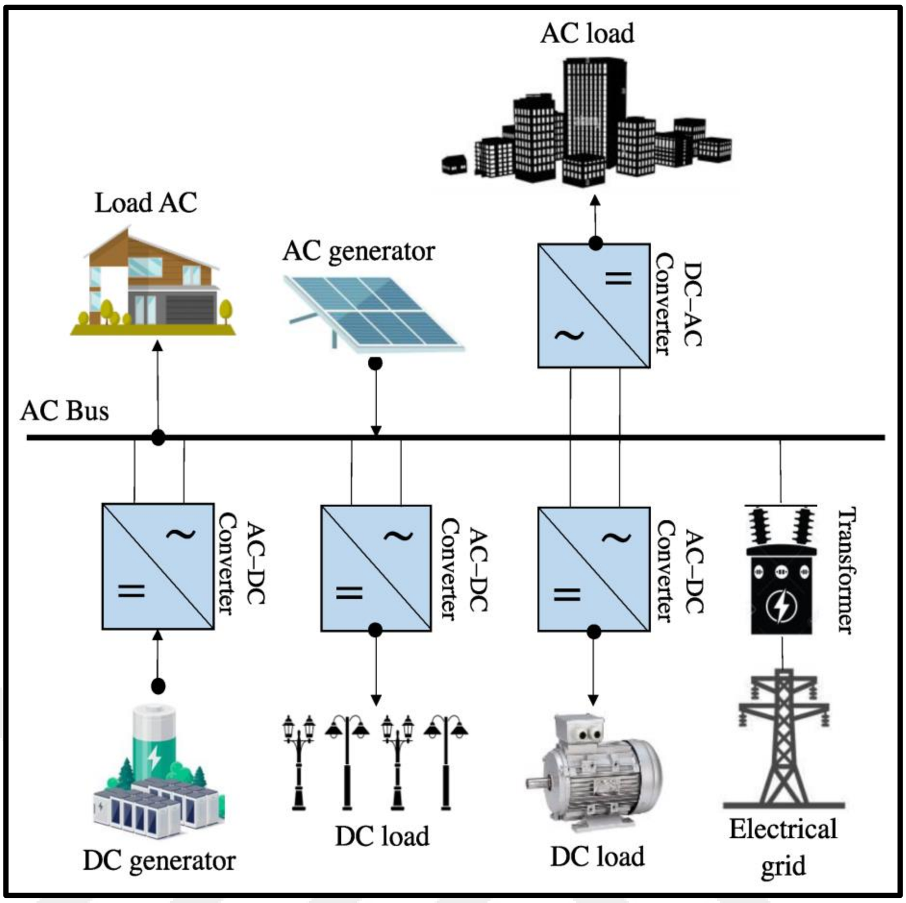

Figure 8 A Comprehensive Review on Power-Quality Issues

(Source: mdpi.com, 2024)

A voltage variation occurs if the load is not balanced or if the generator or transformer break down, leading to the skew in frequency and equipment damages (Palamar, 2020). Due to this intermittency, switch mode, voltage spikes, and drops become a hazard to services stability and reliability.

1. Voltage Fluctuations

In the hybrid energy system world, voltage fluctuations are a major issue that needs to be very carefully studied because they can disrupt the operations and damage the equipment. These are voltage fluctuations that are voltage irregularities and the voltage magnitudes deviating from the set values. Such change continues for some short amount of time. The instability is a result of the combination of factors like the intermittency of the renewable energy sources like the solar and wind and the load variation patterns within the system. One of the main reasons for the voltage fluctuations in hybrid energy systems is the variability of the renewable energy sources that are used. Therefore, systems such as solar PV and wind turbines which are dependent on certain environmental conditions for production, are sources of output power fluctuations. These changes propagate through the group causing an effect of voltage that can exceed the allowed values. In the same way, the deployment of energy storage systems brings in new dynamics as the charging and discharging processes affect the voltage levels. In addition, sudden rise in PV or wind power due to weather conditions that amount of AC power injected to the grid can increate the voltage level too (Von Appen et al., 2013).

The inertia variations in the active power also cause the voltage fluctuations in hybrid systems. Voltage distortions bring negative impacts on the hybrid energy system and the devices that are related to it. The sudden voltage changes can cause voltage sags, swells, and transients, threatening the stability and reliability of the sensitive loads (Shahgholian, 2021). The equipment being exposed to a voltage that goes over its designed limit, which could be the transformers, the control devices, or the inverters, will have an increased chance of early failure or breakdown. Voltage stability is a key issue that must be effectively addressed by the use of innovative control and management strategies in the system of hybrid energy. These advanced voltage control techniques like reactive power compensation, voltage regulation and coordinated control of power electronic devices play a crucial role in keeping the voltage stability within the acceptable limits.

2. Harmonic Distortion

Undoubtedly, in the context of hybrid power systems, the mismanagement of power quality problems firstly the harmonic distortion has great significance. Harmonic distortion means that the waveform deviates from its sinusoidal shape ideally as numbers of generated frequencies that are integer multiples of the fundamental frequency. These harmonics can be a nuisance to the smooth operation of electrical systems, resulting in various undesirable effects such as overheating of equipment, misfiring in variable speed drives, and interference with communication systems (Lorenzini et al., 2021). Nonlinearities caused by power electronic converters count among the most hazardous things within hybrid energy systems. These converters, mostly used with renewable resources such as PV systems and wind turbines, introduce harmonics because of their often non-linear current-voltage characteristics. Furthermore, the existence of energy storage systems, such as batteries and supercapacitors, can also be the source of harmonic distortion because of their switching operations (Prakash, 2021).

For hybrid energy systems to reduce harmonics, several mitigation methods are applied. Passive filters, which is made of inductors, capacitors, and resistors are the most common form of devices that are used to lower specific harmonic frequencies. These filters are the cost-effective option, and also, they are quite easy to install. Yet, this can in some cases lead to resonance problems and cannot be completely effective in suppressing higher-order harmonics. Another means of the harmonic filters is the active harmonic filters which are used for the purpose of mitigating the distortion. These filters use power electronics to create compensating currents that are able to cancel out the harmonic currents that are present in the system. Active filters can dynamically perform any phase and magnitude tuning of the generated currents to effectively suppress a wide band of harmonic frequencies. In addition, they are easily adjusted in their operation and able to handle varying load conditions what is why they are advantageous in hybridized energy systems.

Besides the conventional mitigation techniques, there are many power electronic devices that helps to reduce Total Harmonic Distortion (THD), Distribution Static Synchronous Compensator (D-STATCOM), Pulse Width Modulation (PVM) and also the advanced control algorithms are being created to deal with harmonic distortion in the hybrid energy systems. With these power electronic devices and adaptive control, system designers can monitor real-time harmonic content, hence they can make the required changes to reduce the distortion. Through the use of cutting-edge computers these control algorithms can both balance the system and also meet power quality standards (Halim et al., 2021).

3. Frequency Variations

The relativities of frequency variations in the hybrid energy systems context means the AC power frequency oscillations fluctuations. These variations have consequently high influence that affects the safe and efficient operation of power systems, thus understanding and managing them is becoming more and more important. Frequency variations are mostly caused by the unbalance between system generation and load demand. The frequency deviations in the hybrid energy systems are mostly caused by the intermittent nature of Renewable Energy Sources (RES) such as wind and solar power that are typical components of such systems alongside conventional power sources such as fossil fuels or grid power. On the other hand, solar panels and wind turbines produce a variable amount of electrical power as a result of sudden changes in solar irradiance or wind speed that might cause the AC power supply to become unstable (Soomro et al., 2021). These frequency fluctuations raise a number of issues for the operation of hybrid energy systems. For one thing, such disruptions can cause operating problems with the sensitive equipment tied to the grid, thereby risking destruction of the equipment or failure of the system altogether. The sectors with sensitive equipment systems, especially plants having sophisticated machines and healthcare facilities with medical equipment, are the most sensitive to such disruptions.

In addition, frequency fluctuations may also be the cause of the instability of the entire power grid. When it comes to the interconnected system where there exist several hybrid energy systems either interconnected with one another or connected to the main power grid, frequency fluctuations are capable of spreading out across the power network which, in turn, can cause the cascading failures and blackout if not properly dealt with. For hybrid energy systems to withstand the stress of frequency fluctuations some methods and technologies are used. One way to solve this problem is to use Energy Storage Systems (ESS) like batteries or capacitors to store the extra energy that is generated during the times of high production and release it during the times of low production or high demand. Through smoothing the production fluctuations, energy storage systems can contribute to stabilizing frequency of the power supply (Jufri et al., 2023).

Automation control algorithms and grid management procedures are also employed to ensure that the output of renewable energy is stabilized and system stability is maintained. Predictive control strategies, for instance, can foresee the changes in the generation and dynamically adjust the power dispatch to reduce the frequency deviations. The additional involvement in frequency regulation markets and their grid ancillary services, which provide economic incentives, can motivate hybrid energy system operators to actively participate in managing frequency fluctuations (Aljarrah et al., 2023). Throughout are added to the grid, operators can not only provide system stability services but also collect additional revenue streams.

The frequency changes are a major problem in hybrid energy systems as they can lead to power supply unreliability and grid instability. The deployment of efficient management systems as the incorporation of energy storage, advanced control algorithms and the active participation in grid services markets play an important role in the success of integrating renewable energies into the grid.

4. Transients

Within the scope of hybrid energy systems, the operation of power quality troubles such as transients is a dominant challenge. Transients which are sudden and brief changes in voltage, current or frequency, can have a negative impact on the performance and reliability of such systems. Transients comprehension and mitigation are inherent for smooth energy sources operation and management all through the diversified systems. The randomness of renewable energy sources like solar and wind is the main issue which is directly connected to hybrid energy systems. The oscillatory nature of these sources can result in sudden changes in the power output, which in turn will cause voltage and frequency transients. Furthermore, renewable energy sources which penetrate the grid either suddenly connect or get disconnected and it is this unexpected rapid change in the system that cause transient due to impedance change.

Yet another influencer of transients is the advent of electronic converters and inverters, instead of power electronics. These devices are the ones that are needed to change and control the flow of power between various energy sources and loads (Gonzalez-Abreu et al., 2021). Yet, switching action of their can produce voltage spikes, harmonic distortions and transients. Transients may occur due to defects in the system, such as short circuits in equipment, as well. These errors can cause sudden changes in voltage and current levels, which can be dangerous to sensitive equipment and operations. Therefore, prompt fault detection and isolation becomes the essential tool to minimize the transient’s effect on hybrid energy grids system. The challenges can however be handled by application of different mitigation techniques. One of the ways to do that is to use ESS to smooth out the fluctuations in power output from renewable sources. Storing excess electricity in times of high generation and using it during low generation or high demand periods, ESS ensures the voltage and frequency adjustments and is responsible for reducing transient events.

D. Challenges with Current Power Quality Control Methods

Present power quality control techniques have many limitations. Issues, like difficulty in detecting and eliminating transient disturbances as voltage sags and swells, harmonics, and flicker are included among those. Often by using conventional methods the reliability of finding the issues is usually poor therefore in corrective measures are not measured. Moreover, the grid becomes variable when the renewable energy sources are incorporated, thus adding more complexity to the power quality management. The most common parameters that effect power quality and control methods are defined and detailed as below (Plessis et al., 2022).

1. Inadequate Response Time

In the world of power quality control, the problem of insufficient response time is one of the major problems. Power grids are the complex systems where the different types factors such as voltage, current and frequency disturbances may occur. These interferences cuts across the network, including lightning strikes, switching operations and system faults. The conventional methods of power quality control usually involve the use of monitoring devices such as voltage regulators, capacitor banks, and protective relays to offset the disturbances (Hu et al., 2022). Even though these tools may face the problem of the insufficient response in some cases however, such cases could have serious consequences on stability and reliability of electric power system. The main cause of slow response is the often-delayed identification and reaction time to the disturbances.

The thing that makes the response time inefficient is the algorithms of the current controls. Most control algorithms are designed based on fixed thresholds or rules which may not always be able to capture the dynamic nature of disturbances in real-time. This is the reason why the algorithms are not able to respond instantly to an immediate condition or adjust the dynamic response according to control techniques requirement (Debdouche et al., 2023) . In addition, the intricacy and technicality of today's power systems give a new layer of difficulties for emergency occurrences. Nowadays the power systems are becoming interconnected through distributed energy resources, renewable generation and smart grid technology advancements.

To solve the problem of the insufficient reaction period, a comprehensive approach is necessary that integrates the use of sophisticated monitoring systems and SCADA strong control algorithms and reliable communication infrastructure. The quick monitoring systems with high sampling rates and sophisticated signal processing techniques become essential to the faster speed of detection and response times of environmental pollutions (Araoye et al., 2021). Each of adaptive control algorithms is suitable as far as the real-time conditions are concerned and as a result they can control power quality systems promptly and precisely.

2. Lack of Adaptability

In a world of power quality control, the impossibility to adapt is the main challenge for engineers and system operators. The absence of these essential characteristics limits the ability of the power systems to flexibly and timely respond to the rapidly changing circumstances and evolutionary needs, resulting in the deteriorated quality of the electrical grid. In other words, adaptability means the capability of a system to adjust its functioning under different circumstances and satisfy different demands. The common power quality control systems mostly use the fixed settings and static configurations, which are unable to adapt to the dynamic behavior of the modern power systems (Lipu et al., 2021). Thus, these techniques are incapable of meaningful addressing swings in load demand, fluctuations in generation mode, and integration of renewable energy sources. One of the main problems caused by this inability to adapt quickly is the inability to overcome voltage and frequency variations. Overall, in active environments where a lot of distributed energy resources (DERs) are plugged in, conventional protocols of control may not be able to sustain frequency and active voltages at the desired level.

This may lead to voltage fluctuations, sags, swells or even instabilities in the grid, which in return can pose problems for the power supply to consumers and the risk of damage to delicate devices. Also, the unyielding character of the current control methods limits their scalability and the possibility of integrating them with the new technologies. With increasingly sophisticated power systems designed to include technologies like smart grids, the need for control techniques that permit seamless integration becomes more and more pertinent (Hutasuhut et al., 2022). Yet, the non-flexibility which comes with it can make the integration hard, causing ineffectiveness and sub-optimality. Another implication of this limitation is the difficulty in the implementation of the pro-active measures for power quality improvement. Unless the level of automation can be modified in accordance with real-time conditions and forward-looking analysis, operators will be in a position where they are reactively rather than proactively handling matters that have surfaced.

3. Complexity in Integration

In the area of power quality control, one of the another main problem is the complexity of the integration of different control methods. Such techniques are generally established to provide faulty free, stable and efficient transmission of electric power. The systems and technologies used are frequently very complex. The bedrock of this complexity is the fact that different sources of power production and supply is exploited. Power is obtained from a wide range of sources such as conventional fossil fuels, renewable sources like solar and wind and emerging technologies like fuel cells. All of these power plants possess their own set of traits and issues which in turn are added on the grid. Also, the highly complex integration of DERs is further adding to the complexity layer. DERs, which are small-scale renewable energy systems like rooftop solar panels and wind turbines, are the ones which introduce the variability and the intermittency into the power grid. As the DERs are integrated into the system with a power quality control mechanism becoming imperative will require sophisticated control mechanisms. Additionally, the traditional control scheme of centralized systems is also threatened by the development of smart grids.

Smart grids use the latest communication and control technologies to optimize the operation of the grid in real-time. Although smart grids provide multiple benefits such as enhanced reliability and better efficiency, enabling these to work gives rise to the issues like data management, cybersecurity and interoperability. One of the factors contributing to the complexity of maintaining power quality is the wide usage of power electronic devices (Cordero et al,. 2020). These devices, like inverters and rectifiers, are the key for the conversion between AC and DC power and for the control of voltage and frequency.

4. Reliability Issues

The reliability of power quality control techniques is fundamental in its steadfast support of integrity and efficiency in electric systems. However, despite the advancements in technology, these existing methods also come across many reliability issues that can hinder operational efficiency and even lead to system failures.

a. Challenges with current power quality control methods

Sensor/Devices Failures: The reliability of the system is often influenced by the sensor failure. Conventional power quality control systems largely depend on sensors to monitor parameters like voltage, current, and frequency. Nevertheless, these sensors have a fragility caused by environmental factors such as humidity, electromagnetic interference and aging. Failure of sensors, may cause mis-measurements that can in turn lead to wrong control actions and result in damage of electric equipment.

Communication Errors: Another big obstacle is the communication errors between the control system components. Current power quality control systems typically involve intelligent interconnected systems having the ability to share data and command execution. Communication failures which can be the result of data packet loss, latency or network congestion, can obstruct the process of data exchange between the components.

Control Algorithm Complexity: The credibility of control algorithms is complicated by another reliability problem. With growing implementations of control techniques including model predictive control and adaptive control, power quality is regulated more effectively (Hoseinzadeh et al., 2020).

b. Mitigation strategies

Mitigation strategies in power quality and reliability od hybrid systems are essential for ensuring the stable and efficient operation in electrical systems.

Redundancy and Fault Tolerance: It is necessary to use sensors with redundancy and fault tolerant design to overcome sensor failures. Through the use of multiple sensors for measuring the same parameters and voting algorithms or redundant channels, the system can detect and correct sensor faults in real-time, thus, assuring the system's reliability in the face of individual sensor failures.

Error Detection and Correction Mechanisms: In order to reduce communication errors, the building of error detection and correction tools is a prerequisite. Methods like checksums, cyclic redundancy checks , and automatic repeat request protocols can be used to detect and correct data transmission errors which will in turn increase the reliability of data communication within the control system (Zhang et al., 2020).

Robust Control Algorithm Design: To develop reliable control algorithms, it is essential to apply robust control design methodologies. These methodologies account for uncertainties and disturbances in system modelling. For instance, robust control synthesis techniques such as H-infinity control optimize system performance despite uncertainties. Similarly, sliding mode control, a nonlinear approach, ensures robust performance by forcing the system to "slide" along a predefined surface in the state space, effectively handling parameter variations and external disturbances.

III. CURRENT TECHNOLOGIES FOR POWER QUALITY IN HYBRID ELECTRICAL ENERGY SYSTEMS

Power quality has become a critical concern in modern power systems due to the increasing proliferation of sensitive electronic equipment and the integration of renewable energy sources. Ensuring high power quality involves maintaining the voltage, frequency, and waveform of power within acceptable limits. New control methodologies are essential for addressing the challenges posed by these evolving power systems. This chapter explores some of the latest control methodologies for enhancing power quality.

Adaptive control techniques are gaining traction due to their ability to adjust parameters in real-time to cope with changing conditions in the power system. One such methodology involves adaptive filtering, which dynamically modifies filter parameters to mitigate harmonics and voltage sags (Mariano-Hernández et al., 2021). These filters, particularly adaptive active power filters (AAPFs), are effective in improving power quality by compensating for non-linear loads and ensuring stable voltage and current waveforms. Model Predictive Control (MPC) is another advanced control strategy that predicts future system behaviour and optimizes control actions accordingly. MPC is particularly effective in managing power quality issues like voltage sags, swells, and harmonic distortions. By using a mathematical model of the power system, MPC can forecast potential disturbances and adjust the control inputs to pre-emptively counteract these issues (Bajaj and Singh, 2020). This predictive capability is highly valuable in environments with fluctuating loads and intermittent renewable energy sources. Artificial Intelligence (AI) and Machine Learning (ML) are revolutionizing power quality control by enabling systems to learn from historical data and improve their response to power quality disturbances. Techniques such as neural networks and deep learning algorithms can analyze complex patterns and predict potential power quality issues with high accuracy. For example, AI-based controllers can optimize the operation of compensating devices like Static Var Compensators (SVCs) and Dynamic Voltage Restorers (DVRs), leading to enhanced mitigation of voltage and current disturbances (Hannan et al., 2020).

Hybrid control systems combine multiple control methodologies to leverage their respective strengths. For instance, a hybrid system might integrate MPC with AI techniques to enhance predictive accuracy and adaptive capability. Such systems can provide robust solutions to power quality problems by dynamically adjusting to both short-term disturbances and long-term trends in power usage and generation. These systems are particularly beneficial in microgrids and smart grids where diverse energy sources and loads create complex power quality challenges. The integration of renewable energy sources like solar and wind into the power grid introduces new power quality challenges due to their intermittent nature. Advanced control methodologies are essential for managing the variability and ensuring a stable power supply and for example, control strategies for inverters in PV systems and wind turbines often employ real-time monitoring and adaptive control to smooth out fluctuation and maintain power quality(Bordons, 2020). Additionally, energy storage systems controlled by sophisticated algorithms can provide buffering capacity to balance supply and demand effectively. Figure 9 demonstrates a block diagram of combination of PV and BESS with connection of linear and non-linear load.

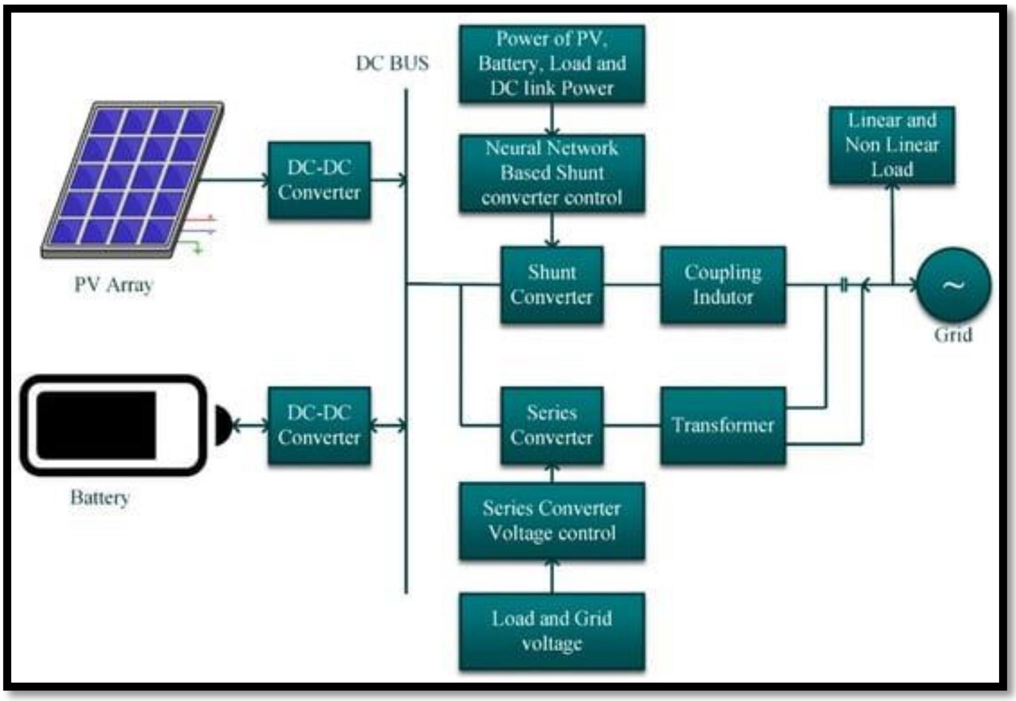

Figure 9 Block diagram of PV and BESS with linear and non-linear loads

(Source: mdpi.com, 2024)

Grid-interactive power quality management involves the coordination between DERs and the main grid to enhance overall power quality. This methodology relies on advanced communication and control systems to dynamically manage power flows and mitigate disturbances (Jha and Shaik, 2023). Techniques like demand response, where consumer load profiles are adjusted based on grid conditions, play a significant role in this approach. Real-time data analytics and Information of Technologies (IoT) technologies facilitate the seamless interaction between DERs and the grid, improving resilience and power quality. Under this chapter mainly control mechanism for active power filters, advanced synchronisation techniques, hybrid systems that include PV, BESS, Wind will be discussed.

A. Active Power Filters

Active Power Filters (APFs) are essential devices in modern power systems, particularly for improving power quality by mitigating harmonics and other electrical disturbances. This part of the study delves into the principles and operation of APFs, their applications in hybrid energy systems, and their benefits and limitations.

1. Principles and Operation

Active Power Filters are power electronic devices designed to eliminate unwanted harmonics and improve the quality of power delivered to electrical loads. Unlike passive filters, which use inductors, capacitors, and resistors to filter out specific harmonic frequencies, APFs actively inject compensating currents to counteract harmonic currents produced by non-linear loads (Li et al., 2021).

Monitoring and detection of APFs are equipped with sensors that continuously monitor the current waveform. These sensors detect the harmonic components present in the load current. During generation of compensating currents, once the harmonics are identified, the APF generates compensating currents that are equal in magnitude but opposite in phase to the detected harmonic currents. This phase opposition is essential for the cancellation of the harmonics. The generated compensating currents are then injected into the power line at the Point of Common Coupling (PCC). This is the point where the electrical system connects to the main power supply.

The performance of APFs is highly dependent on sophisticated control algorithms. These algorithms ensure the real-time and accurate generation and injection of compensating currents. However these systems also generate harmonics due to the nonlinear load to obtain a sinusoidal network (Haddad et al., 2015). Commonly used control algorithms include Proportional-Integral-Derivative (PID) controllers, which provide precise control over the current generation process. Sliding Mode Controllers are also utilized for their robustness and ability to handle system uncertainties and non-linearities.

Real-time performance is crucial for the effective operation of APFs. The control algorithms must respond quickly to changes in the load current and harmonics (Alhamrouni et al., 2024). By effectively mitigating harmonics, APFs help in maintaining the quality of power supplied to electrical systems. This leads to improved performance and longevity of electrical equipment.

There are several types of AFPs it is commonly used. Shunt APFs which is connected in parallel with the load, shunt APFs are the most common type and are primarily used to compensate for current harmonics and reactive power. Series APFs are the types that e are connected in series with the power line and are used to mitigate voltage harmonics and voltage sags/swells. Lastly, Hybrid APFs, These combine the functionalities of both shunt and series APFs, offering comprehensive harmonic mitigation and power quality improvement.

2. Applications of AFPs in Hybrid Energy Systems

Hybrid energy systems, which combine renewable energy sources (RES) like solar and wind with traditional energy sources, present unique challenges and opportunities for APFs (Farhat et al., 2022). Solar PV systems can introduce harmonic distortions due to the inverter operations (Allouhi et al., 2022). Shunt APFs can be deployed to filter out these harmonics, ensuring the smooth operation of PV systems and maintaining power quality. A demonstration of PV systems is shown in Figure 10 as below.

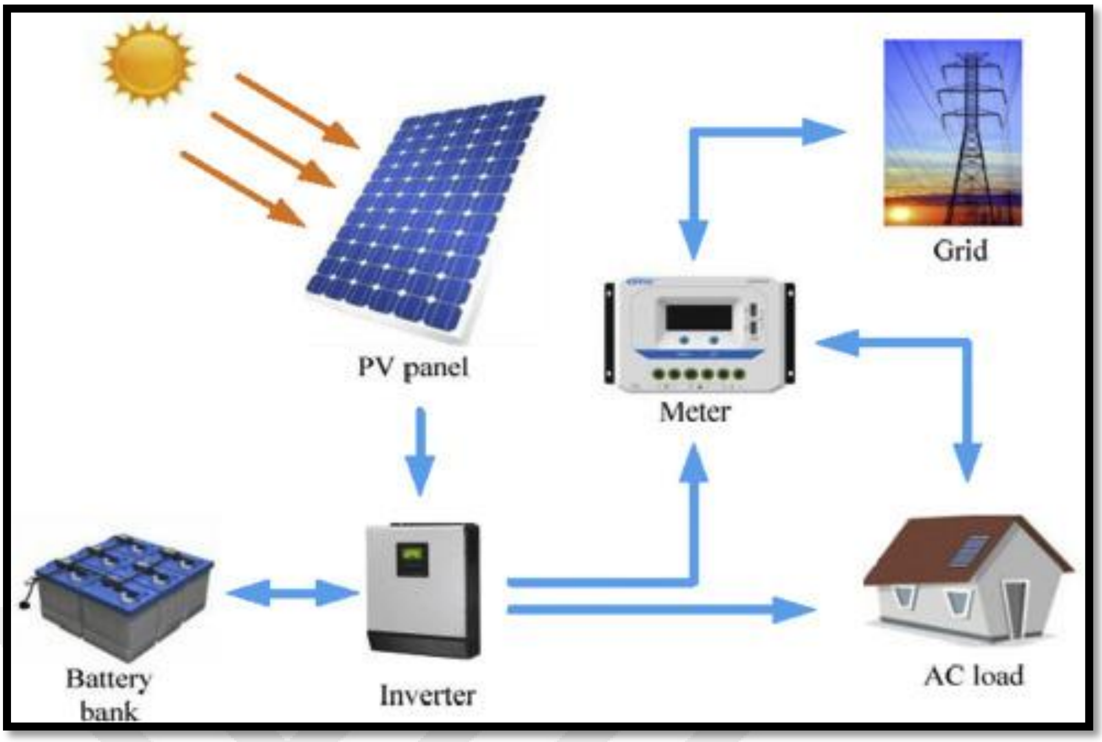

Figure 10 Photovoltaic System Layout

(Source: sciencedirect.com, 2024)

Wind Energy Systems are similar to PV systems, wind turbines using power electronic converters can generate harmonics. APFs can mitigate these harmonics and enhance the stability and efficiency of wind energy systems.

In microgrids, which integrate various distributed generation sources and energy storage systems, APFs play a crucial role in managing power quality. In today's hybrid microgrid systems PV, wind and Storage is the most common renewable energy source combination as shown in Figure 11. They ensure the seamless integration of multiple energy sources and maintain voltage and current waveforms within acceptable limits (Saeed et al., 2021).

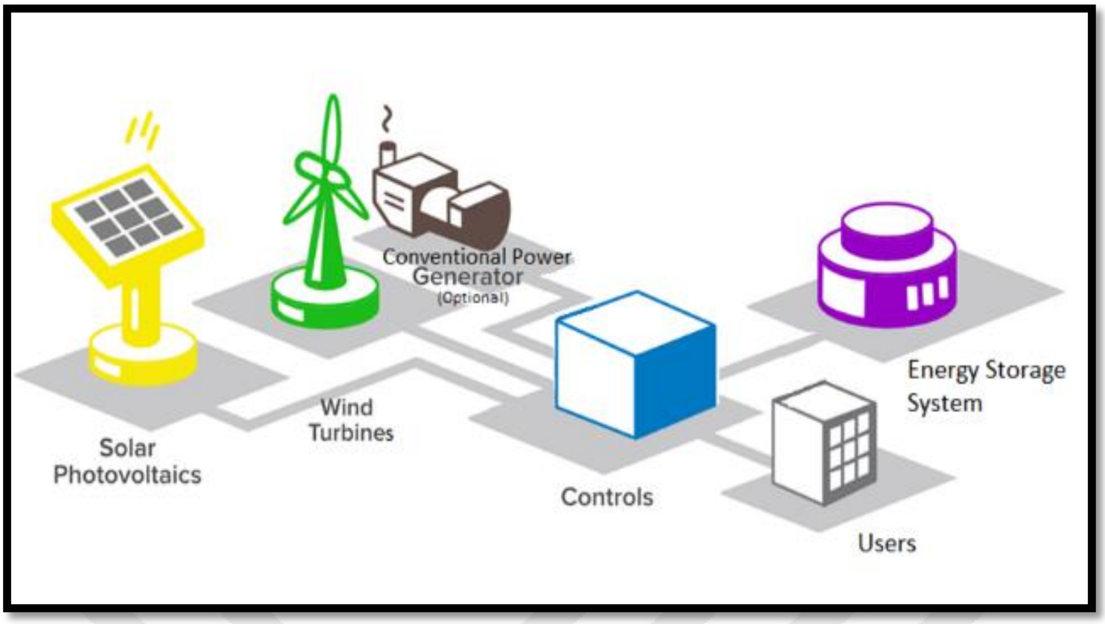

Figure 11 Hybrid Microgrid System Layout

(Source: stellaeenergy.com,2024)

Distributed Generation in APFs help in balancing the load and managing the power quality issues arising from the distributed generation units connected to the main grid or operating in islanded mode (Stock et al., 2021).

Electric Vehicles (EVs) The increasing penetration of EVs and their charging infrastructure introduces significant harmonics into the power grid. APFs can be utilized to mitigate these harmonics, ensuring efficient and safe operation of EV charging stations.

Smart Grids APFs are integral components of smart grids, which rely on advanced communication and control systems to manage power quality (Moreno et al., 2021). APFs ensure that the power delivered in smart grids is of high quality, free from disturbances caused by harmonics and other electrical noise. Smart grid is an advanced electrical grid system that integrates different type of resources and communication which is two-way flow of electricity between utilities and consumers as illustrated in Figure 12.

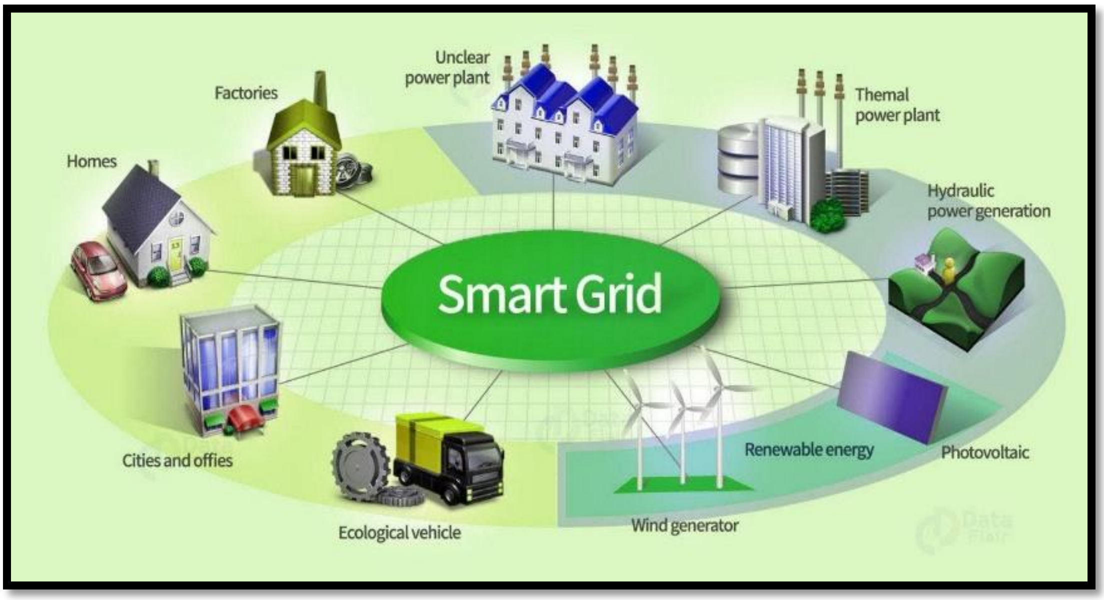

Figure 12 Smart Grid System Demonstration

(Source: hashstudioz.medium.com)

3. Benefits of AFP

APFs offer numerous advantages in improving power quality in Hybrid Electrical Energy Systems.

- APFs provide dynamic and effective harmonic mitigation compared to passive filters, which are limited to specific harmonic frequencies.
- Improved Power Factor by compensating for reactive power, APFs help in improving the power factor, which leads to more efficient use of electrical power.
- Versatility APFs can handle varying loads and adapt to changing conditions in real-time, making them suitable for a wide range of applications (Yap et al., 2020).
- Reduction of Resonance Issues unlike passive filters, APFs do not introduce resonance problems in the power system, thus enhancing system stability.
- Enhanced Reliability and Longevity of Equipment by improving power quality, APFs help in reducing the stress on electrical equipment, thereby extending their operational life and reducing maintenance costs.

4. Limitations of AFPs

While APFs offer numerous advantages in improving power quality, they also have certain limitations that need to be addressed too.

- High initial cost the initial investment required for APFs is relatively high compared to passive filters, which can be a deterrent for their widespread adoption.
- Complexity in design and implementation the design and implementation of APFs involve sophisticated control algorithms and power electronic components, which require specialized knowledge and expertise.
- Maintenance and Operational costs while APFs reduce maintenance costs of other equipment, they themselves require regular maintenance and monitoring, adding to operational expenses.
- Capacity of APFs have a limited capacity for harmonic compensation, and their effectiveness can be reduced if the harmonic levels exceed their designed capacity.
- Power losses APFs, especially those using power electronic converters, can introduce additional power losses into the system, affecting overall efficiency.

B. Advanced Synchronization Techniques

Synchronization techniques are critical in power systems and electronic applications, ensuring the coordinated operation of various system components. As power systems become more complex with the integration of renewable energy sources, EV and smart grid technologies, advanced synchronization methods are necessary to maintain system stability and reliability (Jia et al., 2020). This part of thesis discusses three key advanced synchronization techniques such as Phase-Locked Loops (PLL), Synchronized Switching Technique and Real-time Synchronization Algorithms.

1. Phase-Locked Loops

Phase-Locked Loops (PLLs) are integral components in a variety of electronic systems, functioning to synchronize an output signal's phase and frequency with a reference input signal. A typical PLL is composed of three primary elements: the phase detector, the loop filter and the voltage-controlled oscillator (VCO).

a. Phase detector

The phase detector is the initial stage of the PLL, responsible for comparing the phase of the input reference signal with the phase of the signal generated by the VCO. It outputs a signal proportional to the phase difference, known as the phase error. This error signal is crucial for indicating whether the VCO needs to increase or decrease its frequency to match the input signal. With growth of renewable and communication data processing in monitoring including wired and wireless systems, the phase detector in PLL becomes more important [Yang et al., 2020].

b. Loop filter

Following the phase detector, the phase error signal is directed to the loop filter. This component smooths out the rapid variations in the error signal, effectively reducing noise and ensuring a stable control signal. The loop filter is typically a low-pass filter that helps in removing high-frequency noise and providing a clean error signal for the VCO.

c. Voltage-controlled oscillator

The VCO is the heart of the PLL, producing an output signal whose frequency is determined by the input control voltage (Maghami and Mutambara, 2023). The filtered error signal from the loop filter adjusts the VCO's frequency. If the phase error indicates that the VCO is running too fast or too slow, the control voltage adjusts accordingly, bringing the VCO back into alignment with the input signal.

d. Closed-loop operation

In this closed-loop system, the VCO continuously adjusts its output based on the feedback from the phase detector and loop filter. This dynamic adjustment process enables the PLL to lock onto the frequency and phase of the input signal, maintaining synchronization even if the input signal varies over time.

This intricate interaction among the phase detector, loop filter and VCO which allows PLLs to achieve precise frequency and phase synchronization as well as making them essential in applications ranging from radio communications and signal processing to power electronics and motor control.

e. Principles and operation

Phase Detector compares the phase of the input signal with the phase of the VCO output signal. The difference, known as the phase error, is used to adjust the VCO.

Loop Filter the phase error is passed through a loop filter, which smooths the signal to reduce noise and improve stability. The filtered signal is then used to control the VCO.

VCO adjusts its frequency based on the control signal from the loop filter. The output of the VCO is fed back to the phase detector, creating a closed-loop system that locks the phase of the VCO to the input signal.

f. Types of PLLs

Analog PLLs are the traditional type, implemented using analog components. They are widely used in radio frequency applications and analog signal processing. Digital PLLs use digital components, such as counters and digital filters, making them suitable for digital communication systems.

Software PLLs Implemented in software, these are highly flexible and can be used in various applications, including signal processing in microcontrollers and Digital Signal Processors (DSPs).

g. Applications in power systems

Grid Synchronization PLLs are crucial for synchronizing inverters and other grid-connected devices to the utility grid. Accurate synchronization ensures that these devices operate efficiently and safely without causing disturbances in the grid (Hua et al,. 2021).

In solar and wind power systems, PLLs help synchronize the output of inverters with the grid frequency, ensuring stable and efficient power delivery. In addition, in electric motor drives, PLLs are used to synchronize the speed and phase of the motor with the control signals, enhancing performance and efficiency.

2. Synchronized Switching Techniques

Synchronized switching techniques involve controlling the switching actions of power electronic devices to occur at specific points in the electrical waveform. This synchronization helps in reducing electrical transients, minimizing Electromagnetic Interference (EMI), and improving overall system efficiency and reliability (Lallart and Lombardi, 2020).

a. Key concepts

Zero-Crossing Detection: One common synchronized switching technique is zero-crossing detection, where switching occurs when the voltage or current waveform crosses zero. This reduces the switching transients and associated EMI.

Phase Angle Control: In some applications, switching actions are synchronized to occur at specific phase angles of the AC waveform. This technique is often used in thyristor-based systems, such as controlled rectifiers and AC voltage controllers.

Pulse Width Modulation (PWM): It is a widely used synchronized switching technique in power electronics. By adjusting the duty cycle of the switching signals, PWM controls the output voltage and current while minimizing harmonic distortion.

b. Applications in power systems

- Soft starters use synchronized switching techniques to gradually increase the voltage supplied to electric motors, reducing inrush currents and mechanical stress.
- In SVCs, synchronized switching of thyristors is used to control the reactive power injected into the power system, thereby regulating voltage levels and improving stability.
- Inverters used in renewable energy systems, such as solar and wind, employ synchronized switching techniques to ensure that the output power is efficiently and reliably delivered to the grid.

c. Benefits

- Reduced electrical transients synchronizes switching minimizes electrical transients, reducing stress on power system components and extending their lifespan.
- Improved power quality by carefully controlling the switching instants, synchronized switching techniques help in reducing harmonics and improving overall power quality.
- Enhanced efficiency these techniques optimize the switching actions, leading to reduced power losses and enhanced system efficiency.

3. Real-time Synchronization Algorithms

Real-time synchronization algorithms are designed to ensure that various components of a power system or electronic system operate in perfect harmony. These algorithms are crucial in applications where precise timing and coordination are required, such as in distributed generation, microgrids and communication systems.

a. Characteristics of Real-time synchronization algorithms

- Low latency are real-time synchronization algorithms must operate with minimal delay to ensure that synchronization actions are performed promptly and accurately.
- High precision algorithms require high precision in detecting and adjusting the phase and frequency of signals to maintain synchronization (Abdulwahid, 2023).
- They must be robust to handle variations in the operating conditions such as changes in load, voltage and frequency.

b. Types of Real-time synchronization algorithms

Discrete Fourier Transform (DFT) and Fast Fourier Transform (FFT) these algorithms are used to analyze the frequency components of signals and are essential in identifying harmonics and synchronizing inverters to the grid frequency.

Kalman filters are used for estimating the state of a dynamic system. They are effective in filtering noise and providing accurate synchronization in noisy environments. PLL Variants such as adaptive PLLs and enhanced PLLs, are used in real-time synchronization applications to provide high accuracy and stability.

Artificial Intelligence (AI)-based algorithms are AI techniques, such as neural networks and machine learning algorithms, are increasingly used for real-time synchronization due to their ability to learn and adapt to complex patterns and operating conditions.

c. Applications in power systems

Real-time synchronization algorithms are indispensable in modern power and communication systems due to their ability to maintain precise timing and coordination across various components. In microgrids, these algorithms are vital for integrating diverse distributed generation sources, such as solar panels, wind turbines and battery storage systems. By synchronizing these sources, real-time algorithms ensure a balanced and stable power supply, mitigating the risks of frequency fluctuations and voltage instability.

For inverters connected to the utility grid, real-time synchronization algorithms play a crucial role in maintaining power quality. They synchronize the inverter's output with the grid's frequency and phase, which not only prevents disturbances such as flicker and harmonics but also enhances the overall efficiency of power conversion (Kataria and Puri, 2022). This is particularly important as the penetration of renewable energy sources increases, requiring precise coordination to maintain grid stability.

In protection schemes, real-time synchronization is critical for the accurate detection of faults and the swift operation of protective devices. Differential protection, which compares the current entering and leaving a system component, and distance protection, which measures the impedance to a fault, both rely on real-time synchronization to operate correctly and prevent damage to infrastructure.

In telecommunications, real-time synchronization algorithms ensure the accurate timing of data packet transmission and reception. This synchronization reduces errors, minimizes latency, and enhances the overall quality of service, which is essential for maintaining reliable communication networks, especially as data traffic continues to grow with advancements in technology and increased connectivity demands.

d. Challenges and future directions

As power systems become more complex with the integration of renewable energy sources and distributed generation, real-time synchronization algorithms must be scalable to handle the increased number of components and interactions.

These algorithms must be adaptive to cope with the dynamic nature of power systems, including variations in load, generation, and network topology (Du et al. 2020). With the increasing reliance on digital and communication technologies, real-time synchronization algorithms must be secure to prevent cyber-attacks and ensure the reliability of power systems.

4. Dynamic Voltage Restorers

DVRs are used in hybrid energy systems where they help to manage voltage deteriorations such as sags and swells so as to maintain power quality and supplies. DVRs work on the principle of maintaining the correct voltages at correct places by seating the right voltage levels into the system; this is crucial to accommodate variable sources of energy including solar, wind or conventional grid energy (Aguila-Camacho and Gallegos, 2024). It is mostly used in series with critical or sensitive loads against transient impulses as well as voltage variation. Using power electronics control and superimposing voltage sources, DVRs quickly mitigate voltage swell or sag events within milliseconds, thus avoiding any interference with the system. This capability is especially helpful in microgrids or any system that contains both traditional centralized power distribution and renewable energy sources, where the latter may lead to fluctuations and frequently changing voltage levels (Ahmadi et al., 2024). Hence, DVRs acts as key factor which improves the overall stability and efficiency of the hybrid energy systems and, therefore, lead to improvement of the reliability of energy networks.

5. Flexible AC Transmission Systems

The Flexible AC Transmission Systems (FACTS) is properly involved in improving the efficiency and flexibility of most power systems in the hybrid energy systems. The FACTS has some technical challenges such as power losses, voltage fluctuations and reliability problems in the electrical systems [Ngei and Moses, 2023]. The FACTS devices that include STATCOM, Thyristor Controlled Reactor

(TCR), Thyristor Switched Capacitor (TSC) and SVC functions to control voltage, manage power flow and enhance stability (Ahmad and Sirjani, 2019). The power of these devices combined allows hybrid energy systems to adjust to changes in supply or demand in energy and has the ability to harmonize and utilize several energy sources such as wind, solar, or even the more conventional power sources. The FACTS technology helps in minimizing problems like congestion and instability of the flowing power which thus facilitates an efficient and reliable transmission network (Mousaei et al., 2023). This flexibility is beneficial for integrating renewable power sources which lately are most of the time unpredictable and unreliable. Thus the FACTS are very much needed in order to have more modernized Grid and help to change power flow steady-state condition as well as provide a flexible capacity constraints, and shape the future electricity delivery system (Frolov et al., 2019).

6. Unified Power Quality Conditioners

Unified Power Quality Conditioners (UPQCs) are active components of hybrid energy systems carried out to rectify precise power quality problems including voltage sags, swells, harmonics, and imbalance. They also utilize series and shunt active power filters to reduce the disturbances to a acceptable level, thereby guaranteeing a stable source of power. Thus, the series filters deals with voltage problems by injecting the right value of voltage on the load side, while the shunt filters deal with current problems, including harmonics and reactive power. As a result of offering broad power quality enhancement, the UPQCs support the contemporary integration of renewable power sources into the grid layout, leading to improved reliability and efficiency of the overall system, according to (Badrudeen et al., 2024). They are versatile for many load profiles and effective to address complications in power quality in modern hybrid electricity systems. For this reason, UPQCs contribute to the energy change since they continue to provide a stable power supply to both regular consumers and delicate electrical devices. The Figure 13 demonstrates the block diagram of UPQC with its series and shunt controllers that has a common point of connection [Kumar and Mallesham, 2023].

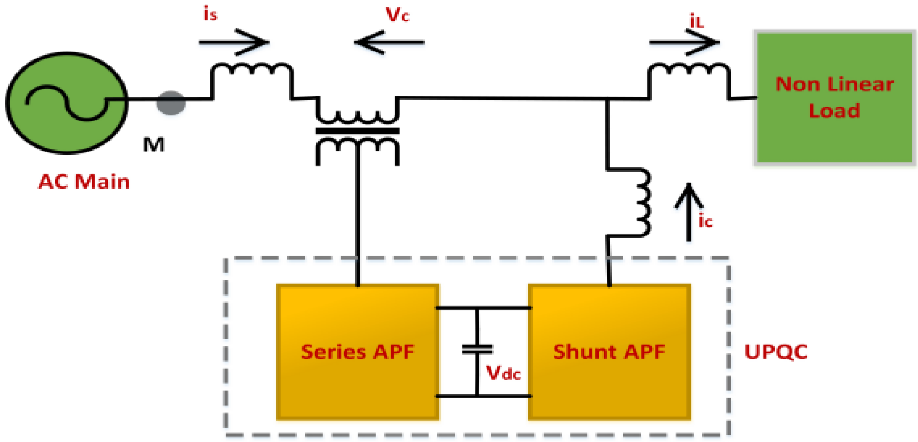

Figure 13 Block diagram of UPQC

C. Hybrid Active Power Filters

Hybrid Active Power Filters (HAPFs) are advanced solutions designed to improve power quality in electrical systems by combining passive and active filtering technologies. Effective mitigation of harmonic distortions, compensation for reactive power, and enhancement of overall system stability are achieved through this combination. Passive filters address lower-order harmonics, while active filters manage higher-order harmonics and provide dynamic compensation. This hybrid approach ensures efficient and flexible performance, making HAPFs ideal for various industrial and commercial applications where maintaining power quality is crucial for the reliability and efficiency of electrical equipment (Li et al. 2021). Scalability and adaptability allow HAPFs to meet diverse power quality needs, supporting the seamless operation of modern electrical infrastructures. By integrating both passive and active elements, HAPFs offer a comprehensive solution for addressing a wide range of power quality issues in complex electrical systems.

1. Integration of APFs and Other Control Methods

The integration of Active Power Filters (APFs) with other control methods significantly enhances power quality management in electrical systems. This approach combines the strengths of various techniques, leading to more robust and adaptive solutions for mitigating harmonics and managing reactive power.

a. Proportional-integral control

Proportional-Integral (PI) controllers are commonly used in APFs to regulate current and voltage. Adjustments to the proportional and integral gains maintain desired setpoints, ensuring effective harmonic compensation and reactive power management. Figure 14 below shows the main difference is that Config. 1 places the active power filter (APF) in series with a shunt passive filter, while Config. 2 uses a combined series APF and a separately connected shunt passive filter, offering more control over both current and voltage harmonics.

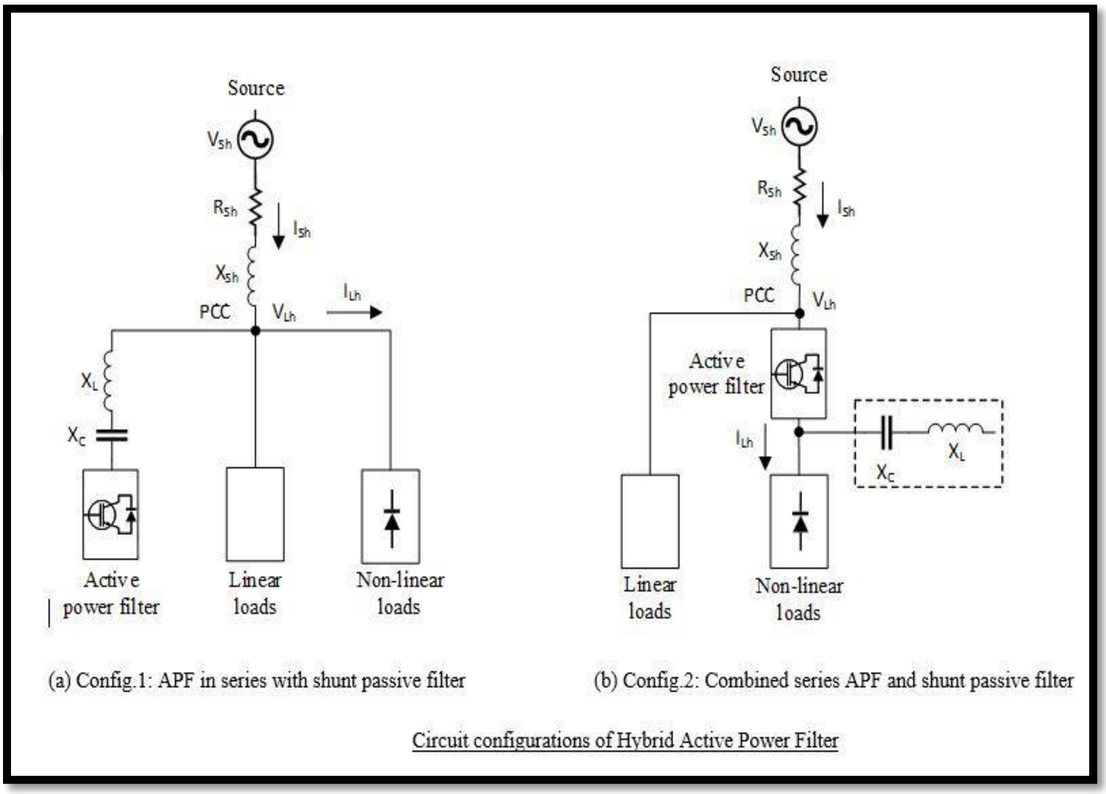

Figure 14 Hybrid Active Power Filters (HAPFs)

(Source: researchgate.net, 2024)

b. Hysteresis current control

Hysteresis current control involves maintaining the current within a predefined hysteresis band. APF switches operate to keep the error between the reference and actual current within this band, resulting in precise harmonic compensation (Hannan et al., 2021). Known for its fast response and robustness against parameter variations. Therefore, hysteresis control is highly effective in APF applications.

c. Predictive control

Predictive control methods, such as Model Predictive Control (MPC), forecast future system behavior and optimize control actions accordingly (Viturino et al., 2020). The anticipating load currents and compensating in advance, MPC achieves superior performance in harmonic reduction and dynamic response.

d. Fuzzy logic control

Fuzzy logic control enhances APF adaptability to varying load conditions. Fuzzy logic controllers manage non-linearities and uncertainties in the system more effectively than traditional controllers. By defining a set of fuzzy rules, APFs can dynamically adjust operations, ensuring optimal performance under different scenarios.

e. Neural networks

Neural network-based control methods learn and adapt to complex patterns in electrical systems. Training the neural network with historical data enables APFs to predict and compensate for harmonics more accurately (Gong et al., 2020). This approach is especially useful in systems with non-linear loads where traditional control methods may be less effective.

f. Genetic algorithms

Genetic algorithms optimize APF control system parameters by simulating natural evolution processes. By selecting, crossing, and mutating potential solutions, genetic algorithms find optimal control parameters that minimize harmonic distortion and improve power quality.

g. Sliding mode control

Sliding Mode Control (SMC) provides robustness and fast dynamic response. By enforcing system states to slide along a predefined surface, SMC ensures efficient APF operation even under rapid load changes. This method effectively handles non-linearities and system uncertainties. The integration of APFs with other control methods provides a comprehensive solution for power quality management, combining the strengths of various techniques to achieve superior performance in harmonic mitigation and reactive power compensation.

2. Performance Enhancement

Enhancing the performance of APFs involves implementing advanced strategies and technologies to improve efficiency and effectiveness in power quality management. Various methods can be employed to achieve optimal performance in APFs, ensuring reliable harmonic compensation and reactive power management.

a. Advanced control algorithms

Adaptive Control Techniques: These techniques allow APFs to adjust parameters in real-time based on load and system condition changes and continuous monitoring (AI/ML) and optimization ensure effective harmonic mitigation and reactive power compensation under dynamic scenarios (Taghvaie et al., 2023).

b. Model predictive control

Utilizing a mathematical model, MPC predicts future system behaviour and optimizes control actions. This approach enables proactive compensation, enhancing dynamic response and reducing total harmonic distortion (THD) in hybrid systems.

c. Artificial intelligence and machine learning

Artificial Intelligence (AI) and Machine Learning (ML) algorithms analyze historical and real-time data to identify patterns and optimize APF operations. These technologies enable APFs to learn from past performance and adapt to new conditions, providing intelligent and efficient power quality management (Zulu et al., 2023).

3. Hardware Improvements

a. High-speed digital signal processors

High-speed Digital Signal Processors (DSPs) enhance computational capabilities, allowing APFs to handle complex algorithms and large datasets more efficiently. Improved processing power leads to better harmonic compensation and faster response times.

b. Advanced power electronic devices

Innovations in power electronic devices, such as Insulated-Gate Bipolar Transistors (IGBTs) and silicon carbide (SiC) components, improve switching performance and efficiency. These devices offer lower switching losses, higher thermal stability and faster switching speeds that contributing to enhanced APF performance.

c. Modular design

Implementing a modular design allows for scalability and redundancy. Dividing the APF into smaller, interchangeable modules facilitates expansion for higher loads and improves fault tolerance and system reliability.

4. Integration with Renewable Energy Sources

a. Photovoltaic systems

Integrating APFs with PV systems provides enhanced harmonic compensation and reactive power support, optimizing renewable energy utilization. PV systems often cause harmonic distortion and voltage fluctuations, especially under varying solar irradiance. By integrating APFs, these power quality issues are mitigated by dynamically compensating for harmonic currents and stabilizing voltage. The APF generates compensating currents that counteract harmonic distortions produced by nonlinear loads or inverters used in PV systems, thus maintaining a cleaner current waveform. APFs enhance the overall efficiency and reliability of PV systems by reducing losses associated with harmonics and poor power factor, extending equipment life and improving energy yield.

b. Wind power systems

Integrating APFs with Wind Power Systems is a growing area of interest in renewable energy to enhance power quality and improve system reliability. Wind energy systems can introduce power quality issues like harmonics, reactive power, and flicker due to their variable output and nonlinear nature, especially when interfaced with the grid. APFs offer a solution by dynamically compensating for these disturbances and ensuring smoother power delivery. The integration of Active Power Filters with Wind Power Systems plays a crucial role in mitigating power quality issues, thus making wind energy a more reliable and grid-friendly renewable source. The synergy between APFs and wind systems supports the stability and compliance of wind power with modern grid standards, enhancing the adoption of renewable energy in power networks.

c. Energy storage systems

Combining APFs with ESS, such as batteries or supercapacitors, enhances stability and reliability, providing additional reactive power support and smoothing power fluctuations. Enhancing the performance of APFs involves a combination of advanced control algorithms, hardware improvements, integration with renewable energy sources and robust communication and monitoring systems By adopting these strategies, APFs can provide more effective and efficient power quality solutions as well as ensuring the stability and reliability of modern electrical systems.

d. Adaptive control strategies

Adaptive control strategies optimize the performance of APFs by allowing real-time adjustments to parameters, ensuring effective harmonic compensation and reactive power management in dynamic electrical environments.

e. Self-tuning control

Self-tuning control continuously adjusts controller parameters based on real-time system performance. Algorithms monitor system responses and automatically modify control settings to maintain optimal operation. Real-Time Optimization continuous adjustment of parameters ensures peak efficiency under varying load conditions. It maintains system stability even with unexpected disturbances or non-linear loads. It also provide a quick adaptation that minimizes overshoot and reduces stabilization time.

f. Model reference adaptive control

Model Reference Adaptive Control (MRAC) employs a reference model to define desired system behaviour, adjusting control parameters to minimize the error between actual output and reference model output. It is striving to match the reference model ensures high accuracy in harmonic compensation and reactive power management and handles changes in system dynamics by continuously adapting control parameters. It also uses the reference model for future behaviour prediction, allowing proactive adjustments.

g. Fuzzy logic adaptive control

Fuzzy logic controllers handle uncertainties and non-linearities using linguistic rules and fuzzy sets, providing robust and adaptable control. It manages non-linear system behaviours, ideal for complex power systems with variable loads. It inherent robustness maintains performance even with significant disturbances to overcome for adaptive control in APFs.

h. Neural network-based adaptive control

Neural networks learn and adapt to complex system behaviours through training, optimizing APF operation. It analyses historical and real-time data to identify patterns and optimize control actions. It continuously updates control strategies based on new information, suitable for dynamic environments to have adaptive learning. This control system also achieves precise harmonic compensation and reactive power management through learning capabilities provide a better accuracy.

i. Genetic algorithm-based adaptive control

Genetic algorithms optimize control parameters through natural evolution simulation, finding optimal solutions. It creates best optimization to perform global search for optimal parameters, avoiding local minima. The system evolves control parameters over time to adapt to changing system conditions as well as has a robust system against system uncertainties and variations.

Adaptive control strategies significantly enhance the performance of APFs by allowing them to dynamically adjust to changing electrical environments. Techniques such as self-tuning control, MRAC, fuzzy logic, neural networks, and genetic algorithms provide robust, accurate, and efficient solutions for maintaining power quality (Elbarbary and Alranini, 2021). By implementing these adaptive control strategies, APFs can effectively mitigate harmonics, manage reactive power, and ensure the stability and reliability of modern electrical systems.

D. Energy Storage Systems for Power Quality Enhancement

Energy Storage Systems (ESS) play a pivotal role in enhancing power quality by providing reliable energy management solutions. These systems mitigate power fluctuations, stabilize voltage, and compensate for reactive power, improving overall reliability and efficiency of electrical grids. ESS, such as batteries and supercapacitors, store excess energy during low-demand periods and release it during peak demand, ensuring a continuous and stable power supply. Integrating ESS with renewable energy sources and advanced power conditioning equipment, such as APFs, significantly enhances power quality, supporting the seamless operation of modern electrical infrastructures and ensuring stability in power distribution networks. ESS also facilitates renewable energy integration for further boosting grid resilience.

1. Battery Energy Storage Systems

Battery Energy Storage Systems (BESS) are integral to modern electrical grids, providing critical support for power quality enhancement. These systems store electrical energy in batteries during periods of low demand and release it when demand is high, thus ensuring a stable and reliable power supply. BESS can significantly improve power quality by mitigating power fluctuations, voltage sags and swells and harmonic distortions. Key components of BESS are the batteries, Battery Management System (BMS) and Power Conversion System (PCS). Figure 15 below demonstrates a BESS system.

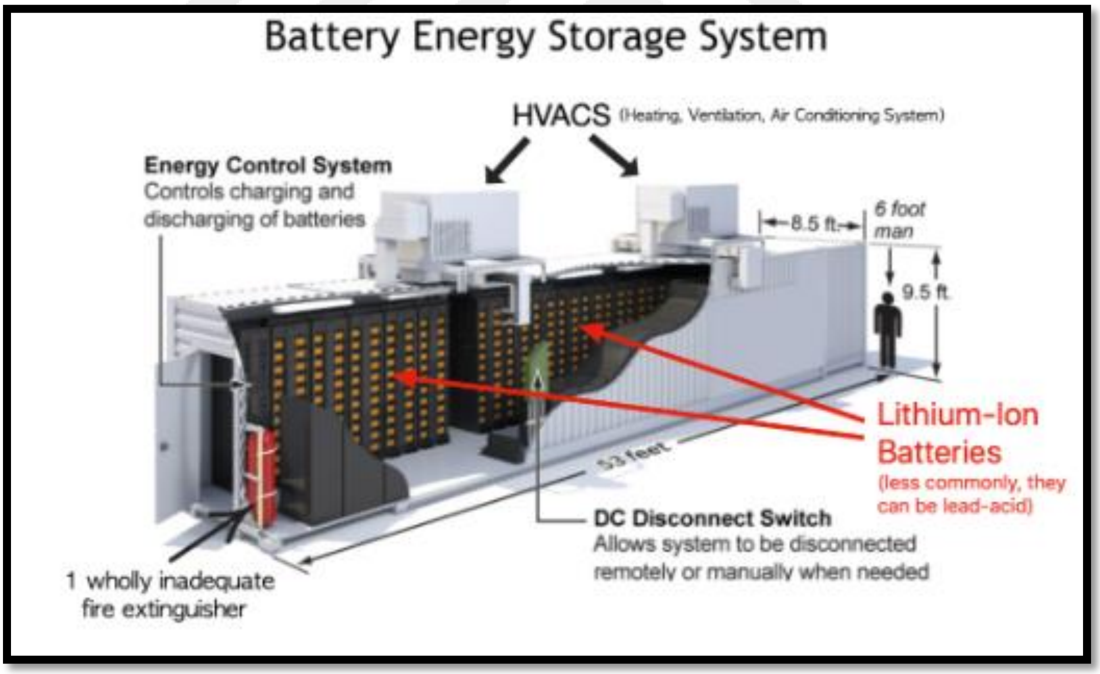

Figure 15 Energy Storage System Demonstration

(Source: innoliaenergy.com, 2024)

a. Batteries

Batteries are the primary components of BESS, capable of storing and discharging electrical energy. Various types of batteries, including lithium-ion, lead-acid, nickel-cadmium, and flow batteries, are used based on the specific requirements of the application. Lithium-ion batteries are particularly popular due to these high energy density, long cycle life and efficiency.

b. Power conversion system

Power Conversion System(PCS) manages the conversion between AC and DC power, ensuring that the energy stored in the batteries can be effectively utilized by the grid (Stecca et al., 2020). It includes inverters, rectifiers, and bidirectional converters, which facilitate the charging and discharging processes.

c. Battery management system

The BMS monitors and controls the battery's state of charge, temperature, voltage, and current. It ensures the safe and efficient operation of the BESS, preventing overcharging, deep discharging and thermal runaway.

2. Applications in Power Quality Enhancement

Applications in power quality enhancement address issues related to voltage, frequency, and waveform deviations in power systems, ensuring efficient and reliable operation of electrical equipment. Here are some key applications.

a. Voltage regulation

BESS can help maintain a consistent voltage level in the grid by injecting or absorbing reactive power as needed. This capability is crucial in preventing voltage sags and swells, which can damage sensitive equipment and disrupt industrial processes as well as grid stability.

b. Harmonic mitigation

By providing a clean and stable power supply, BESS can reduce the harmonic distortions caused by non-linear loads. This is particularly important in industrial environments where equipment such as variable frequency drives and power electronics can generate significant harmonics (Shukir, 2021).

c. Frequency stabilization

BESS can respond rapidly to frequency deviations by discharging or absorbing power to balance supply and demand. This rapid response helps maintain the grid frequency within acceptable limits, ensuring the stable operation of electrical systems.

d. Load levelling and peak shaving

During periods of high demand, BESS can discharge stored energy to reduce the load on the grid, a process known as peak shaving. Conversely, during periods of low demand, BESS can store excess energy, control system and a process known as load levelling (Ferreira et al., 2023). This helps to balance the load, reducing the need for additional generation capacity and improving overall grid efficiency .

3. Integration with Renewable Energy Sources

Integrating BESS with renewable energy sources, such as solar and wind, enhances power quality by addressing the intermittency of these sources. For example,

a. Solar energy integration

BESS can store excess solar energy generated during the day and release it during the night or during periods of low sunlight, ensuring a continuous power supply and mitigating fluctuations in solar power output.

b. Wind energy integration

Similarly, BESS can store energy generated during periods of high wind and release it during calm periods, smoothing out the variability in wind power generation. Battery Energy Storage Systems (BESS) offer a versatile and effective solution for enhancing power quality in modern electrical grids. By providing voltage regulation, harmonic mitigation, frequency stabilization, and load balancing, BESS contribute to a more stable and reliable power supply (Reddy et al., 2022). Their integration with renewable energy sources further enhances their role in achieving sustainable and efficient energy management. As technology advances and costs decrease, BESS are expected to play an increasingly important role in the future of power quality enhancement.

4. Supercapacitors and Flywheels

Supercapacitors and flywheels are two advanced energy storage technologies that significantly contribute to power quality enhancement. These systems provide rapid response to power fluctuations, voltage sags, and frequency deviations, ensuring a stable and reliable power supply. These unique characteristics make them ideal for applications requiring high power density and fast energy discharge.

Supercapacitors, also known as ultracapacitors, store energy electrostatically rather than chemically, which allows for faster charge and discharge cycles compared to conventional batteries (Barra et al., 2021). These are characterized by high power density, long cycle life, and the ability to deliver quick bursts of energy.

a. High power density

Supercapacitors can deliver and absorb high power rapidly, making them suitable for applications that require quick energy bursts to stabilize voltage levels or compensate for power fluctuations. This high-power density is crucial for mitigating voltage sags and swells, which can affect sensitive equipment and industrial processes.

b. Long cycle life

Unlike batteries, supercapacitors can endure millions of charge-discharge cycles with minimal degradation. This longevity ensures sustained performance over time, reducing the need for frequent replacements and maintenance.

c. Fast response time

Supercapacitors can respond almost instantaneously to power quality issues, providing immediate support to the grid. This rapid response is essential for frequency stabilization and short-term power support during transient disturbances.

d. Applications

Voltage Stabilization of supercapacitors can stabilize voltage by providing reactive power support during voltage sags and swells. Power Fluctuation Mitigation of these sources can absorb and release energy quickly to smooth out power fluctuations caused by intermittent renewable energy sources or fluctuating loads.

Flywheels store energy mechanically by spinning a rotor at high speeds. When energy is needed, the rotational energy of the flywheel is converted back into electrical energy (Zhao et al., 2020). Flywheels are known for this high-power output, durability, and efficiency in short-term energy storage. High Power Output of Flywheels can provide large amounts of power in a short time, making them effective for applications that require rapid energy discharge. This capability is vital for maintaining power quality during sudden load changes or grid disturbances.

Durability and Low Maintenance of Flywheels have a long operational life and require minimal maintenance. These mechanical nature means these are less susceptible to the chemical degradation that affects batteries, ensuring consistent performance over time. High Efficiency of Flywheels offer high round-trip efficiency, typically between 85% and 95%, making them an efficient option for energy storage and power quality applications.

Applications for them are usually frequency Regulation and Uninterruptible Power Supply (UPS). Flywheels can quickly inject or absorb power to maintain grid frequency within acceptable limits. UPSs provides instantaneous power support during brief outages or disruptions, ensuring continuous power supply to critical loads.

5. Integration and Synergies

Integrating supercapacitors and flywheels with other power quality solutions, such as BESS and APFs, can create a comprehensive approach to power quality management. This combination leverages the strengths of each technology, providing a robust and adaptable solution for various power quality challenges.

a. Hybrid systems

Supercapacitor-Battery Hybrid combination is combining supercapacitors with batteries can enhance overall system performance by using supercapacitors for quick response and batteries for sustained energy supply.

Flywheel-Battery Hybrid combination is about flywheels can handle high power demands and rapid response needs, while batteries provide longer-term energy storage.

b. Renewable energy integration

Supercapacitors and flywheels can smooth out the intermittency of renewable energy sources, ensuring a stable and reliable power supply. By rapidly compensating for power fluctuations, these technologies help integrate renewable energy into the grid more effectively. Supercapacitors and flywheels offer unique advantages for power quality enhancement, including high power density, fast response times, long cycle life, and durability (Elahi et al., 2022). Their integration into modern electrical grids, alongside other energy storage systems, provides a comprehensive solution for maintaining power quality, ensuring stability, and supporting the reliable operation of renewable energy sources. As technology advances, these systems are expected to play an increasingly important role in the future of power quality management.

6. Control Strategies for Energy Storage Integration

Effective control strategies for integrating Energy Storage Systems are essential to maximize the benefits of these technologies and enhance power quality. These strategies ensure that ESS operates efficiently, providing reliable support for voltage regulation, frequency stabilization, and energy management. Various control methods can be employed, each offering unique advantages for different applications.

- Proportional-Integral-Derivative (PID) Control

PID controllers are widely used in ESS integration due to these simplicity and effectiveness. By continuously adjusting the control inputs based on the error between the desired and actual system states, PID controllers maintain stability and optimal performance (Xiang et al., 2020).

- Proportional Control

Responds to the magnitude of the error, providing immediate correction.

- Integral Control

Addresses accumulated errors over time, ensuring long-term accuracy.

- Derivative Control

Predicts future errors based on the rate of change, improving response times. PID control is particularly effective for managing voltage levels and ensuring smooth transitions during charge and discharge cycles.

- Model Predictive Control

Model Predictive Control (MPC) uses a mathematical model of the system to predict future behaviour and optimize control actions. MPC can handle multi-variable control problems and constraints, making it suitable for complex ESS applications (Lu et al., 2023).

- Prediction

Forecasts future system states based on current data and control inputs.

- Optimization

Solves an optimization problem at each time step to minimize a cost function, balancing performance and operational constraints.

- Receding Horizon

Continuously updates predictions and optimizations as new data becomes available.

- Fuzzy Logic Control

Fuzzy logic controllers use linguistic rules and fuzzy sets to handle uncertainties and non-linearities. This approach provides robust and adaptable control, especially in systems with variable and unpredictable conditions (Basit et al., 2020).

- Rule-Based System

A Rule-Based System defines control actions based on a structured set of IF-THEN rules, which serve as a framework to capture and formalize expert knowledge or domain-specific insights. These rules enable the system to make decisions or take actions by evaluating conditions and applying predefined responses, ensuring consistency and transparency in the decision-making process.

- Fuzzification

Converts crisp inputs into fuzzy sets, representing degrees of truth.

- Defuzzification

Transforms fuzzy outputs back into precise control actions. Fuzzy logic control excels in managing non-linear load profiles and integrating renewable energy sources.

- Neural Network Control

Neural networks can learn and adapt to complex system behaviours through training. By analysing historical and real-time data, neural networks optimize ESS operation for enhanced performance.

- Learning Capability

Neural networks can identify patterns and in data, improving control accuracy.

- Adaptability

Continuously updates control strategies based on new information, making it suitable for dynamic environments.

- Non-Linear Control

Effectively handles non-linearities and complex interactions within the system such as neural network control which is beneficial for applications involving high variability and complex interactions, such as renewable energy integration. In addition, Hybrid Control Strategies hat also combining different control methods can leverage the strengths of each, providing a more comprehensive and robust solution for ESS integration.

- PID-MPC Hybrid

Integrates the simplicity of PID with the predictive capabilities of MPC, ensuring both immediate response and long-term optimization.

- Fuzzy Logic-Neural Network Hybrid

Combines the adaptability of fuzzy logic with the learning capabilities of neural networks, enhancing robustness and accuracy. Hybrid strategies offer a flexible approach to managing diverse power quality challenges. Implementing effective control strategies for energy storage integration enhances power quality by ensuring stable voltage, reliable frequency regulation, and efficient energy management (Zhao, 2022). Methods such as PID control, MPC, fuzzy logic, neural network control and hybrid strategies each offer unique benefits, making them suitable for various applications and conditions.

IV. NEW CONTROL STRATEGIES FOR POWER QUALITY

Due to the fact that hybrid energy systems are considered to make up of different components, any variation in voltage level is crucial when it comes to the installation of these systems and also where they are connected. A significant role in the achievement of this goal belongs to the sophisticated control methods, which remove the potential issues, connected with the fluctuations and harmonics, as wells as with the automatic frequency regulation, which may emerge due to the variability of renewables and the interactive nature of the combined systems.

Among the significant objectives achieved within a hybrid energy system, voltage regulation is one of the most challenging goals. There are voltage drop in system due absence of load balance and dispatchable energy production that characterize renewable power (Bahr et al., 2024). Smart control methods make use of complex mathematical formulas coupled with various sensors for automatic monitoring of voltage levels in relation to the generation, distribution and consumption of power. This makes it easier to avoid situations where the voltage level is too high or too low by closely regulating it to the standard voltage level needed for various electrical appliances and equipment hooked to the grid.

There are two major subtopics in relation to power quality: The first one is harmonics which are frequencies that are not wanted since they distort wave forms and can disrupt the functioning of sensitive electronic equipment. Hybrid energy systems that combine both renewable energy and a conventional energy system are exposed to distortion in current harmonics because of differing renewable energy stream characteristics (Chankaya et al., 2024). There is employments of filters and amplitude and phase modulation as identified sophisticated control methods so as to enhance reduction in harmonics thus enhance quality of electricity provided to consumers.

In addition, the other major power quality issue is the grid frequency stability which is crucial for proper functioning of the HESs where grid can be interconnected. Fluctuations can cause desynchronization of generators in charge of providing power to the networks or even system outcomes as it hampers the operation. Sophisticated control frameworks also use prognostic models to predict changing power demand in the grid and adapt the generating control signals to keep the grid frequency within standard ranges quickly.

Furthermore, when implementing ESS in HES, their capability of managing power quality is notably improved. Superior control mechanisms can allow for precise control of the interconnection between the different resources apart from the renewable energy generation and the conventional generation methods alongside the energy storage units essential to control any instabilities in power production.

Therefore, future advancements in control strategies that are aimed at controlling the power quality of the systems that are coupled within hybrid energy systems represent a possible field for applied research. Through active voltage management, harmonic compensations, grid frequency improvement, and controlling energy storage, these strategies help operate with reliability and efficiency (Davari et al., 2024). As mentioned, hybrid energy systems are expected to be an increasingly important part of the global energy mix in the foreseeable future to meet the growing end-use energy demand and address the challenges of climate change and energy security. Therefore, further improvements in control strategies of hybrid energy systems will remain a crucial task in the future to enhance their performance and use in practice. Control strategy for all distributed energies is complex and covers many type of different sources and control strategies as it is demonstrated below in Figure 16.

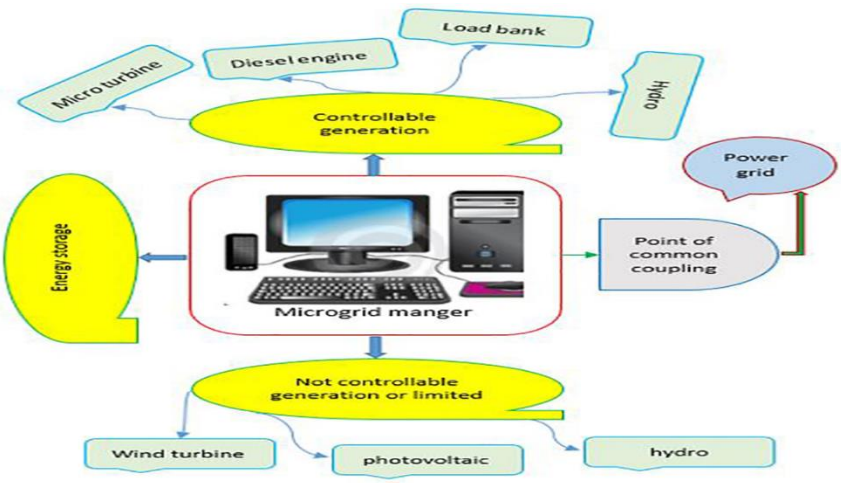

Figure 16 Schematic of a microgrid with different connected energy sources

(Source: Shahgholian G. 2021)

A. Voltage Regulation and Stabilization

Microgrid systems which include a combination of renewable energy such as solar, wind and conventional generators have widely received interesting for their capability to improve power performance. An important part in these systems is the application of sophisticated control methods to enhance power quality, which refers mainly to voltage management and control. It is important to monitor and control the voltage rating in hybrid energy systems, especially given the variability of renewable energy sources and the unpredictable loads that have to be supplied. High level control techniques employ computationally intensive and/or data acquisition techniques to achieve a voltage which has to be kept within a stipulated range to satisfy load demands. These strategies involve the use of control techniques which may be of PID controllers, fuzzy logic controllers, and adaptive systems of control according to (Debdouche et al., 2024). Their principal entails varying the operation parameters of the system depending on the variations in energy supply and consumption. Besides the traditional control strategies, recent ones leverage machine learning and artificial intelligence to be more effective in predicting and, therefore, mitigating a range of conditions when needed. For example, power quality can be forecasted to be a problem in the future through the use of predictive control algorithms which uses data from previous occurrence and current trends to make changes in advance. In addition, the decentralized control systems work where there are several controllers which act in cooperation but autonomously in HES to increase the reliability and vitality. A hierarchical control scheme for hybrid systems that consists of three control levels as shown in Figure 17. A multimode operation control strategy is demonstrated below which is highly used for hybrid energy systems and distributed systems.

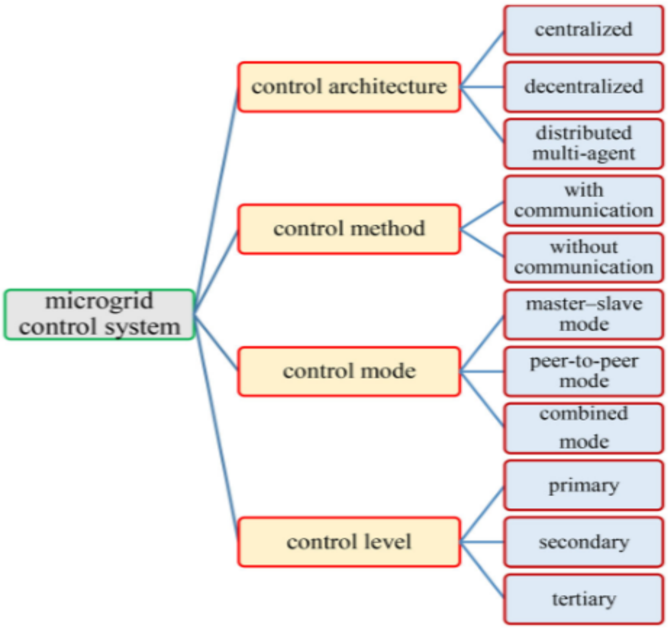

Figure 17 Control method of a microgrid system

(Source: Shahgholian G. 2021)

In general, the need to adopt these control techniques for voltage control and stabilization is crucial for the improvement and efficiency of the feature HESs (Dhara et al., 2024). The proffered strategies help to maintain a stable voltage level to adequately incorporate renewable energy options and minimize the effects of power disturbances on transmission networks, thereby enhancing the stability and reliability of the power grid system.

1. Voltage Control Techniques

Micro-grids or two interconnected power systems are also where energy from various sources is provided to improve dependability and effectiveness, so voltage control methods are crucial here as well. Voltage regulation of such systems is proactive, because of the variability of the interconnected energy solutions which may include Photovoltaic solar power, wind power, batteries and diesel power. Volts in these components influence the system, with some being adjustable to provide specific voltage levels depending on the need of its operation. Voltage Source Converters (VSCs) are the main way of controlling the voltage in voltage control methods, to regulate the voltage level within the desired range. VSC is crucial in controlling power flow between different sources and the grid, more so the voltage level is regulated to the required level (El Myasse et al., 2024). VSC is well know for the control and stabilation of volate in hybrid systems. A topology of VSC system is shown below in Figure 18.

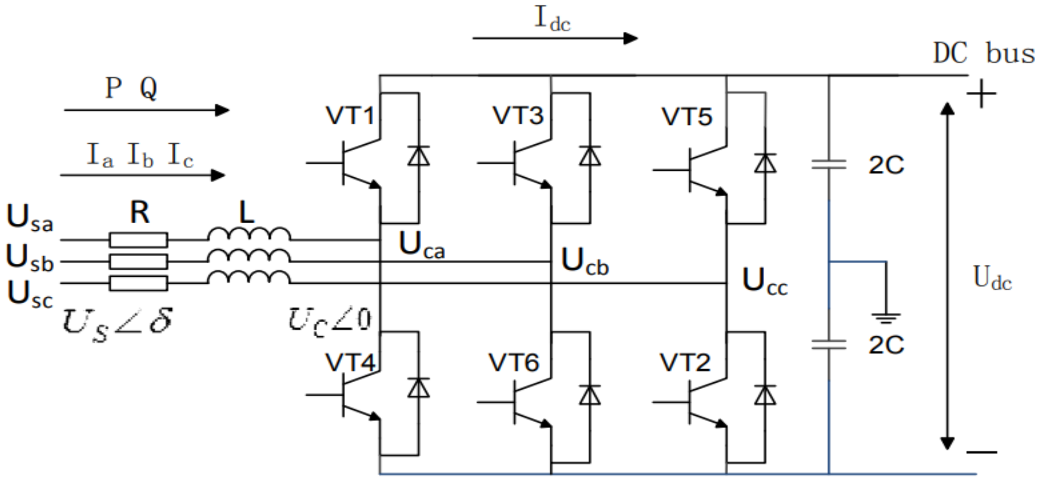

Figure 18 The topology of VSC

(Source: Xu *et al.*, 2016)

By incorporating VSC technology in hybrid systems, voltage control systems gain enhanced precision, stability, and adaptability to meet the demands of modern power systems. VSCs provide numerous benefits when used in voltage control systems as its control diagram can be seen below in Figure 19, particularly in modern power networks. These advantages make VSCs critical components in managing power quality, stability, and efficiency

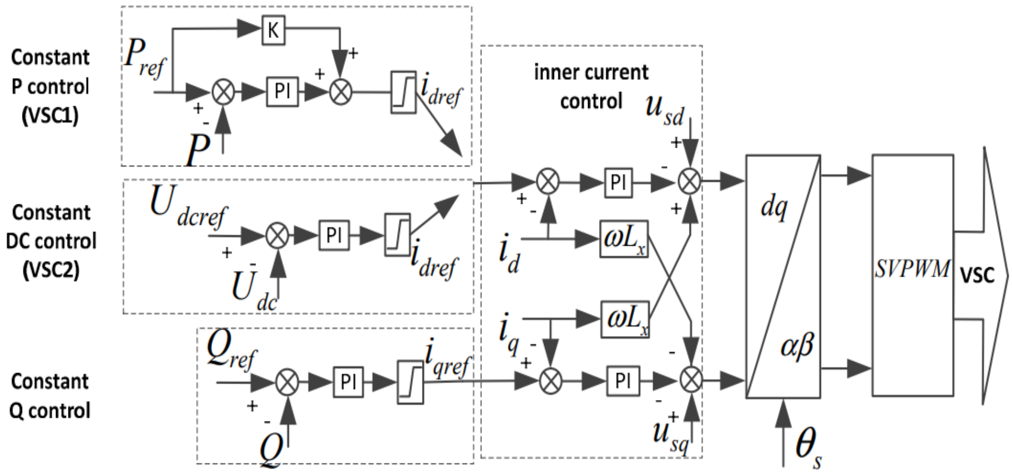

Figure 19 Control System of VSC

(Source: Xu *et al.*, 2016)

This is done by having them convert direct power acquired from the renewable resources into an alternating power that is compatible with the grid as well as supporting in the provision of reactive power for management of voltage. Another crucial method used in operation is the droop control methods (Akpolat et al., 2020). Droop control enables loads to be divided proportionally between several generators or inverters based on the amount of power that each can produce without the actual need for exchanging information. This concept, decentralizes the control of the output voltage of each source and allows it to change thereby regulating the total system voltage levels to permissible limits given the load conditions.

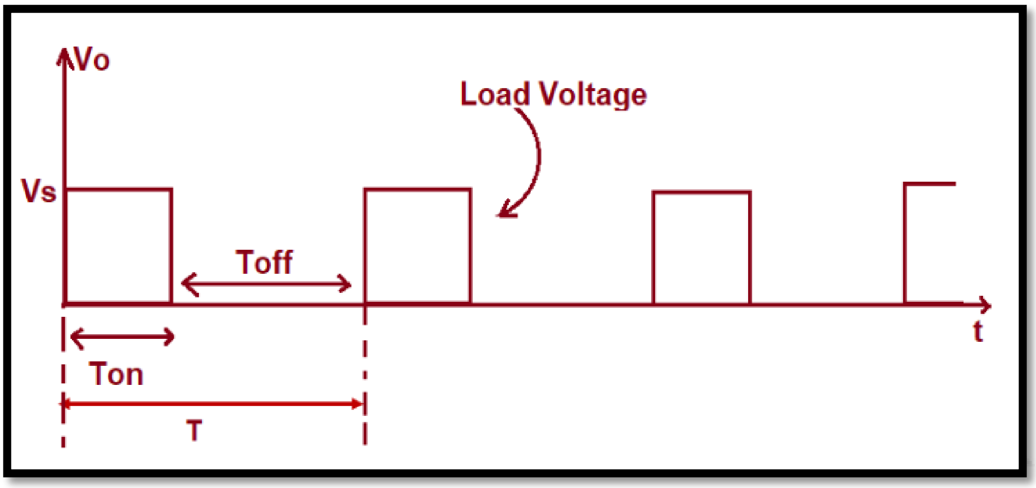

Figure 20 The principle of Pulse Width Modulation Scheme

(Source: El Myasse *et al.* 2024)

The figure 20 above illustrates the principle of the Pulse Width Modulation (PWM) scheme, which is used for controlling the output voltage of power electronic converters. It shows a waveform where the load voltage is modulated by switching between high and low states with defined Ton (on-time) and Toff (off-time) intervals within a switching period *T*. By adjusting the duty cycle, the average output voltage can be regulated to achieve the desired power control in applications such as motor drives, inverters, and power supplies. This also support VSC a lot in control of voltage flactuations.

Moreover, control of modern hybrid energy systems includes not only relevant regulatory mechanisms, but also sophisticated predictive and adaptive ones. These methods uses real time data and statistical models that forecast the load and generation change in advance and voltage control mechanisms are adjusted accordingly (Huang et al., 2024). This post graduate program not only helps in stabilizing the system but also increases its efficiency and reliability.

Overall, Voltage control strategies is about use of VSCs, droop control, integration of ESSs, and advanced prediction methods that play an important role for reviewing effective voltage control in the hybrid energy system. When used together these techniques allow for the constant provision of power, something that cannot be guaranteed when using hybrid energy sources on account of their fluctuations in the energy they generate.

2. Reactive Power Compensation

Control and compensation of reactive power is one of the essential components of functioning and regulation of combined sources of energy. In such systems especially when combined generation from renewable energy options like solar and wind power with the normal generation systems, the question of reactive power management is particularly challenging. Reactive power is crucial to maintaining the voltage levels required for energy transmission. Another benefit of reactive power compensation is voltage control and this is among the key uses of reactive power compensation in hybrid energy systems. In order to ensure that electrical equipment is well function and to also ensure stability of the electrical current in the power grids, proper voltage regulation is imperative. When an appropriate compensation package is not provided, there will be some leading to inefficiencies in operations and potential damage to parts of the system (Imran et al., 2024). These are compensations equipment that are used to control the fluctuations such as capacitor banks, synchronous condensers and static Var compensators (SVCs).

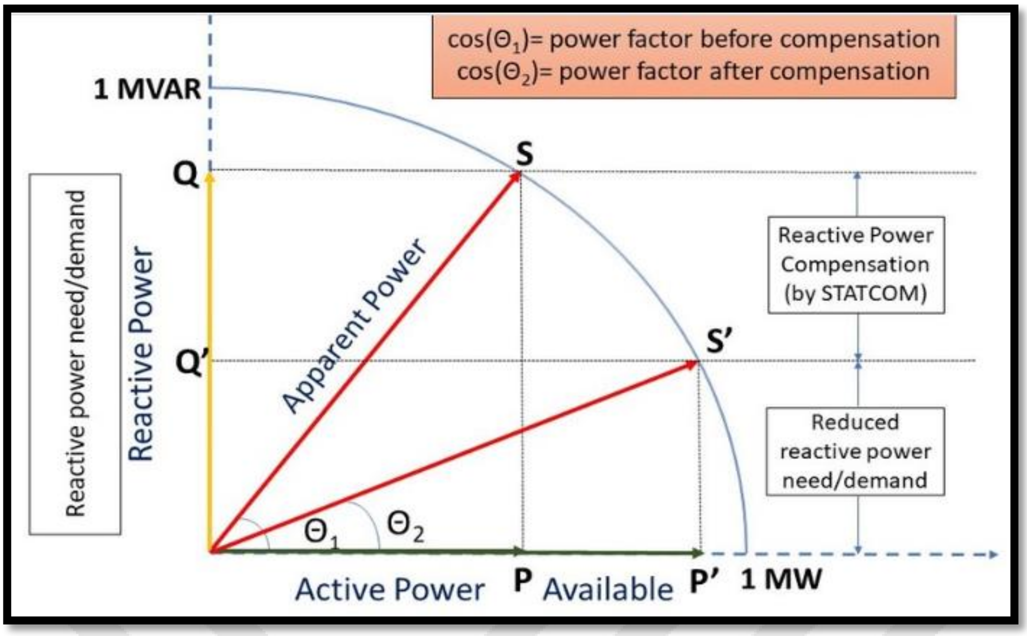

Figure 21 Reactive power compensation curve

(Source: Imran *et al.* 2024)

Figure 21 shows that reactive power compensation helps in the reduction of transmission losses. When there's inadequate reactive power, current that passes through the transmission lines rises and thus more power is lost through the resistance offered by the transmission lines. Through the transformation of reactive power at the respective locations, the compensation devices help to minimize the currents through the system thus reducing on the transmission loss of the system. This aspect is specifically impactful in the integrated systems where renewable power resources are typically installed far from the load demand points, hence requiring extensive transmission. In addition, reactive power compensation improves the quality of the power supply through the correction of the power factor of the system. A poor power factor also suggests that a higher proportion of the electrical power is of the reactive kind, and this results in wastage of the electrical infrastructural resources (Ouchen et al., 2020). The compensation devices assist in enhancing the pf by providing or absorbing the reactive power, as is required and useful, so that the power that is supplied is essentially active. This improvement not only increases the efficiency of the electrical power system but also leads to lesser cost of power distribution.

Figure 22 below describes an iterative approach to designing a robust reactive power compensation scheme for urban power grids. It integrates static measures for steady-state conditions and dynamic solutions for transient scenarios to ensure grid reliability under varying load and operational conditions which will be also used in a simulation to reduce reactive power and harmonics in the hybrid system.

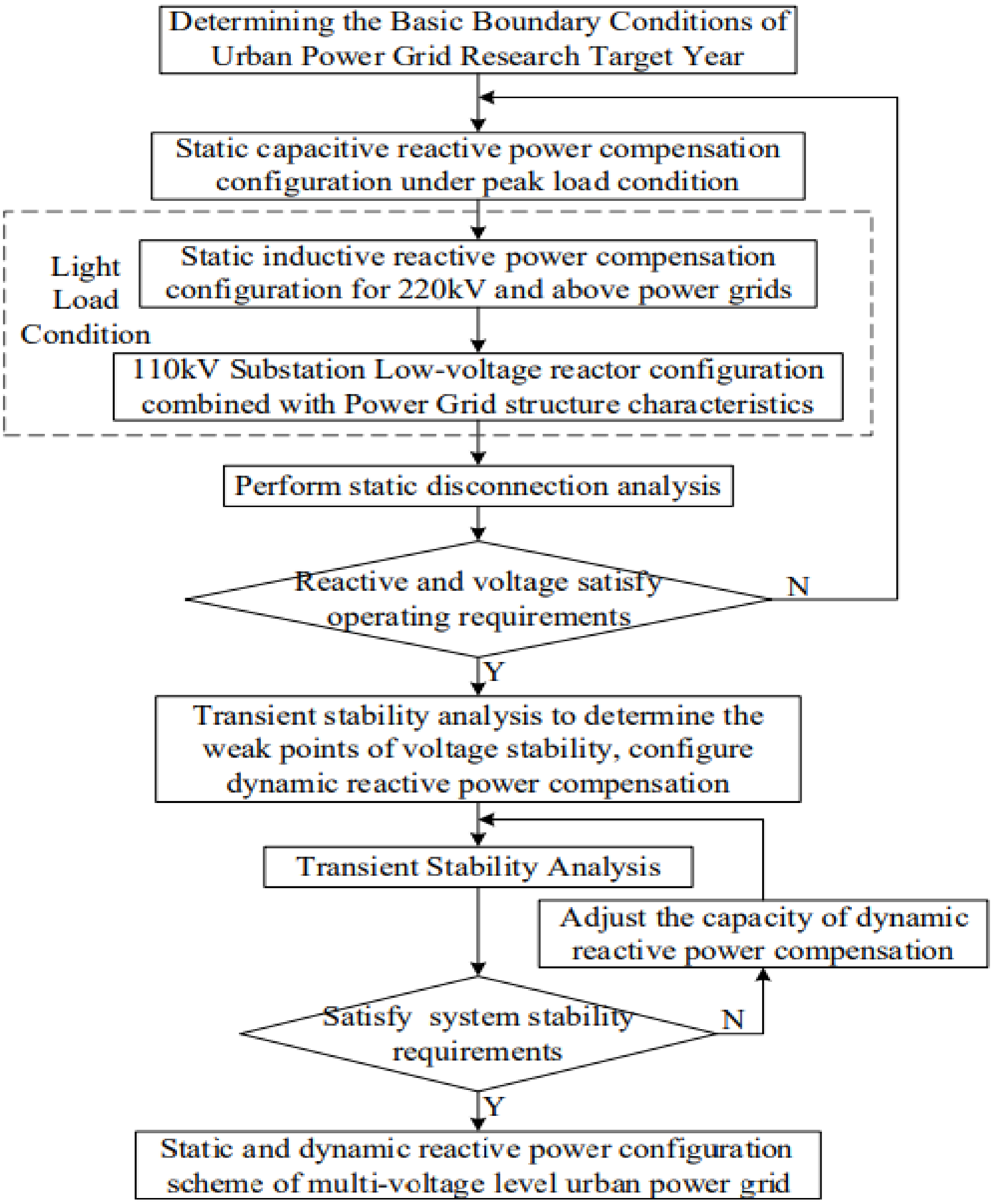

Figure 22 Multi-voltage level static, dynamic and reactive configuration process.

(Source: Song *et al.* 2023)

Therefore, it can be concluded that the assessment of reactive power compensation is critical in achieving the efficient integration of hybrid energy systems to maintain voltage control, reduce transmission loss and enhance the power factor as determined in (Kundu et al., 2024). Precise control of low reactive power contributes to the stable, efficient, and reliable operation of these systems, thus facilitating the connection of distributed power resources into the power grid.

3. Integration with Energy Storage Systems

Storing energy in an efficient manner and integration of different types of hybrid energy systems is one of the greatest advancements in modern energy management. Biogas hybrid energy systems connected with more than one energy like solar, wind and biomass, etc. are stochastic and non-dispatchable by nature. These fluctuations mean that a dependable way is needed to conserve energy in excess of that producible at any one time and to meet energy demand in periods of limited production. Energy storage systems assume this important function to support the resilience and efficacy of the hybrid energy systems.

Nonetheless, there are several advantages associated with the integration of energy storage with hybrid energy systems which includes the aspect of providing a buffer for the changing energy supply for the system (Loulijat et al., 2024). For instance, solar power is produced only in the day time and wind power depends hugely on the weather conditions. This means that it is a reserve of excess energy produced in the initial productive period so that it can continue to supply energy to the grid during low productive times. This capability is especially important to keep level of power output constant and to prevent blackouts from occurring, thus making hybrids more suitable for utility-tie and standalone applications alike. The flexibility of power injection is facilitated by the Energy Storage Systems as demonstrated in figure 23 below, wherein the battery is charged or discharged in response to the active power demand, exemplifying the control strategy of the photovoltaic (PV) system integrated with the ESS. ESS support any other hybrid energy sources in the same way too.

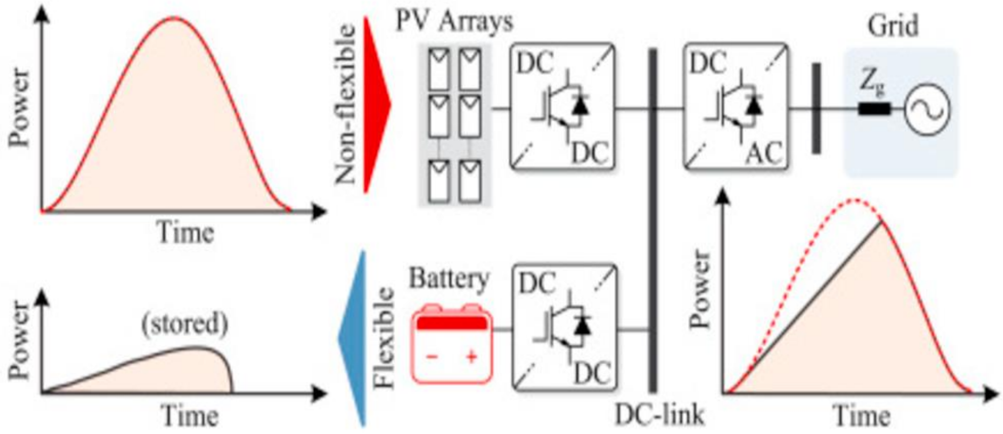

Figure 23 Flexible active power control for grid-connected PV and BESS system

(Source: Yang *et al.* 2018)

In addition, energy storage systems help in load control and effective connection to the grid which is very vital. Hybrid systems offer the flexibility of stored energy to lessen demand on actual electrical demand at peak hours thus reducing the need to generate costly and dirty peaking power plants. This load-shifting ability is not only helpful in resolving issues of supply and demand constraints but also to reduce cost aspects in the total energy system (Kalaiarasi et al., 2023). Besides, storage systems can be integrated to allow hybrid energy systems to support ancillary service such as frequency regulation, voltage control and add to the stability of the grid.

The various types of batteries, particularly lithium-ion and future batteries such as solid-state batteries, have enhanced the functionality, longevity, and affordability of storage solutions. These innovations make it possible, as well as financially feasible, to combine storage systems with hybrid power systems. More information about hybrid energy can be found in the paper of (Mei at al., 2024). Furthermore, flexible generation and energy storage enables more effective uses of grid structures, smart grids, and energy usage and management systems.

Thus, the interconnection of storage systems with the configurations is crucial in stemming volatility nature of RE, reliability and stability of the grid. This integration is quite important and is a step towards the future with a sustainable energy infrastructure.

B. Harmonic Mitigation and Filtering

Harmonic distortion is one of the most complex issues demanding recognition and solution in the integrated or 'hybrid' electrical energy system that incorporates renewable and conventional energy sources. When combining sources of continuous and constant power, which differ in terms of voltage and frequency, harmonics may be produced. These are frequencies that are integer multiples of the basic frequency of the power system and can cause degradation or even shortened service life of assets connected to the system. hence effective strategies for reducing and eliminating harmonics include harmonic filtering and mitigation techniques, as these are critical for reliable and efficient operation of hybrid energy systems (Mesbah et al., 2024). To prevent renewed production of harmonics within the system, there are mainly two strategies of harmonic mitigation; these are; There is usually a common technique used that include passive filter which are series reactors, shunt reactors and the tuned filters. These filters are intended to reduce certain frequency harmonics and while not the cheapest available, the costs are moderate. For example, series reactors are quite useful for controlling the level of high frequency harmonics since shunt reactors on the other hand are capable of absorbing and counteracting low frequency harmonics. On the other hand, tuned filtered to those specific harmonic frequencies and typically offer specific protection against them.

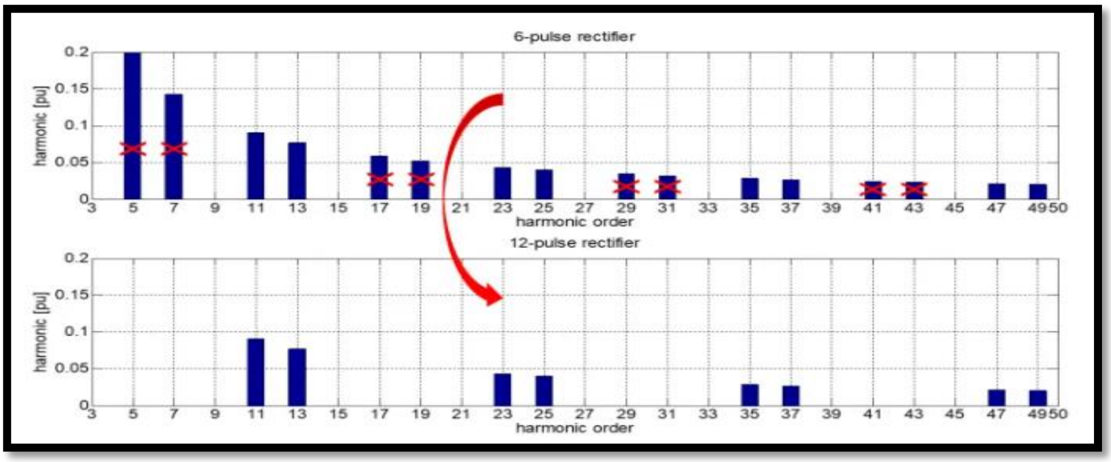

Figure 24 Harmonic cancellation, comparison of 6-pulse and 12-pulse spectrum

(Source: Muduli *et al.* 2024)

Another new-age method of harmonic minimization is through the use of active harmonic filters. While passive filters can only act as dumping to remove harmonic currents, active filters can sense active harmonic currents and further create anti-harmonic currents to cancel them out in real-time. This makes such filters suits appropriately for dealing with numerous forms of harmonic distortion across various load conditions. Though, its usage is cheaper and quite complicated when compared to some of the types of passive filters in use.

Hybrid photovoltaic, wind, diesel generator or grid interfaced systems in which renewable sources of energy are intermixed with conventional energy sources like diesel generator or grid, the variability and stochastic nature of renewable energy sources have potential to produce or intensify harmonics (Muduli et al., 2024). For instance, if there are frequent variations in solar irradiance and wind speed, the voltage and the frequency will also be altered thus harmonies distortions in the systems will be nonnegative. However, to make the hybrid system run efficiently the correct design and implementation of the harmonic filters different for the certain characteristics of the used components is necessary.

Furthermore, the recent innovations have seen the emergence of mixed passive and active filters attributed to the progress of the digital signal processing (DSP) systems. These hybrid filters utilize some of the positive features found in the two categories including higher ability to suppress harmonics and the ability to change parameters if the system conditions change.

Therefore, harmonic mitigation and filtering can be considered as critical complement for improving the operational dependence and effectiveness of the integrated energy systems. Here it can be noted that through the use of passive as well as active and hybrid filters arranged and integrated into the power system, the operators can control and eliminate major harmonic distortions and meet the interrelated international standards of power quality (Li et al., 2021). This paper has ascertained that with the ever-growing development of integrated hybrid energy systems accompanied by incorporation of new renewable energy sources and necessary smart grid innovations, further research and development in order to mitigate harmonic disturbances will remain crucial to cater for challenges brought about by innovation as well as to enhance overall integrated hybrid system performance.

1. Harmonic Identification and Analysis

Total Harmonic Distortions (THD) and filtering are paramount in working with amplification of multiple sorts of energy such as solar, wind and conventional fossil energy in hybrid facilities. Synchronous and other frequency components of voltage or current referred to as harmonics, may be the result of a wide range of issues, for instance, contamination of power supply, signal distortion or non-linear load and may lead to increased losses and overheating of equipment as well as malfunction of devices. Hence, we consider the identification and analysis of these harmonics as critical in the reliability and efficiency of a system that uses hybrid energy sources.

Harmonic detection involves ascertaining the presence as well as amount of harmonic frequencies that are integral in the power system. This process uses FFT, Wavelet Transform or others complex methods of signal processing depending on particular applications. In fact, these methods are capable of assessing the magnitude and phase of all the harmonic frequencies present in the electrical signals by evaluating the frequency spectrum of the signals (Abubakar et al., 2023). With specific harmonic identification, the system operators are in a better position to dictate the type and extent of harmonics in the hybrid energy system, which is mandatory for a solution to the situation.

When frequencies are found harmonics, harmonic analysis is then performed using the frequencies to determine the system effect. Harmonics are generated from power electronic converters, and nonlinear loads, and their characteristics and behavior described in this analysis include propagation in the network (Choma et al., 2002). The results determined through harmonic analysis are used to implement a mitigation technique that involves application of passive filters, an active filter or both. Electrical loads that include coils, capacitors, and resistors are adjusted to particular harmonic frequencies so as to either clamp or dissipate malicious harmonics. Switch mode power supplies introduce harmonics into the system and active filters employing power electronics allow second currents that resemble the original harmonics to be generated and add with them to cancel out the harmonics

There are a few major factors, which make hybrid energy systems more vulnerable to the development of harmonic problems in contrast to the other large complicated structures of power. Therefore, it is essential to have a holistic strategy in place in addressing harmonic generation and filtering (Ras et al., 2024).The proposed work will help in enhancing the performance of the hybrid energy systems along with the overall stability by implementing accurate harmonic identification and detailed analysis followed by efficient filtering solution.

2. Active and Passive Harmonic Filters

Some of the issues may be associated with power quality thereby making a hybrid energy system consisting of renewable energy technologies interconnected with conventional power plants a challenge. There is one major factor with regard to such systems this is with the presence of harmonic distortion factors that impacts the efficiency and reliability of the systems. For these distortions, there are two categories of harmonic filters which are active and passive harmonic filters though they both serve the same purpose but with variation in their efficiency and regions they are useful.

They are harmonic source type compensators that are able to inject back into the system compensating currents that cancel out the harmonic effects. They are very useful in accomplishing real-time compensation of harmonics in very short period of time and in numerous frequencies. AHFs incorporate electrical circuit power and control systems so that they can constantly control and fine-tune the filtering process (Saw et al., 2023). This makes them particularly desirable for cases where the loading is not constant throughout, and where the harmonic content of the load can vary quickly. Furthermore, proper application of AHFs can increase the power factor as well as the overall reliability of the source of hybrid energy systems. Their advantage is versatility and ability to change depending on the conditions, but active protection solutions are generally more costly and complex than passive ones.

Passive harmonic filters (PHFs), on the other hand, are purely passive components like inductors, capacitors as well as resistors that are arranged in the manner that they form resonance circuits to filter or trap particular frequencies of harmonics. It is clear that the implementation of PHFs is easier, relatively less complex, and cheaper compared to the concerns posed with the implementation of AHFs. The most effective for suppressing the lower odd harmonics they are mainly adopted in fixed, stationary conditions, where duty cycle and the harmonic imprint does not change significantly (Benali et al., 2020). Nevertheless, in comparison to the other filters, it is noteworthy that, because of their permanent tuning and incapability to respond to the variations in the conditions of harmonics, PHFs can work ineffectively in dynamic atmosphere. Moreover, there are cases of poor design or installation of PHFs and this might even increase chances of resonance that may worsen power quality instead of improving it.

Therefore, active and passive harmonic filters have a very important role to harmonize the power quality in the hybrid energy systems which has been stated by (Hekss et al., 2021). Which one to select depends on the type of load, the harmonic spectrum, and of course the costs of application. That way, the application of those filters is usually effective in guaranteeing the reliability and the efficiency of systems of hybrid energy.

3. Control Methods for Harmonic Elimination

Harmonic elimination control techniques relevant to hybrid systems remain a critical aspect to minimize overall inefficiencies within the hybrid systems. Harmonics, that are the deviations in the shape of electrical signals, may create numerous issues in power systems, namely decreased energy efficiency, increased levels of heating in accessories, and disturbances in communication links. Due to such occurrences, several control measures have been put in place and adopted since the future of the farming industry looks bleak. Figure 25 below shows the real-time operation of the converter and each set of angles corresponds to a modulation depth. The modulation index m, computed by the control algorithm,

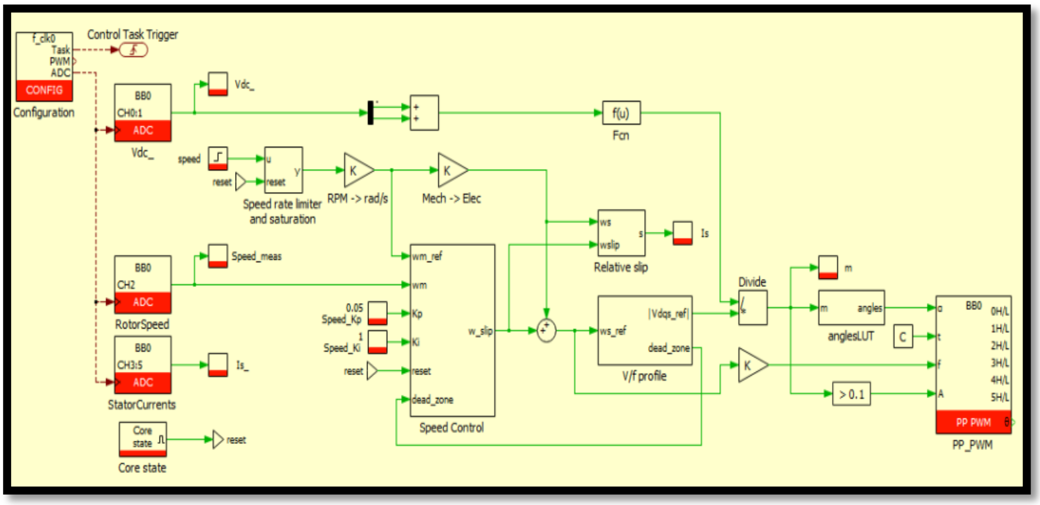

Figure 25 Implemented v/f speed control with selective harmonic elimination

(Source: imperix.com, 2024)

There are diverse methods for the realization of shunt active power compensation, among which the most popular is the use of APF. APFs operate as active elements in feeding their compensating currents to the system to counteract the harmonics arising from the nonlinear loads. These filters are very efficient and can modify their filtering capability according to the number of harmonics that are being introduced into the system, thereby offering dynamic compensation (Ghaly et al., 2025). They usually utilize elaborate control methods like the Synchronous Reference Frame theory, or the instantaneous reactive power theory for precise identification and elimination of harmonics.

Another common technique is passive filtering, employed to navigate and filter the web contents. In contrast to the APF arrangement, the passive filter uses fixed inductors, capacitors, and resistors tuned to specific harmonic frequencies. These filters are less complex and hence, cheaper; this type of suppression can be useful where the harmonic spectrum is known and unchanging. However, it should be indicated that their performance will be lower due to changes in the impedance of the mains and loading conditions.

Self-healing filters also called the hybrid filters, which use both the active and passive strategies to filter the harmonics, provide the most suitable solution (Hassan et al. 2023). Hybrid filters leverage the strengths of both methods: the possibilities offered by APFs in terms of the abilities to reshape the utilities' demand curves and convertible natures, and the qualities of passive filters in terms of their one-size-fits-all solutions and relatively low costs. In this way these components can provide a more global approach to deal with nonlinear load harmonics and more diverse load frequency and loading conditions.

Sophisticated control methods include the use of intelligent controllers namely the fuzzy logic control and the neural network control. These controllers can help improve the performance of harmonic elimination techniques from the system by enabling it to gain experience on how this system performs. This leads to better harmonic detection and even better compensation as indicated in the earlier developmental prediction by (Snehal and Dnyaneshwar 2016). In conclusion, it is significant to note that in the control of harmonic elimination within hybrid energy systems, numerous control methods have been discussed above; and all of the mentioned methods have their strong points and weaknesses. Therefore, active power filters along with passive filters, hybrid filters, and intelligent controllers play a role in ensuring at the improvement of power quality and system reliability simultaneously counteract to the problems resulted by the harmonic distortions.

C. Frequency Regulation and Control

When it comes to the hybrid energy system (HES), both frequency regulation and control are critical and core factors to the stability as well as the reliability of the system at large. With the emergence of renewables such as photovoltaic systems and wind power in the grid and operating parallel with traditional generators, frequency regulation becomes a paramount concern.

In hybrid energy systems, frequency regulation is regarded as the capability of the system to stick to an optimal range of frequency either around fifty or sixty hertz depending on the given region in respect with the varying supplies and demands of power (Snehal and Dnyaneshwar 2016). This task becomes today’s especially complicating in HES due to the varying nature of the renewable energy sources. He mentioned that generation from solar power for instance drops or surges depending on the weather and this greatly affects the system frequency hence causing fluctuating power output or generation.

To address these challenges, HES employ various frequency regulation and control strategies:

Primary Frequency Control: Another name of this kind of control is the automatic generation control. The scope of primary frequency control is from within the seconds to the minutes, and it is responsible for regulating generation power output in response to the sudden change in load or generation. In HES, this function is normally provided by conventional generators with robust elasticity over response time demand to supply time.

Secondary Frequency Control: Whereas, secondary control offers better fine tuning for sustained frequency modulation changes. It encompasses even more refined techniques and can integrate ESS like batteries. ESS are of significant importance to the HES, they either store energy when the renewable sources are producing too much or supply the extra energy when there is less generation to help in maintaining frequency.

Tertiary Frequency Control: While tertiary control mechanisms are deployed to balance the system and fine-tune it to bring back the frequency to the planned value after the initial intervention of primary and secondary control techniques in case the imbalance is not addressed (Srivastava et al,. 2024). This may include processes such as market structures where generators and consumers tender with an aim of supplying or reducing power depending on the requirements of the system.

Advanced Control Algorithms: Modifications in such theories as control theory and computer potency made it possible to incorporate predictive and adaptive control algorithms into the hybrid energy systems. These intelligent algorithms predict variations in renewable generation and also make changes to control parameters proactively in order to increase systemic resilience (Kumawat et al., 2023).

Grid Integration and Communication: Additional aspects also include frequencies regulation efficiency in HES structures to ensure that generators; grid operators and ESSs have had effective communication channels. Synchronization of power supply and load through real-time data sharing lets control overs work in tandem to manage deviations in frequency and optimize the use of resources.

Consequently, the sustainable regulation and control of the frequency in the hybrid energy systems are critical in supporting the stability of the grids with the high integration of renewable energy facilities (Arul et al., 2015). In fact, by building an adequate mix of conventional generation capacities that are capable of both Commencement and Load following alongside Energy Storage Systems combined with adequate control strategies, HES can look forward to being capable of effectively addressing issues of variability and intermittency associated with renewables. Further studies in this field will remain concerned with the elaboration of new ways of controlling and balancing the microgrid, advancement of integration of the microgrid to the main power grid, as well as increasing the reliability and stability of the microgrid as a backbone of the overall shift towards environmentally friendly power sources.

1. Frequency Response Capability

Frequency Response Capability (FRC) in the context of the so-called ‘hybrid energy systems’ and more specifically about FRC capabilities of individual nodes are important in the context of the mentioned subject area. FRC is important especially with increasingly incorporating renewable energy and other forms of energy into power grids to enhance the reliability and stability of power grids (Greenwood et al., 2017). Frequency regulation is concerned with control of grid frequency fluctuations originating from its reference, which are typically 50 or 60 Hz However, in hybrid energy systems with untidy sources such as the sun and wind, which fluctuates to generate power, frequency response mechanisms become more vital.

The primary methods for frequency response include:

Conventional Generation Control: Such plants, based on conventional fossil fuel, modulate their power generation swiftly in reactions to changes in the frequency. These plants are important features in hybrid systems because they enable fast reaction to a variety of situations.

Energy Storage Systems (ESS): Generation technologies have the capability to respond quickly to changes in frequency by injecting or absorbing power in a matter of seconds at most, where batteries take just seconds. For this reason, technologies with this ability are favorable for maintaining frequency stability in systems with a high content of renewables. The increase of ESS in hybrid systems becomes very popular way to support frequency in power systems (Meng et al., 2020).

Demand-Side Response: Frequency control is also conducted through the engagement of consumers; they also play an active role in controlling frequency through regulation of electricity consumption (Zhao et al., 2020). This method has begun to emerge as an attractive solution to improve the stability of the grid at much lower costs.

Advanced Control Strategies: Hybrid systems based on advanced algorithms and the effective application of real-time data and information processing techniques can improve the effectiveness of the management of generation, storage, and demand response measures to stabilize the frequency.

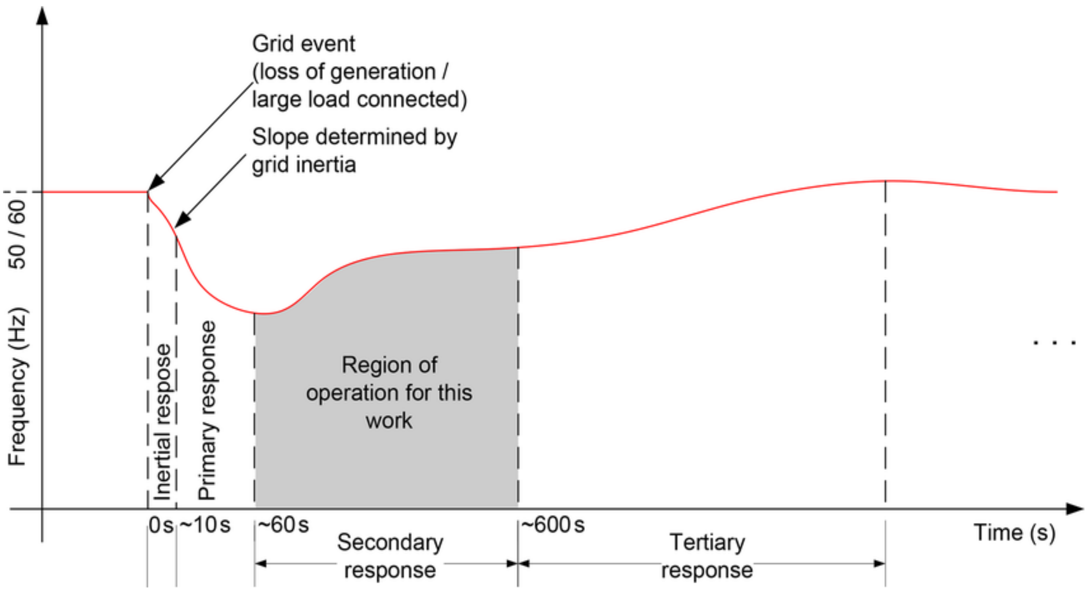

Figure 26 Frequency response of system in Grid

(Source: researchgate.net, 2024)

To sum up, achieving the FRC and controlling the frequency in the hybrid energy systems require both generic capability of generation as well as energy storage, demand side, and sophisticated and advanced control techniques that give response to (Meng et al,. 2024). With the growing trend of the integration of renewable energy sources in the electricity production over even more buoyant in the elimination of frequency response as it can be seen in Figure 26, the diagram illustrates the grid's frequency response to sudden events, showing the inertial, primary, and secondary response region.

2. Load Shedding and Frequency Droop Control

When it comes to hybrid energy systems control and management load shedding and frequency droops turns out to be critical control issues. This work also acknowledges load shedding as a deliberate and intentional reduction of electrical power in certain regions due to high demand in comparison to the available supply as crucial in setting up and enforcing strategies to keep the grid secure and avert extensive power losses. This practice becomes especially of importance with modern systems that involve a combination of different energies like solar, wind, and conventional generators all of which are needed given the different load patterns involved. Load shedding involves the deliberate disconnection of electrical loads to prevent system-wide blackouts during severe disturbances, such as significant generation losses or unexpected demand surges. By reducing the load, the system can stabilize frequency and prevent cascading failures (Omar et al., 2010).

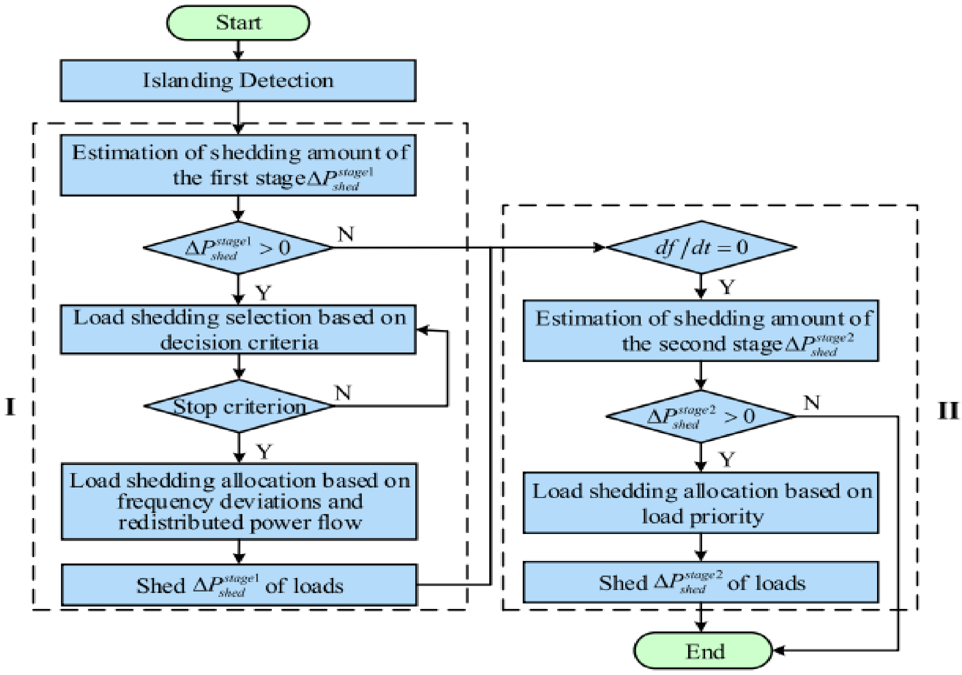

Figure 27 Flowchart of the secondary control with two-stage load shedding

(Source: Zhou *et al.* 2019)

While load shedding seeks to shed load from the overburdened power system, frequency droop control works to stabilize the frequency of electrical power with interconnected systems as it can be seen from above figure 27. In system configurations of this type wherein solar and wind, with their intermitting characteristics, are incorporated, the challenge of maintaining a steady frequency throughout the grid is an enormous one. Frequency droop control maintains the frequency at which the generators output power, control the balance of supply and demand with the grid. This primary control response of inverters in PV, wind and BESS sustain the grid frequency enormously (Sockeel et al., 2020). This mechanism has useful application in the balancing of the electricity supply and demand that characterizes most power grids where constant-frequency generation resources are not available.

It is critical to notice and coordinate these active and storage mechanisms within hybrid renewable power systems for achieving maximum energy efficiency, dependability, and sustainability. Scientists evaluate new and complex computational technologies and approaches to improve load shedding and frequency droop control solutions. The goal of such measures is to rule out the wastage of energy at some particular phases and also improve on the stability of the electricity network of a country. Furthermore, modern energy storage technologies including battery and capacitors also provide aid to load shedding by supplying the base load electricity during moments of peak consumer demand or when the electricity generation has dramatically dropped.

As distributed generations may disconnect in terms of under-frequency or over-frequency situation it is critical to follow the grid requirements and standards as also mention in ENTSO-E codes. Therefore, the various features that involve load shedding and frequency droop control mechanisms as applicable in hybrid energy systems is worthy of research. Thereby, as penetration of renewable energy sources deepens, there is need to fine-tune such strategies to subsequently maintain grid balance and reliability especially when supply and demand are volatile.

3. Resilience against Frequency Fluctuations

In the context of hybrid energy systems, another significant factor come out to the naked foresight that is the resilience to frequency disturbances. Variably these systems incorporate renewable power sources like solar power, wind power or battery power together with conventional power like fossil fuel power to deliver efficiency of power generation and consistent power supply despite changing circumstances.

Frequency variations are as a result of force variations in the power system which can be caused by force fluctuations in renewable energy production because of weather variations or a fast variation in the load demand (Tierielnyk, and Lukovtsev, 2024). These variations can cause imbalances in the grid, for example leading to cases where there may be power shortages or even destruction of equipment.

To this end, hybrid energy systems eliminate this problem by utilizing the available power types and storage systems. For example, in the peak times of the renewable power generation, this electricity excess can be either stored in batteries, or utilized to generate hydrogen via the use of electrolyzes. On the other hand, during low production of renewable energy, energy stored in the battery can help balance the grid, maintain stability and control for frequency.

Furthermore, these systems are frequently equipped with some sort of sophisticated control systems and predictive models in order to correctly forecast the unpredictable changes and regulate the generation and distribution of energy correspondingly (Tang et al., 2021). This is not only beneficial for the increased stability of the grid, but also the general functioning and steadiness of the power system as a whole. In addition, the gensets are not sensitive to fluctuations in frequency levels due to the modular design of hybrid systems, which provides ease of scalability and optimization of energy generation and utilization patterns based on current and future needs and conditions (Varga et al., 2024). It also means that capacity to deliver energy is not disrupted due to the challenges that may occur from time to time in the market place.

In conclusion, hybrid energy systems are useful all together Integrated energy sources and storage systems within hybrid energy systems are critical for improving robustness against frequent changes in frequency. These systems reduce variability, balance the generation and management of the power generated from renewable energy sources and help towards bringing the stability and reliability of the present-day power grids.

D. Adaptive Control for Dynamic Power Quality Improvement

The further stressed that power quality control senior strategies are critical for improving the effectiveness and reliability of HES plans. Because of the multitype system integration we have in HES comprising of various renewable energy sources and storage systems, there is a need for advanced control methods to control the fluctuation in power, stability of the power stored as well as to counteract the effects of disturbances in the grid (Egeland-Eriksen et al., 2021). This paper aims to present various forms of the advanced control methods used in HES and ensure the power quality is excellent.

Another main difficulty associated with implementing HES is that renewable energy sources like solar and wind are not constant producing energy. These changes can result in voltage fluctuations, frequency swings and harmonics when measured in the supply voltage or the current, which in turn adversely affects the quality of power supplied to the utility or the consumer (Ourahou et al., 2020). These issues are managed by enhanced control techniques involving monitoring of the system, analysis of its performance and use of control algorithms with provisions for adjustments. The figure 28 below is one of the example of adaptive control systems in HES that illustrates a supervisory MPC framework that optimizes energy output.

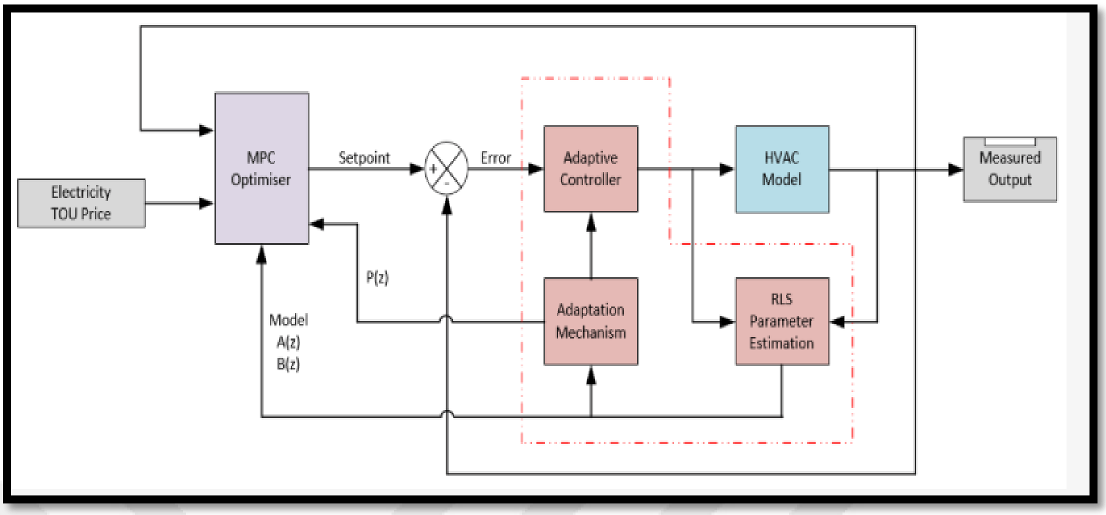

Figure 28 MPC plan and breakdown of the inner loop adaptive controller

(Source: Wu *et al.* 2024)

Most of the grid connected microgrids use a master-slave system of hierarchy control system in that there are number of levels of controllers to supervise procedures. Superior control mechanisms at the supervisory level employ anticipation mechanisms and predictive models for fluctuations in renewable energies and consumers' demand. This also helps in efficient scheduling of dispatch and storage of energies that are needed in the electric power system and that which reduces interruption of the grids while enhancing the usage of energy.

At the operation stage, there Active power control, Reactive power and voltage control (Wu et al., 2024). For example, droop control methods change the number of renewable resources supplied back to the system according to fluctuations of the frequency and voltage. Likewise, energy storage systems (ESS) are also managed using some of the highest control techniques like model predictive control (MPC), which allow ESS to constantly balance charge/discharge cycles and promptly respond to signals from the grid.

In that regard, the more superior inverters that have the ability to form the grid improve the HES stability through mimicking the synchronous generators. These inverters can participate in provisions like frequency control in addition to voltage control so as to enhance the quality of the actual power supplied at the grid level. Communications and control CPS and digital twin technologies are incorporated more into the HES control paradigms to monitor, diagnose, and manage faults, and improve the control performance (Sinsel et al. 2020). CPS frameworks incorporate data analysis techniques or even machine learning algorithms to manage energy fir in a way that would achieve reliable prognostics and even self-diagnosis of faults thus making the system to perform more effectively in terms of maintenance.

To sum up, the controllability of hybrid energy systems and power quality is the decisive factor for increasing the efficiency of the system and its functioning. These concepts ensure that HES features a system that can efficiently handle the movement of power involving real-time analysis of data, functional prediction of results, as well as adaptive control algorithms thus ensuring that the gird is steady and the utilization of renewable energy is reliable. In future with technology enhancement the further work done in control strategy will create more opportunities in enhancing efficiency and to transform the world towards sustainable energy.

1. Real-time Monitoring and Feedback

In the field of hybrid power systems, it can be noted that the proposed adaptive control category for dynamic improvement of power quality is a major development. This approach seeks to increase the standard and capability of the supply and distribution of power influences reliance on monitoring and feedback plans.

He notes that adaptive control techniques are very important in compensating for fluctuations and disturbances that may happen in hybrid energy systems, which can use renewable and conventional energies in tandem. Renewable energy generators like the solar and wind power are dynamic because they are associated with some order that is sometimes irregular and unpredictable hence affecting power quality (Talaat et al., 2020). Conventional acceleration control techniques could prove ineffective to meet the demands of such conditions, hence, the need for adaptive control.

Online assessment constitutes the basis of this approach being aimed at the constant monitoring of Power quality parameters like voltage stability, frequency control, and harmonics. Thus, with help of sensors and including the features of employing superior monitoring technologies, an early identification of any sub-standard conditions in the powered system is made possible.

One form of reinforcement is feedback loops which is essential in adaptive control as it offers immediate correcting mechanism derived from monitoring results. These adjustments are vital to keeping the quality of power supply within certain parameters, thus guaranteeing consumers of stable voltage levels.

Development of adaptive control strategies for Power Quality (PQ) not only tackles current problems concerning dynamic power spectrum alteration but also serves the higher objectives of lasting energy preservation and a secure, dependable power grid for future generations (Xu et al., 2024). The demonstrated capability to manage and control energy output and also address disruption problems is advantageous to the systems since it raises efficiency and effectiveness of the energy systems.

Over the course of time, other improvements in control theory and available sensors will be expected, guaranteeing even higher accuracy and stability in the balance of the quality of power. This development has important implications for the future integration and smooth operation of hybrid power systems to enhance the robustness of energy systems and their sustainability.

2. Adaptive Control Algorithms

When it comes to micro combined heat and power systems or any interconnected power system, Adaptive Control Algorithms allow for the processes to be controlled and maximized throughout a system. These algorithms are used to modify the systems' definitory values and control approaches to reflect the prevailing conditions as a method of improving on the system's efficiency, reliability and performance.

Since in hybrid energy systems there are numerous energy sources including; the solar, wind, battery, and conventional generators, therefore, Adaptive Control Algorithms are quite beneficial in such systems (Xu et al., 2024). These systems undergo fluctuations in energy production and consumption, and thus, have a necessity to develop flexibility-based approaches to regulate and optimize the energy's usage. Concerning the case of using hybrid energy systems, it must also be mentioned that adaptive control algorithms do matter significantly for system performance and various indicators. These algorithms are designed to adapt the parameters and operations of a system according to the fluctuations within the environment, a decrease in performance of the components, or variations in the energy prerequisites. Below Figure 29 demonstrates the flow chart of adaptive control system and how is algorithm wors in energy systems.

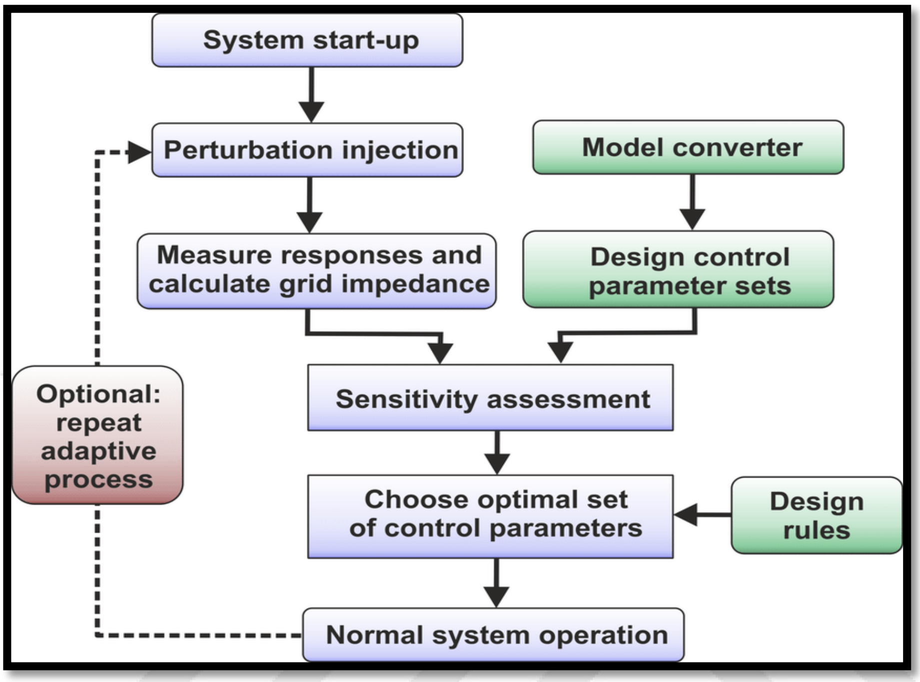

Figure 29 Flowchart of the adaptive control algorithm

(Source: Xu *et al.* 2024)

Real-time power control by means of ESS and adaptive control ensures efficient operation of hybrid renewable and non-renewable power sources including solar power, wind, batteries, and fuel. These algorithms can make instantaneous decision making regarding the solar irradiance, wind speed, battery charge to decide the right blend of production and storage as well as grid demand in order to enhance the effectiveness of the overall system.

Another merit associated with adaptive control algorithms is the capacity in boosting the system robustness and stability (Chenchireddy et al., 2021). They do this through hedging which is the management's use of reasonable methods and tools to reduce the risks associated with fluctuations in energy supply or demand. For instance, in low levels of solar intensity or wind strength, the algorithms can ensure the stored energy is utilized or the backup generators engaged to ensure there is a standby power supply.

However, when developing adaptive control algorithms, they help to ensure the economic feasibility of hybrid energy systems due to the proper utilization of available energy resources. Thus, they can reduce the overall operation costs by either avoiding overloading energy derived from costlier peak-demand electricity from the grid or prolong the lifespan of a battery by carefully coordinating its charging and discharging cycles. Overall, adaptive control algorithms are essential elements of hybrid energy systems since they make the system capable of controlling the process effectively, responding to various challenges stimulus, as well as managing different energy sources proficiently (Behabtu et al., 2020). The application of these solutions to boost the stability of the energy systems, increase the efficiency of resources, and decrease operating costs creates their value in achieving the progressive development and stability of the infrastructures for energy systems in the modern world.

Of the various adaptive control areas in the context of hybrid energy systems, one of the most important is the balance and distribution of power among the components. It implies that for example through the weather conditions, energy demands, or system component health, it can automatically optimize operation parameters and settings (Jafari et al., 2020). For example, when the levels of solar irradiation or wind speed are high, the control algorithms can prefer the use of renewable energy systems to generate power, hence, the use and dependence on renewable energy resources is maximized while that of conventional energy resources is minimized.

Also, through its capacity to provide anticipative control actions against disturbances or faults, adaptive control improves system robustness. It can quickly close or reopen energy routes, or change other parameters to prevent and avoid disruptions and keep energy production and distribution running without interruption.

Moreover, these algorithms can promote the incorporation of new technologies and further, the system adaptability during its evolution (Zhang et al., 2024). They allow for the easy integration of energy storage systems, smart grid functions and complexity levels, and very importantly advanced forecasting models, all of which makes hybrid energy systems ready to efficiently work with future existing technologies or changing environmental factors.

In conclusion, Adaptive Control Algorithms are useful in the control and maintenance of hybrid energy systems, are adaptive, dynamic and provide highly responsive control of energy and have a focus to improve energy conservation, increase system availability, and foster the use of renewable energy. It thus highlights the relevance of modern high controlling methods when enhancing the efficiency as well as performance of the current energy systems.

3. Machine Learning and AI in Adaptive Control

Among the conceptual ideas of developing complex HES, the combined use of ML and AI when applying adaptive control is a groundbreaking innovation. This technological synergy is paramount when it comes to calibrating the operation and functionality of hybrid power systems which are normally shaped from various sources of renewables and conventional power.

The applications of machine learning algorithms are central to these systems since they employ data analytics and artificial intelligence to improve the estimations, early fault identification, and choices in these contexts. By analyzing constant data from the field, parameters and configuration settings within the MLS models can be optimized periodically to enhance energy production and reduce overhead (McPherson and Stoll, 2020). For instance, through the use of the ML in generating predictive maintenance models, one can forecast equipment breakdowns so that these can be averted and the general expenses of maintenance lowered.

AI enhances these capabilities by making control strategies adjustable because it controls variableness. Neural networks and reinforcement learning as the examples of AI are efficient for analyzing complex patterns and finding the best control actions in the real-time. In a hybrid energy scenario, AI optimizes the supply and demand of power and adjusts the ratio between different types of energy depending on the changes in demand, temperature, and grid restrictions. Including energy storage systems to renewably power networks is important for balancing and achieving stability in decentralized systems. Below Figure 30 shows an intelligent techniques aimed at enhancing the stability, control, and protection of power systems, especially in the context of increasing integration of hybrid energy sources [Jumani et al., 2020].

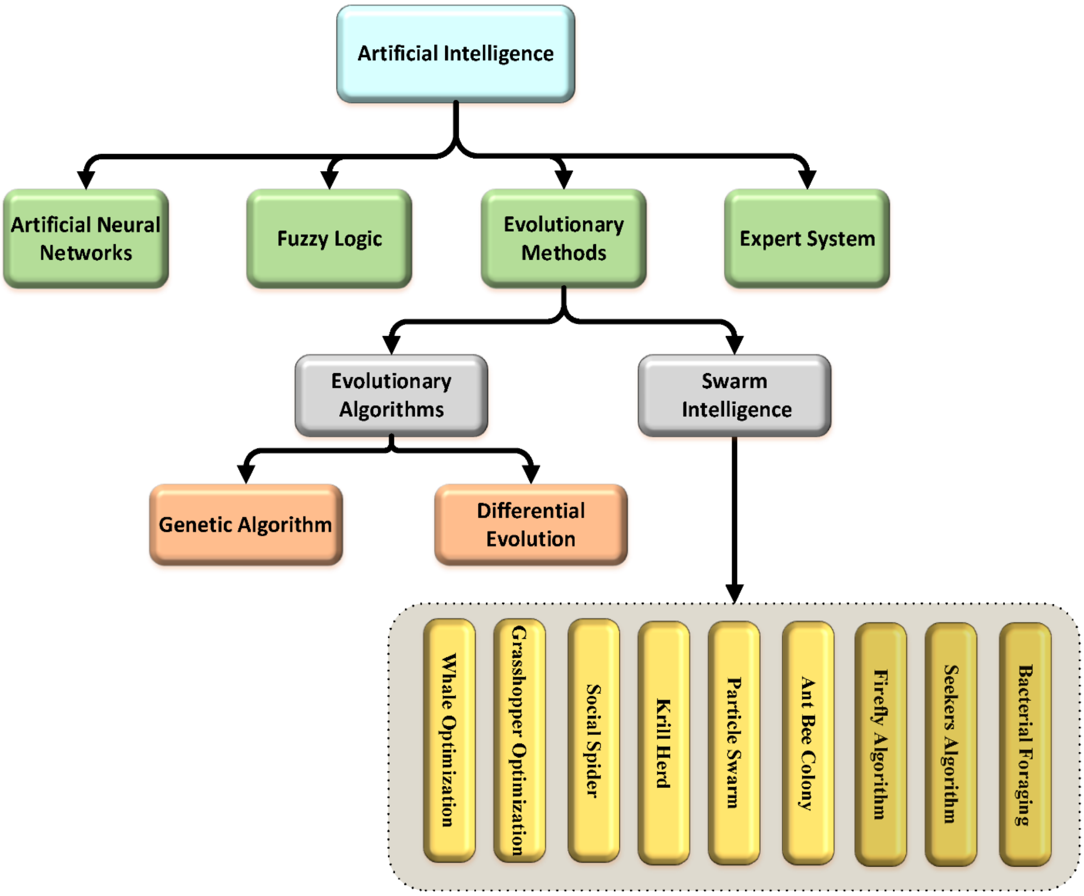

Figure 30 AI-based optimization techniques used to solve power quality issues

(Source: mdpi.com, 2020)

Furthermore, the combination of ML and AI enables the stabilization and interconnection of renewables which as we know are unreliable and inconsistent, for instance, solar and wind power. Because of the high-powered forecast capabilities and variations control mechanisms, these technologies can effectively level or balance supply irregularities or energy production and stabilize the power grid. A machine learning-based optimal feedback control scheme to improve microgrid stability aimed large disturbances as demonstrated below in figure 31 [Xia et al., 2022] This approach utilizes neural networks trained on historical data to provide real-time optimal feedback control, effectively enhancing the resilience of microgrids integrating renewable energy sources

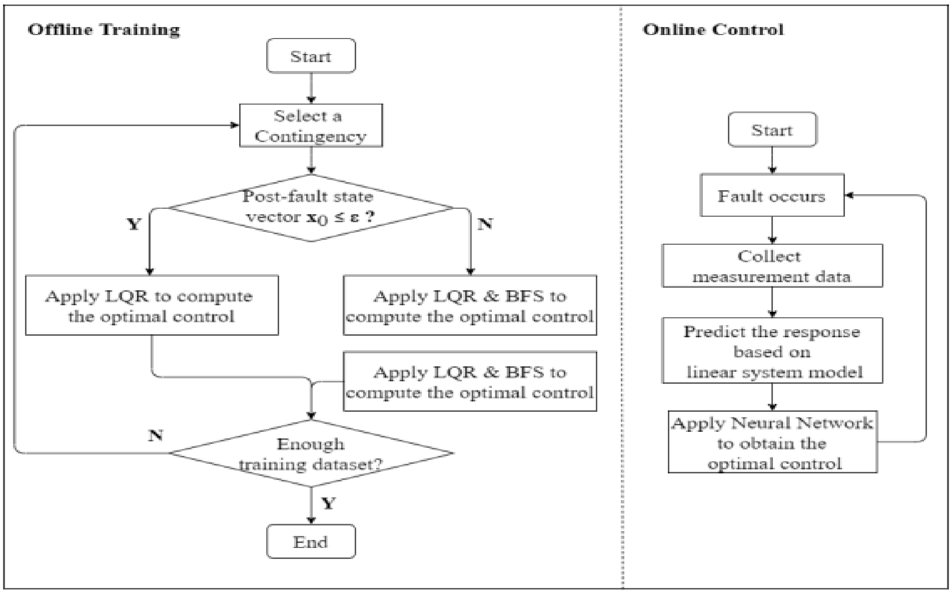

Figure 31 Flowchart of the machine learning approach

(Source: Xia et al., 2022)

Within R&D the use of ML & AI in adaptive control is unveiling new horizons in the realm of HES control. Several authors have proposed new algorithms and expert techniques to increase not only the efficiency of energy management but also the system scale and robustness (Stonier et al., 2020). Research activities bridging the gap among academia, industries and government organizations are constantly attempting to advance state of art methods on predictive analytics, control theoretical approach and optimization algorithms particularly well suited to the unique requirements of hybrid energy systems integration.

In conclusion, the enhancement of adaptive control comprises the integration of artificial intelligence and machine learning, which reflects a significant progressive step in hybrid energy systems. The new generation technologies do not only provide enhanced operational effectiveness and performance but also offer opportunity for effective efficient reliable utilization of a number of energy resources meeting the need of various user segments with lesser detrimental effects to the environment.

Considering the possibilities of hybrid energy systems, the use of Machine Learning (ML) and Artificial Intelligence (AI) as means for adaptive control occupies a pivotal position. This approach entails the application of efficient computation methodologies in enhancing the performance and operations of a hybrid power system that includes both the renewable and non-renewable energies like the solar, wind, hydro, etc., and the legendary fossil based energy as well as energy storage systems.

Machine learning algorithms are crucial in such systems because they have to process large amounts of data, including streaming data and data from the system's memory. They can decide demand for energy in the future, how to use energy storage most efficiently prospective, and renewable energy sources. As for over-arching theories, AI evolves decision-making pertaining to systems control by incorporating control dynamics that change the setting of the system based on the changing environmental conditions and energy requirement.

The use of ML and AI in control of hybrid power systems has the following benefits for adaptive control. Consequently, it optimizes overall system performance by continuously rendering parameters across the system, which alter when energy inputs or demands change (Zheng et al., 2023). Secondly, it provides a solid ground for applying predictive maintenance techniques, which prevent the development of problems in order to minimize periodic detractions and maintenance expenses. Third, it aligns with integration of new renewable energy sources into existing grids since renewable energy sources fluctuate in their supply.

In addition, the integration of ML and AI pushes society towards smart grids, in which production, distribution, and consumption of energy are managed in time. This evolution is pivotal where there is a concern with sustainability objectives as well as the resultant carbon emissions linked to energy production.

To sum up, the application of machine learning and AI to control systems is an evolutionary step toward the efficient use of hybrid systems. Besides, it also improves their performance levels, as well as the dependability of their facilities and systems The move also provides for the development of a stronger and less fragile energy sector. Moving forward, with the advancement in research thus more innovations it is likely that the world will steadily trend towards cleaner and smarter energy solutions.

V. EXPERIMENTAL RESULTS

A. A brief introduction to the results and scope

This section presents the experimental results and analysis derived from the hybrid electrical system designed to enhance Power Quality (PQ) and efficiency. The scope of the results encompasses the evaluation and validation of control algorithms, system components and their interactions under various operating conditions. The experimental setup is outlined which is including the description of the power quality control system and the MATLAB/Simulink layouts used for simulation.

Key parameters for photovoltaic and wind power generation are analysed, including mathematical modelling and the integration of DC-AC controllers. Advanced control algorithms such as MPPT, P&O Algorithm, UPQC, active power filters and voltage source converters are employed to optimize system performance.

The results are categorized into several critical performance metrics: voltage regulation, active and reactive power balance THD, transient response, power factor correction, and frequency control. These results validate the effectiveness of the proposed control strategies and system architecture in achieving reliable and efficient hybrid renewable energy integration.

This comprehensive analysis contributes to understanding the interplay between renewable energy sources and advanced control mechanisms in enhancing PQ and system stability.

B. Experimental Setup

1. Description of the Power Quality Control System

The Power Quality Control System used in this thesis is designed to address and mitigate common power quality issues, such as voltage fluctuations, harmonic distortion and reactive power imbalance in a hybrid electrical energy system integrating PV and wind energy sources. This system combines advanced control algorithms and power electronic devices to optimize the performance of the hybrid system while ensuring stable and efficient energy delivery to the grid or load.

At its core, the system utilizes components such as DC-AC controllers, active power filters and voltage source converters to regulate voltage, minimize harmonics, and maintain a balanced power flow. Key algorithms, including the MPPT algorithm for PV systems and UPQC and D-STATCOM for comprehensive PQ enhancement are implemented to ensure maximum efficiency and reliability.

2. MATLAB/Simulink Model for the Hybrid Electrical System

As a result of this thesis, the MATLAB/Simulink model proved to be an effective tool for designing, simulating and validating the proposed power quality control methods for the hybrid electrical energy system. The layout of the MATLAB/Simulink model, shown in Figure 32, integrates the PV system, wind power system, UPQC, D-STATCOM, active power filters, and the inverter control systems. This model successfully demonstrated the practical implementation of advanced control algorithms and provided valuable insights into system performance.

The simulation results reveal that the proposed system achieved significant improvements in power quality and efficiency. By employing control strategies such as for PV systems and the UPQC for addressing harmonic distortion and reactive power issues, the hybrid system delivered superior voltage regulation and minimized THD. Additionally, the active power filters and inverter control system ensured smooth integration of renewable energy sources with the grid, resulting in a balanced and stable energy supply. Through the simulation, the control strategies are fine-tuned to enhance efficiency and output and resulting in improvements.

The MATLAB/Simulink model facilitated an in-depth evaluation of the system under various conditions, including fluctuations in environmental factors, load demand and input power from renewable sources. The simulation verified that the hybrid system could respond dynamically to these variations while maintaining optimal performance. The modular nature of the model allowed for iterative refinement of system parameters, further enhancing its reliability and efficiency.

The results highlight the efficiency of the MATLAB/Simulink layout in representing real-world scenarios and validating the proposed control system. The improvements in PQ and system stability demonstrated through the model underscore its potential for practical applications in renewable energy integration. This thesis successfully showcases how advanced simulation techniques can lead to tangible advancements in hybrid electrical systems.

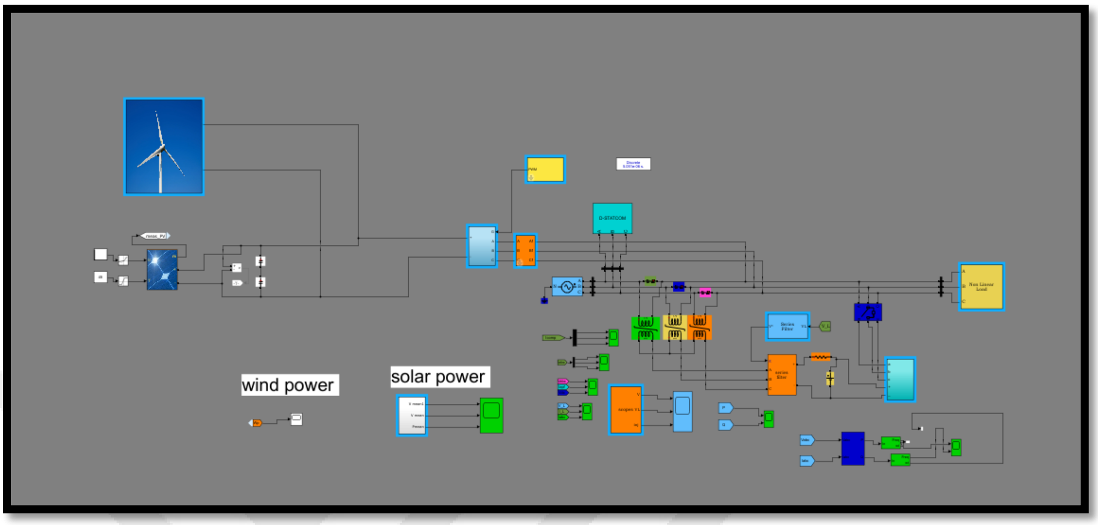

Figure 32 Proposed Simulation Model of a Hybrid Renewable Energy System

The Simulink layout above in Figure 32 represents a hybrid renewable energy system that combines wind power and solar power integrated with an electrical grid. It features a wind power system consisting of a wind turbine connected to a control and conversion module, alongside a solar power system that includes a PV array with MPPT for efficient energy conversion. Power electronics, such as converters and inverters, are included to ensure proper power conditioning and synchronization with the grid. The grid connection is designed for bidirectional energy flow while adhering to grid needs. Additionally, load distribution represents the energy consumers and their management, supported by an integrated control system that optimizes the operation of wind, solar, and capacitor components. This layout is designed to simulate the interaction between renewable energy sources, storage and the grid under varying conditions, enabling performance, stability and energy dispatch analysis.

3. Mathematical Modelling and Parameters for PV and Wind Power

The mathematical modelling of the PV system involves the use of the single-diode model to represent the photovoltaic module, incorporating parameters such as irradiance, temperature, series resistance and shunt resistance to simulate power generation accurately. For the wind power system, the mathematical model is based on the power output equation of a wind turbine which depends on parameters like wind speed, air density, rotor swept area and the turbine's power coefficient. These models is used to simulate the dynamic performance of the hybrid system under varying environmental conditions.

a. Mathematical modelling of PV

The equivalent circuit of a PV cell is shown in Figure 33, the current source I_{ph} represents the cell photocurrent. R_{sh} and R_s are the intrinsic shunt and series resistances of the cell respectively. Usually the value of R_{sh} is very large and that of R_s is very small, hence they may be neglected to simplify the analysis Practically, PV cells are grouped in larger units called PV modules and these modules are connected in series or parallel to create PV arrays which are used to generate electricity in PV generation systems. The equivalent circuit for PV array is shown in Figure 34.

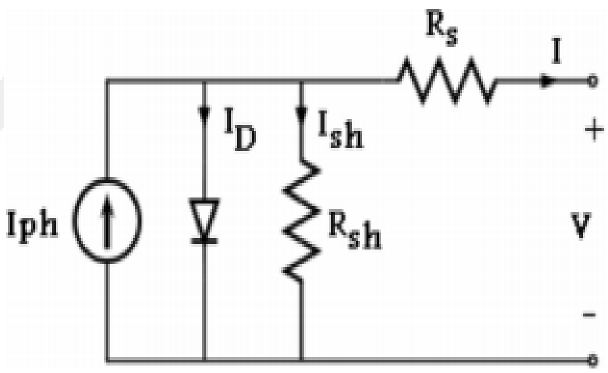

Figure 33 Circuit of Photovoltaic cell

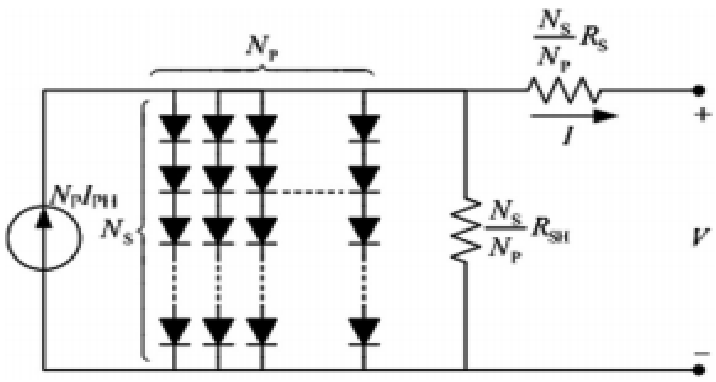

Figure 34 Photovoltaic Cell

The voltage–current characteristic equation of a solar cell is provided: Module photo-current I_{ph} :

$$I_{ph} = [I_{sc} + K_i(T - 298)]\frac{Ir}{1000} \qquad (1)$$

Here, I_{ph}: Photo-current (A); I_{sc}: short circuit current (A); K_i: short-circuit current of cell at 25 °C and 1000 W/m^2

T: operating temperature (*K*); I_r: solar irradiation (W/m^2)

Module reverse saturation current I_{rs}:

$$I_{rs} = \left[\frac{I_{sc}}{\left[exp\left(\frac{qV_{oc}}{N_s knT}\right)\right] - 1}\right] \qquad (2)$$

Here, *q*: electron charge, $q = 1.6 \times 10^{-19}C$; V_{oc}: open circuit voltage; N_s: number of cells connected in series; *n*: the idealist factor of the diode; *k*: Boltzmann's constant, $k = 1.3806 \times 10^{-23}\, J/K$.

The module saturation current I_0 varies with the cell temperature, which is given by:

$$I_0 = I_{rs}\left[\frac{T}{T_r}\right]^3 exp\left[\frac{qE_{g0}}{nk}\left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \qquad (3)$$

Here, T_r: nominal temperature $T_r = 298.15\, K;$: E_{g0} is band gap energy of the semiconductor, E_{go}= 1.1 eV; The current output of PV module is:

$$I = N_p I_{ph} - N_P I_0 \left[\exp\left(\frac{\frac{V}{Ns} + \frac{IRs}{Np}}{nVt}\right) - 1\right] - I_{sh} \qquad (4)$$

With: $$V_t = \frac{k\,T}{q} \qquad (5)$$

$$I_{sh} = \frac{\frac{VNp}{Ns} + I_{rs}}{R_{sh}} \qquad (6)$$

Here: N_p: number of PV modules connected in parallel; R_s: series resistance (Ω); R_{sh}: shunt resistance (Ω); V_t: diode thermal voltage (V). In addition, THD will be demonstrated on the simulation results too that will follow below formulation;

$$THD = \sqrt{\sum_{n=2}^{\infty} \frac{V_n^2}{V_1^2}} \times 100\% \qquad (7)$$

Where V_n is the RMS value of the n harmonic number and V_1 is the RMS value of the fundamental frequency.

The PV system variables include 10843 strings in parallel; each string has ten modules connected in series in 24 panels, 33kV/ 50Hz high voltage. The PV modules are modelled as Jinko Solar Tiger Pro 72HC-BDVP 535W, Maximum power is 535 W. Below Table 1 shows the parameters that is used for PV part in the simulation.

Table 1 PV Parameters

Parameter	Value	Unit
Number of Strings	10843	Str
Modules per String	24	Pcs
Frequency	50	Hz
PV Module Type	Jinko Solar	
Maximum Power (Each Module)	535	W
Cells per module	144	
Open circuit voltage	49.54	Volt
Short circuit current	13.83	Amp
Vmp	40.94	Volt
Imp	13.07	Amp

b. Mathematical modelling of wind turbine

The mathematical modelling is used in simulation is use of wind turbine involves the characterization of aerodynamic, mechanical and electrical components to analyse its performance under varying wind conditions. Figure 35 demonstrated the layout that is used in Simulation and the fundamental equations are fallowing it below.

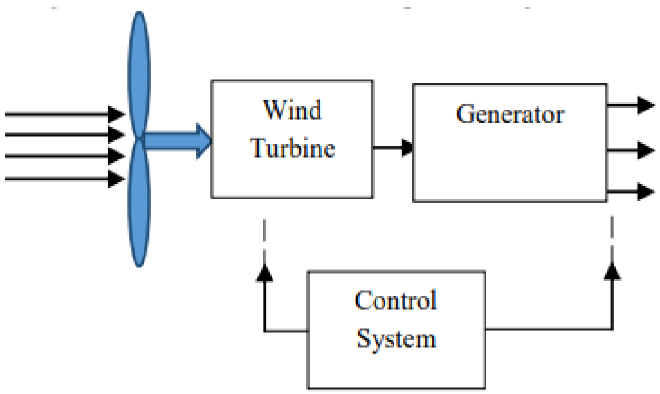

Figure 35 Basic system of Wind Power

Under steady acceleration a, the dynamic energy E of an object with mass m and speed v is equivalent to the work done W in dislodging that object from rest to s under a power F, i.e.

$$E = W = F.s \tag{8}$$

According to the Newton's second law of movement.

$$F = m.a \tag{9}$$

thus, the kinetic energy becomes

$$E = m.a.s \tag{10}$$

From kinematics of solid motion $v^2 = u^2 + 2as$ where u is the initial velocity of the object. This implies that $a = \frac{v^2-u^2}{2s}$ Assuming the initial velocity of the object is zero($u = 0$), we have that $a = \frac{v^2}{2s}$

Hence from equation (9) we have that

$$E = \frac{1}{2}mv^2 \tag{11}$$

This kinetic energy formulation is based on the fact that the mass of the solid is a constant. The power P in the wind is given by the rate of change of kinetic energy, i.e.

$$P = \frac{dE}{dt} = \frac{1}{2}\frac{\mathrm{dm}}{\mathrm{dt}}\ v_w^2 \tag{12}$$

But mass flow rate dm/dt is given by $\frac{dm}{dt} = \rho\, A_{vw}$ where A is the area through which the wind in this case is flowing and ρ is the density of air. With this expression, equation (11) becomes

$$P = \frac{1}{2}\rho A v_w^3 \tag{13}$$

The actual mechanical power P_w extracted by the rotor blades in watts is the difference between the upstream and the downstream wind powers.

$$P = \frac{1}{2}\rho A\ v_w\ (v_u^2 - v_d^2\ ) \tag{14}$$

now from the mass flow rate, we may write

$$\rho A v_w = \rho A(v_u + v_d) \qquad (15)$$

v_w being the average of the velocities at the entry and exit of rotor blades of turbine. With this expression, equation (15) becomes

$$P_w = \frac{1}{2}\rho(v_u^2 - v_d^2)(v_u + v_d)\frac{1}{2} \qquad (16)$$

Expanding this expression in terms of rotor area A, we obtain:

$$P_w = \frac{1}{2}\rho A(v_u^3)\left\{\frac{\left(1 - \left(\frac{v_d}{v_u}\right)^2 + \left(\frac{v_d}{v_u}\right) - \left(\frac{v_d}{v_u}\right)^3\right)}{2}\right\} \qquad (17)$$

$$Cp = \frac{\left(1 - \left(\frac{v_d}{v_u}\right)^2 + \left(\frac{v_d}{v_u}\right) - \left(\frac{v_d}{v_u}\right)^3\right)}{2} \qquad (18)$$

$$P_w = \frac{1}{2}\rho A\, v_u^3\ C_p \qquad (19)$$

The expression for Cp in equation (18) is the fraction of upstream wind power captured by the rotor blades. Other names for this quantity are the power coefficient of the rotor or rotor efficiency. The power coefficient is not a static value. It varies with tip speed ratio of the wind turbine.

Let λ represent the ratio of wind speed V_d downstream to wind speed v_u upstream of the turbine, i.e.

$$\lambda = \frac{v_d}{v_u} \qquad (20)$$

λ is called the tip speed ratio of the wind turbine. The blade tip speed (in meters per second) can be calculated from the rotational speed of the turbine and the length of the blades used in the turbine, i.e.

$$\lambda = \frac{wR}{\mathrm{v}_w} \qquad (21)$$

If the rotor of a wind turbine turns too slowly most of the wind will pass through the openings between blades with little power extraction. On the other hand the rotor turns too fast, the rotating blades act as a solid wall obstructing the wind flow again reducing the power extraction. The turbines must be designed to operate at their optimal wind tip speed ratio λ in order to extract as much power as possible from the wind stream. Theoretically the higher the λ the better in terms of efficient operation of the generator. There are disadvantages however. High λ causes erosion of leading edges of the blades due to impact of dust or sand particles found in the air. This would require use of special erosion resistant coating material that may increase the cost of energy. Higher λ also leads to noise generation, vibration, reduced rotor efficiency due to drag and tip losses and excessive rotor speeds can lead to turbine failure. Other factors that impede complete energy conversion in a complete turbine system are things such as gearbox, bearings, number and shape of blades etc.

Air density ρ is another flow input quantity at the rotor system. ρ is a function of both air pressure and temperature. When air pressure increases ρ increases. When air temperature decreases ρ increases. This is in accordance with the equation of state.

$$P = \rho RT \qquad (22)$$

P is pressure (Pa), R is the gas constant $(J/kg \cdot K)$, T is the absolute temperature (K).

Both temperature and pressure decrease with increasing elevation, significantly affecting power generation. At atmospheric pressure $P_{atm} = 14.7\, psi$, temperature $T = 60°F$, and ensity $\rho = 1.225\, kg/m^3$, air density varies with elevation according to:

$$P = \rho_0 e^{(\frac{0.297}{3048})H_m} \qquad (23)$$

Where H_m is site elevation in meters. At high elevations the air density corrections can be important.

The power coefficient C_p is the most important parameter in the case of power regulation. It is modelled as a function of the tip speed ratio λ and the blade pitch angle θ (in degrees):

$$C_p(\lambda, \theta) = C_1 \left(C_2 \frac{1}{\beta} - C_3 \beta\theta - C_4 \theta^x - C_5 \right) e^{-C_6(\frac{1}{\beta})} \qquad (24)$$

Where the values of the coefficients C1,C2,C3,C4,C5,C6, and x are coefficients that depend on the turbine type.

$$\frac{1}{\beta} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{1 + \theta^3} \qquad (25)$$

Where θ is the pitch angle of the blade in degrees. Based on this formulation it can be also seen hat characteristic of the Wind turbine that is used in the simulation as below in Figure 36.

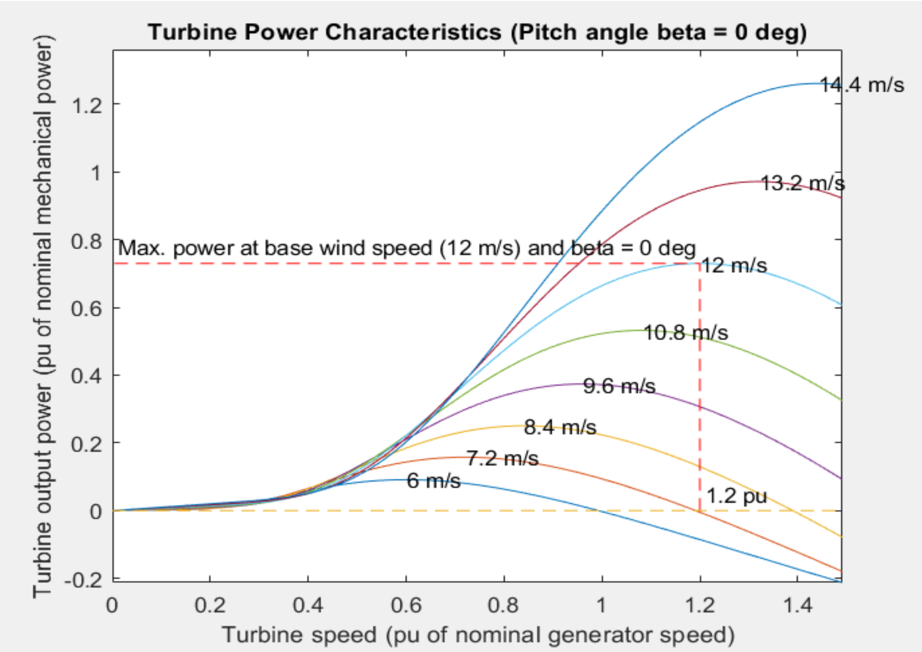

Figure 36 Wind Turbine Power Characteristics at Different Wind Speeds

Table 2 below presents the key parameters of the wind turbine, including its nominal mechanical output power, base electrical generator power, wind speed, rotational speed and pitch angle settings. These parameters define the turbine's operating conditions and performance characteristics, essential for modelling and simulation.

Table 2 Wind Turbine Parameters

Parameters	Value
Nominal mechanical output power (W):	1.5x10^6
Base power of the electrical generator (VA):	$\frac{1.5\text{x}10^6}{0.9}$
Base wind speed (m/s):	12
Maximum power at base wind speed (pu of nominal mechanical power):	0.73
Base rotational speed ($p.u.$ of base generator speed):	1.2
Pitch angle beta to display wind-turbine power characteristics (*(β≥0) (°)*)	0

Figure 37 below Simulink model represents a wind turbine system with a Permanent Magnet Synchronous Generator (PMSG). The wind turbine receives wind speed input and controls the pitch angle to regulate power output. The mechanical torque generated by the turbine is fed into the PMSG, converting mechanical energy into electrical energy. The generated AC voltage is then rectified using a diode rectifier to produce DC voltage. The DC voltage is further processed through an LC filter to smooth the output before being supplied to the load. The model includes measurements for generator speed, wind speed, and electrical power, making it useful for analysing the performance of wind energy conversion and control strategies.

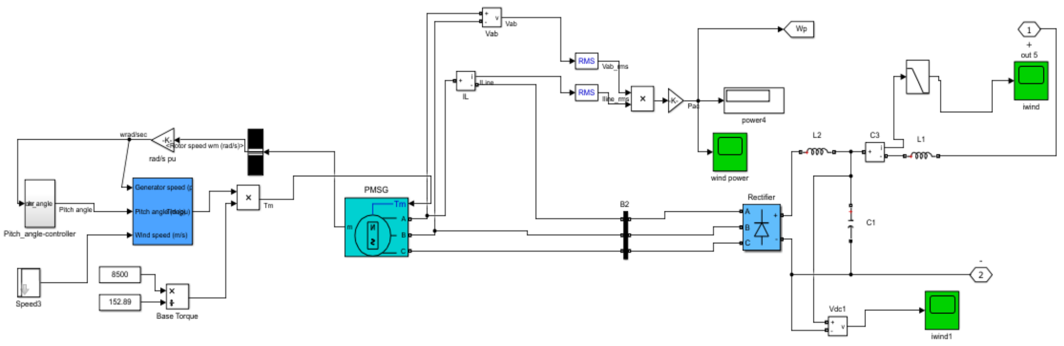

Figure 37 Simulink Model of a Wind Energy Conversion System with PMSG

c. DC-AC controllers

The inverter employs a hybrid voltage and current mode control strategy to function as a current source, enabling it to generate the reference power in grid-tied mode. The output power of the inverter is the sum of the power injected into the grid and the load demand, represented as $P_{load} + jQ_{load}$. Assuming the load is modelled as a parallel *RLC* circuit thus, the real and reactive power can be expressed as follows:

$$P_{load} = \frac{3}{2} V^2{}_m \ \frac{1}{R} \qquad (26)$$

$$Q_{load} = \frac{3}{2} V^2{}_m \cdot \left(\frac{1}{wL} - Wc\right) \qquad (27)$$

In the overall block diagram of the proposed unified control strategy, key parameters such as the inductor current (i_{Labc}), utility voltage (v_{Labc}), load voltage (v_{Cabc}) and load current (i_{Llabc}) are monitored. The three-phase inverter is controlled in the synchronous reference frame (SRF), where three-phase variables are transformed into DC quantities for easier analysis and control.

The control diagram consists of three main components which are the inductor current loop, the PLL and the current reference generation module. In the inductor current loop, the PI compensator is employed in both D-axis and Q-axis, and a decoupling of the cross-coupling, denoted by $w_0 L_f / k_{PWM}$ is implemented in model to mitigate the couplings due to the inductor. The output of the inner current loop d_d and d_q together with the decoupling of the capacitor voltage, denoted by 1/ k_{PWM} sets the reference for the standard Space Vector Modulation (SVM) that controls the switches of the three-phase inverter in the simulation.

It should be noted that k_{PWM} denotes the voltage gain of the inverter which equals half of the DC voltage in this paper.

The PLL in the proposed control strategy is based on the SRF PLL (Synchronous Reference Frame Phase-Locked Loop), which is widely used in the three-phase power converter to estimate the utility frequency *(f)* and phase (*θ*). Furthermore, a limiter is inserted between the PI compensator G_{PL} and the integrator, in order to hold the frequency of the load voltage (f_{load}) within the normal range in the islanded operation. In Figure 38, it can be found that the inductor current is regulated to follow the current reference $i_{L,ref}^{dq}$ and the phase of the current is synchronized to the grid voltage $v_{g,abc}$. If the current reference is constant, the inverter is just controlled to be a current source, which is the same with the traditional grid-tied inverter.

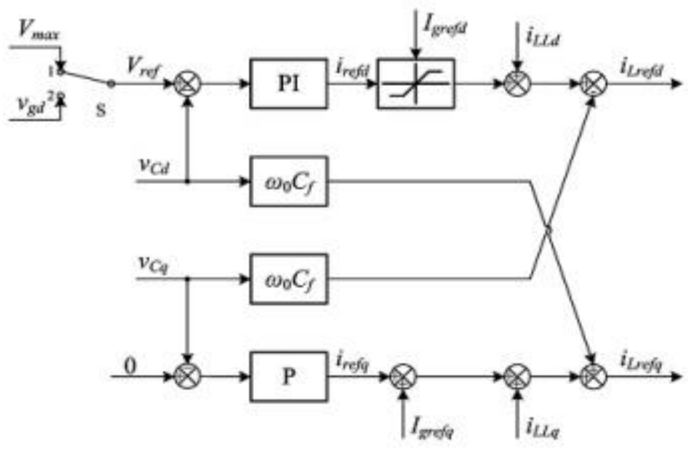

Figure 38 Block diagram of the current generation module

One of the new part in this paper is the current reference generation module shown in Figure 38, which regulates the current reference to guarantee the power match between the PV and Wind. Moreover, the unified load current feed forward, to deal with the nonlinear local load, is also implemented in this module.

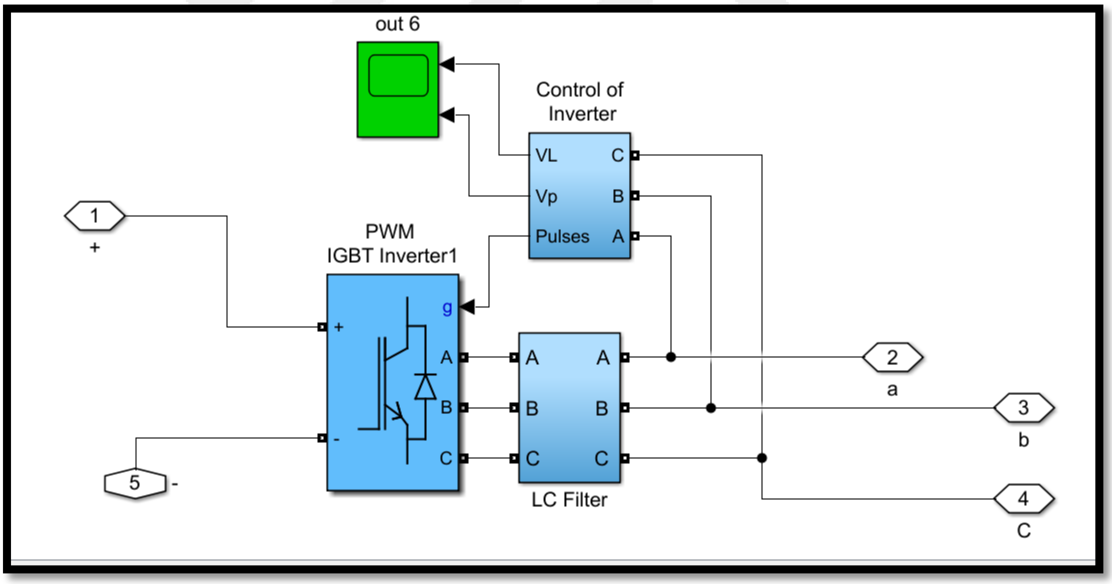

Figure 39 Inverter and LC Filter Layout

Figure 39 MATLAB/Simulink model above represents a PWM-based IGBT inverter system with an LC filter for power conversion and smoothing. The inverter receives a DC input voltage and converts it into AC output using PWM control. The control block provides switching pulses to the inverter based on voltage references V_L and V_P. The LC filter at the output helps reduce harmonics and smooth the AC waveform before it is delivered to the load. In the simulation an universal bridge as

PMW IGBT inverter is used with parameters are given below in Table 3.

Table 3 Inverter and Filter Specifications

Number of Bridge arms	3
Snubber resistance	5000 Ω
Ron	*1* mΩ
Switching Frequency	10 kHz
Input Voltage	1500 V DC
Output Voltage	800 V AC
LC Filter Inductance (L)	1Mh
LC Filter Capacitance (C)	100 µF
Control Signals	95%

The figure 40 below represents internal part of a three-phase capacitor bank with inductive components that is used in Figure 39 for filters for power factor correction or reactive power compensation in the simulation. It shows line connections, inductors (L4, L5, L6), and capacitors (C4,C5,C6) arranged in a balanced three-phase configuration.

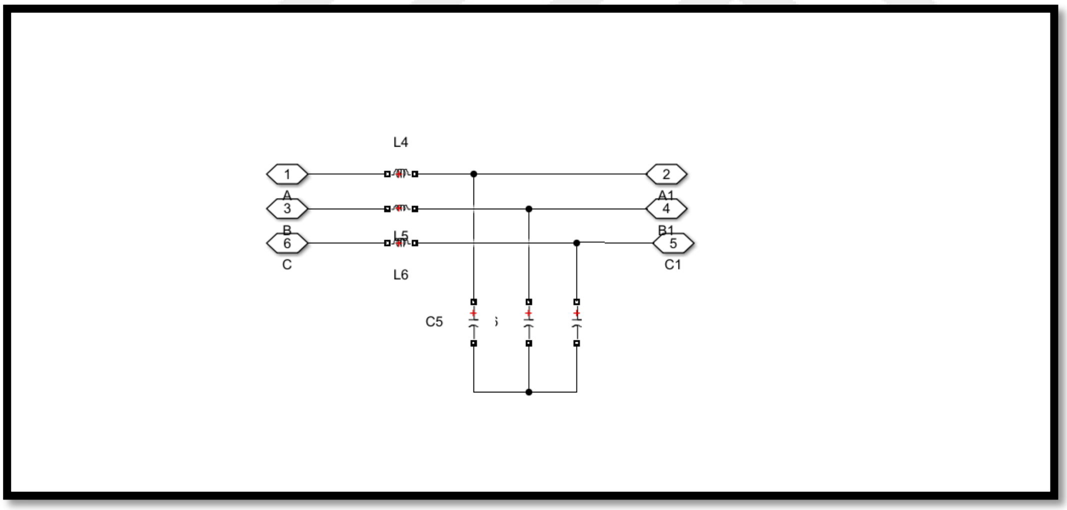

Figure 40 Schematic of a Three-Phase LC Filter Circuit

With an input inductance value of $L = 36 \times 10^{-4} H$ and a capacitance value of $C = 6.85 \times 10^{-6} f$ and the filter reduces signal harmonics and smooth the output signals.

4. Control Algorithms

a. MPPT algorithm (P&O Algorithm)

MPPT is the tracking algorithm that is used in this simulation with the

Perturb and Observe (P&O) method to ensure maximum power output from the PV and wind power systems.

The MPPT operates based on the power equation:

$$P = V \times I \tag{28}$$

Perturb and Observe adjusts the operating voltage (V) as:

$$\Delta V = \text{sign}\left(\frac{\Delta P}{\Delta V}\right) \times k \tag{29}$$

Where (K) is a small step size.

This algorithm continuously puts the operating point of the systems at the maximum power point under the fluctuating environmental conditions. The Figure 41 Simulink diagram below represents an MPPT Controller using the Perturb and Observe (P&O) algorithm. The controller takes PV voltage (V_PV) and current (I_PV) as inputs and adjusts the duty cycle (D) to optimize power extraction from the photovoltaic system. The MPPT parameters are defined through the "Param" block and the system is enabled via an external signal.

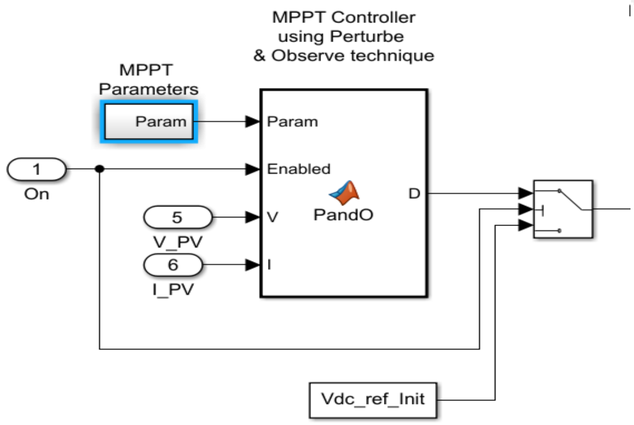

Figure 41 Simulink Model of MPPT Controller Using P&O Method

b. UPQC

Specifically, the control strategy used in the Unified Power Quality Conditioner plays an important role in this simulation. The UPQC is used in the simulation that consists of a shunt active power filter and a series active power filter which helped a lot to enables the compensation of voltage sags and swells, reactive power and harmonics in the simulation results. The simulation employs an advanced control strategy using Fourier analysis for harmonic extraction, PLL for synchronization and PWM techniques for precise compensation. The Fourier transform-based approach ensures real-time harmonic detection and correction. Simulation results show that UPQC effectively reduces THD and stabilizes voltage, improving overall power system reliability. The shunt active power filter controls the amplitude of the third voltage and compensates for the reactive power as its control diagram shown in Figure 42.

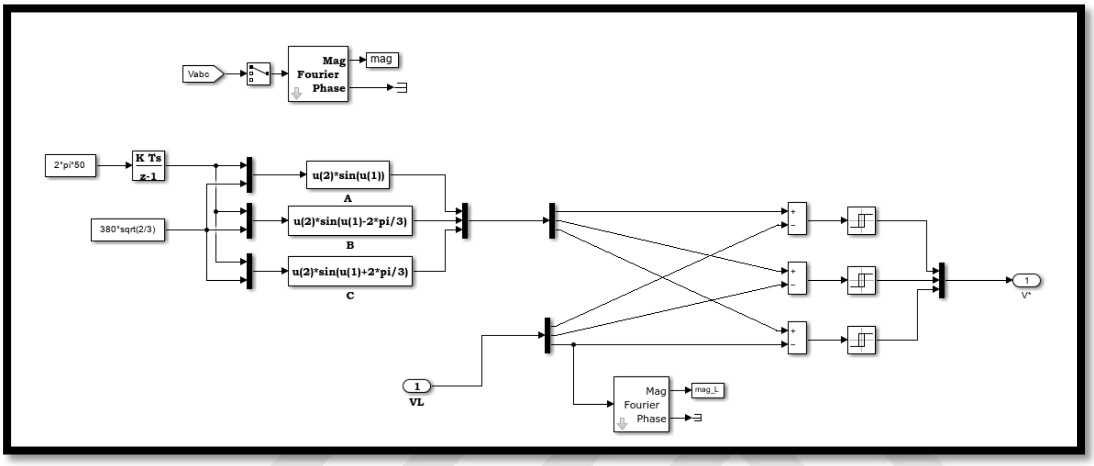

Figure 42 Simulink Model of a Unified Power Quality Conditioner (UPQC)

c. Active power filters and LCL filters

The active power filters and Inductor-Capacitor-Inductor **(**LCL) filters are used as complementary to one another to enhance the various power quality parameters. There are active power filters for removing harmonic components and supplying reactive power, while the LCL filters are designed for high-quality interconnection to the grid in the MATLAB/Simulink.

These filters has proven an effective support in handling non-linear loads that introduce harmonic distortions. On the other hand, LCL filters helped in the simulation as a passive components designed to smooth out switching ripples and reduce high-frequency harmonics when interfacing converters with the grid. Their three-stage topology (inductor-capacitor-inductor-LCL) provides superior harmonic attenuation compared to traditional L filters, making them ideal for grid-connected converters in renewable energy and active filtering applications as it is simulated in below Figure 42.

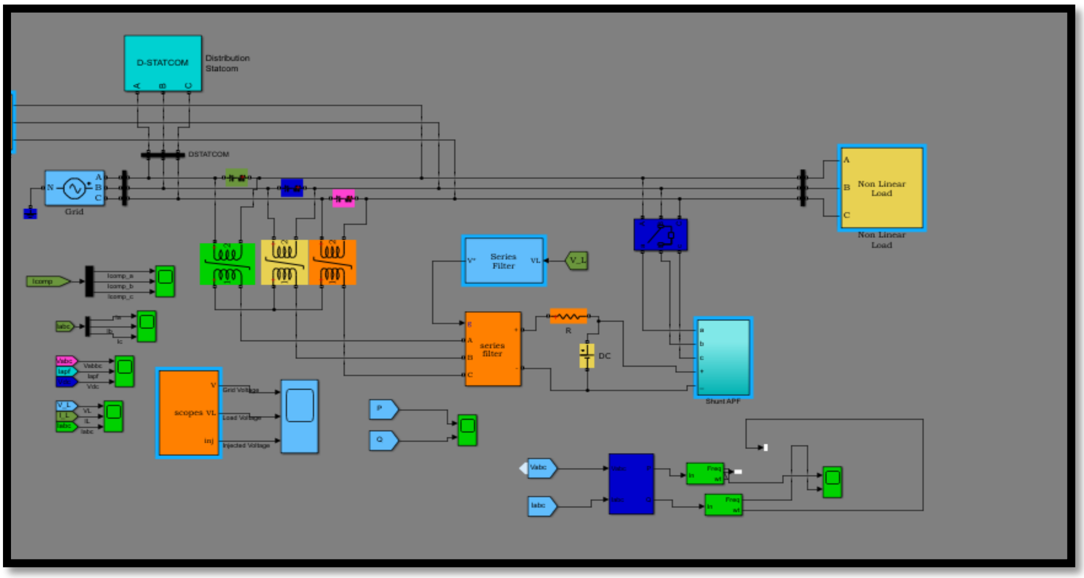

Figure 43 Simulink Model of Active Power Filters

In addition to figure 42, the above Figure 43 Simulink model represents a power quality compensation system utilizing a three-phase inverter with a hysteresis current controller. The system includes a PI controller that regulates the DC-link voltage by compensating power losses (P_{loss}). A Universal Bridge (IGBT-based inverter) generates compensation currents based on the reference current (I_{ref}) computed by the PQ & Compensation Calculation block.

The Controller ensures accurate current tracking. The compensated current is injected into the system through a Coupling Inductor, improving power quality by mitigating harmonics and reactive power. The PQ measurement block monitors the system's performance by analysing voltage (V_{abc}) and current (I_{abc}) parameters. This is usually creating better efficiency when it is used with APFs and grid-tied inverter applications as simulated in our MATLAB/Simulink model.

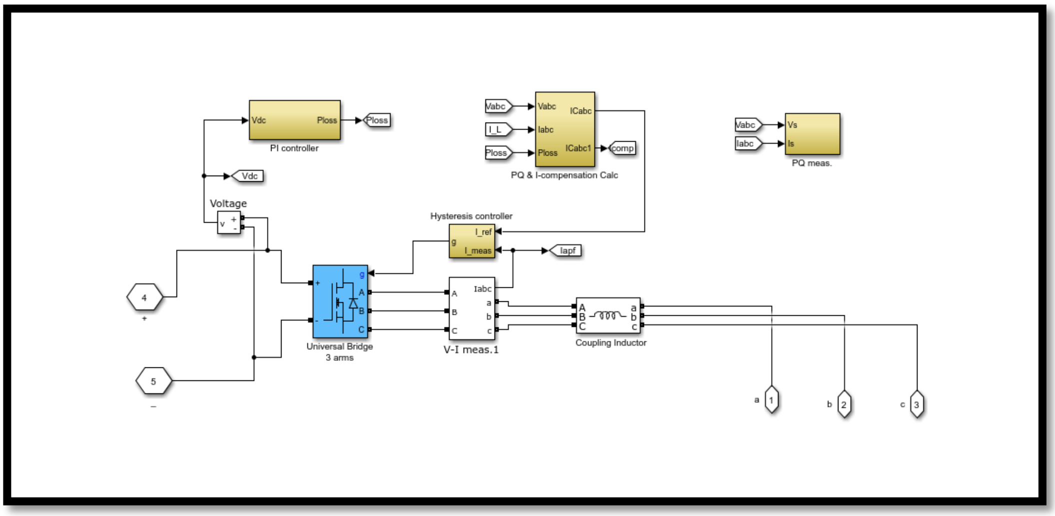

Figure 44 Active Power Filter for Harmonic and Reactive Power Compensation

Here, it is important to address to PQ measurements that demonstrated in Figure 44 used in APF to improve power quality. This Simulink model represents a Power Quality Compensation System which is designed to improve the quality of electrical power by reducing unwanted harmonics and reactive power. It takes voltage (V_{abc}) and current (I_{abc}) as inputs and processes them using a transformation which converts three-phase signals into two-phase (α-β) components for easier analysis. The PQ calculation block then determines how much power needs to be compensated is it can be seen from below figure 45. A separate block calculates the compensation current which is injected back into the system to correct power imbalances. Additionally, a loss compensation mechanism ensures stable operation by adjusting for system losses as it is shown in below Figure 45.

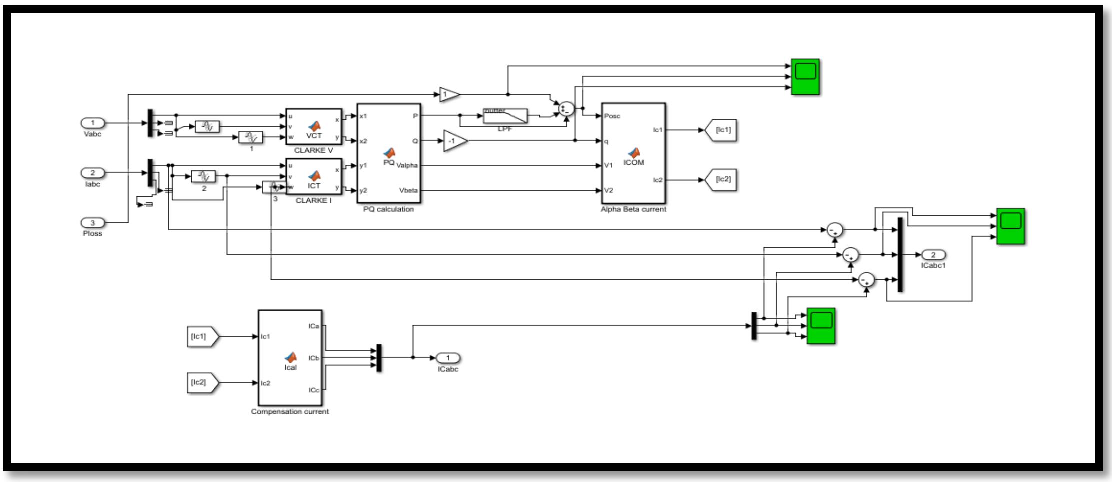

Figure 45 Power Quality Compensation System Layout that is used in APFs

d. Inverter control system

Specifically, the inverter control system employs three-phase inverters, distribution static synchronous compensators and D-STATCOM for power control and synchronisation with the grid. The PWM system generates the correct pulse signals to switch on the inverters required to manage power conversion.

In the MATLAB/Simulink, a three-phase inverter is the most important part of controlling the power quality control. The inverter operates by converting DC power into AC, ensuring proper synchronization with the grid while compensating for power quality issues such as harmonics, reactive power imbalance, and voltage sags/swells. The control of the inverter is typically implemented in Simulink with using PWM, where switching signals are generated to shape the output waveform to closely match the reference signal. Additionally, PLL ensures synchronization with the grid voltage, which is critical for maintaining a stable and efficient power exchange.

The control system of the three-phase inverter integrates advanced current and voltage control strategies to enhance power quality. The circuit of inverter control strategy is used in simulation is shown as below in Figure 46. When inverter control system is combined with LCL filters, the inverter ensures smooth power delivery with minimal switching ripples and harmonic interference. This control approach makes three-phase inverters highly effective in mitigating power quality disturbances in both grid-connected hybrid system.

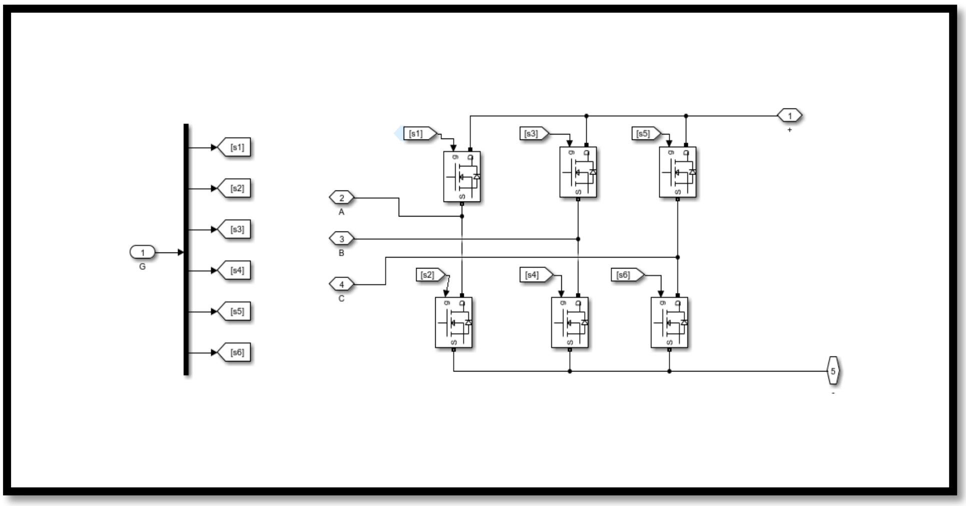

Figure 46 Three-Phase IGBT-Based Inverter Circuit from Simulink

e. D-STATCOM

The D-STATCOM is interfaced with the inverter control system for controlling the reactive power at the PCC where the voltage regulation is required. The D-STATCOM employs a voltage source converter to provide or absorb respectively reactive power actively, in such a manner that the reactive power at PCC can be controlled accurately.

A MATLAB/Simulink layout and control system of DSTATCOM is demonstrated below in Figure 47 and Figure 48 which is giving support for voltage stability and also reduce THD.

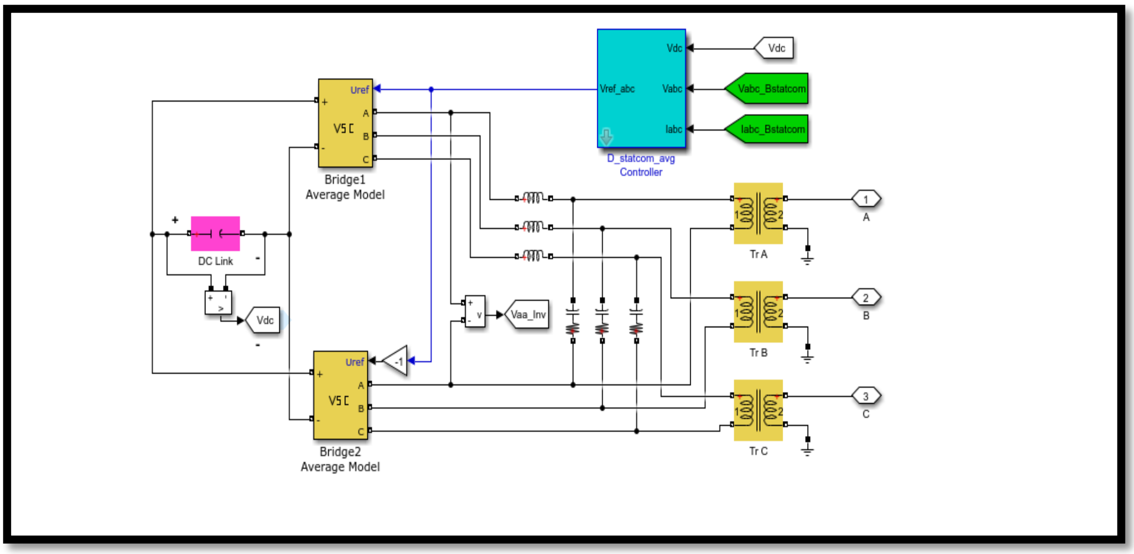

Figure 47 Simulink Model of a STATCOM

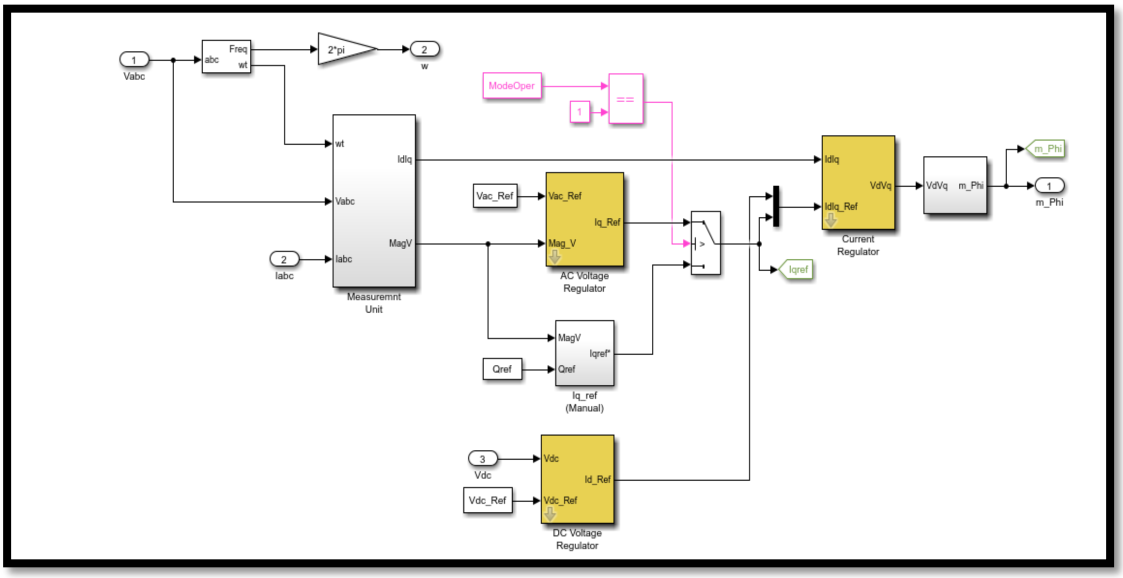

Figure 48 Control Layout of the system of DSTATCOM

f. PWM system

The PWM system produces the correct switching signals to drive the inverters whilst maintaining a proper power conversion and synchronising with the grid. The PWM technique involved a high-frequency carrier signal that is compared to the reference voltage or current signals in order to obtain the switching patterns of the inverter switches. This method gives good regulation of the active and reactive power from the inverter side so as to control the flow of power, eliminate harmonics and regulating the frequency in order to keep phase with the utility grid. PWM is integrated in the MATLAB/Simulink as shown below in Figure 49 which is crucial for a better efficiency of the system.

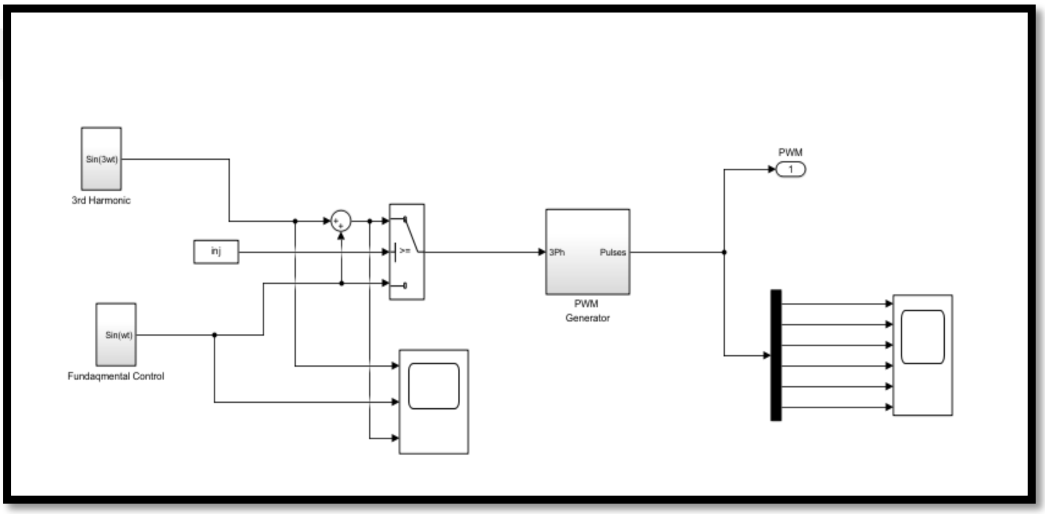

Figure 49 Simulink Model of Pulse Width Modulation

g. Voltage source converters

In the simulation VSCs is used to enable the PV, wind power and other control circuitries to interface with the electrical utility grid. These are required for the conversion of the output generated by the renewable energy sources in terms of variable-frequency and variable-voltage output to the grid-requirement of fixed-frequency and fixed voltage. As it will be seen in the results too, in below Figure 50, the VSCs contributed to the regulation of active and reactive power flow and ensure compliance with the power quality standards that the hybrid electrical system has to achieve in order to interface with the utility grid.

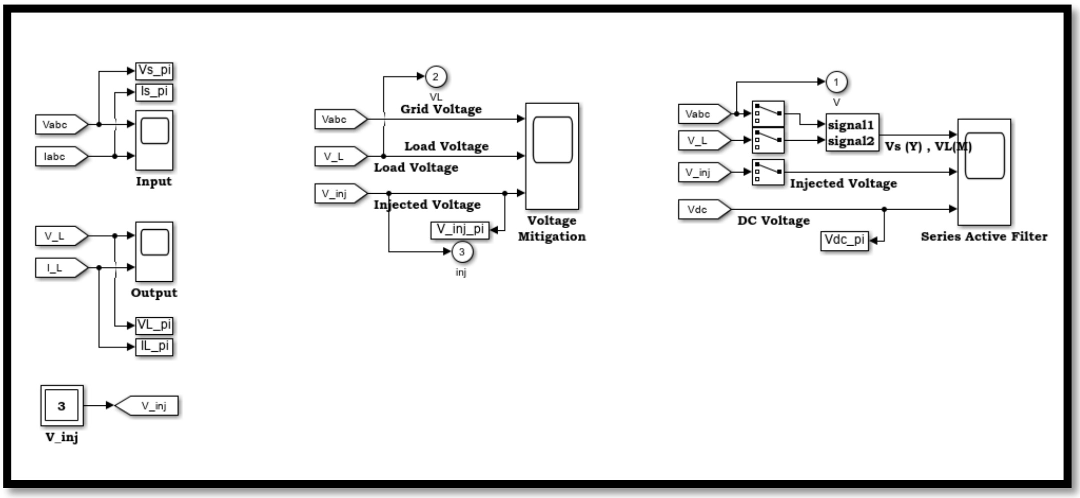

Figure 50 Control Model of Voltage Source Converters

C. Results and Analysis

1. Voltage Regulation Performance

Voltage regulation is a critical aspect of power quality, ensuring that the supplied voltage remains within acceptable limits despite disturbances such as voltage sags and swells. The provided analysis focuses on how the UPQC effectively mitigates these disturbances by dynamically adjusting the voltage supplied to the load.

In the Figure 51 below, a voltage sag occurs between 0.5 seconds to 0.7 seconds, where the grid voltage momentarily drops below its nominal value. However, as seen in the results, the UPQC successfully compensates for this voltage drop by injecting the required voltage to maintain a stable output. Similarly, voltage swells, which represent a temporary increase in voltage beyond the normal level, were also mitigated, ensuring a properly regulated AC voltage supply.

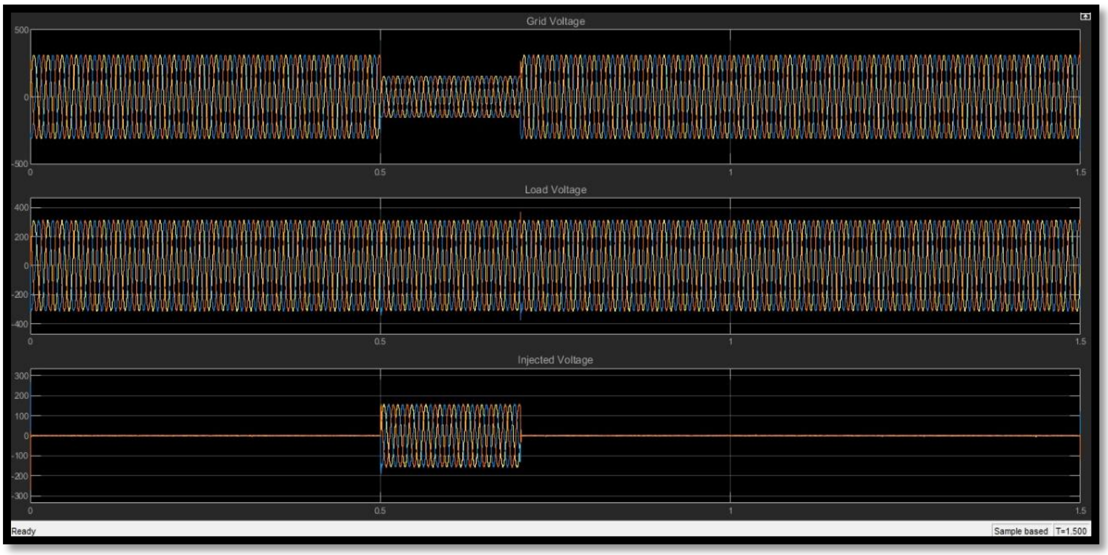

Figure 51 Voltage Regulation Performance

The graph results further confirm the effectiveness of the UPQC in regulating voltage. The top plot represents the grid voltage, where the sag is clearly visible between 0.5s and 0.7s as indicated by the reduction in waveform amplitude. However, despite this disturbance, the middle plot, which illustrates the load voltage, remains stable throughout the event. This demonstrates that the UPQC actively compensates for the voltage drop, ensuring that the load experiences minimal deviation from the expected voltage profile. The bottom plot shows the injected voltage, where a clear waveform is visible within the same time range, indicating the corrective action taken by the UPQC. By injecting the appropriate voltage, the system ensures that voltage remains unaffected by disturbances occurring in the grid.

2. Current Regulation Performance

The figure 52 simulation result presents the time-domain waveforms of three-phase compensating currents (Icom_a, Icomp_b, Icomp_c) generated by the hybrid electrical simulation. The compensating currents are sinusoidal and balanced with a consistent frequency (50 Hz). A brief transient is seen around 0.5 seconds due to a load change and compensator devices are activated and that leads to load change which is APF and UPQC that stabilize currents very quickly and demonstrating a fast dynamic response and robust control performance. The 120° phase shift between the waveforms confirms a symmetrical and balanced three-phase operation, which is essential for effective harmonic and reactive power compensation. Overall, the results demonstrates that the current control strategy is functioning efficiently and maintaining steady-state behaviour and improving power quality for hybrid electrical energy systems.

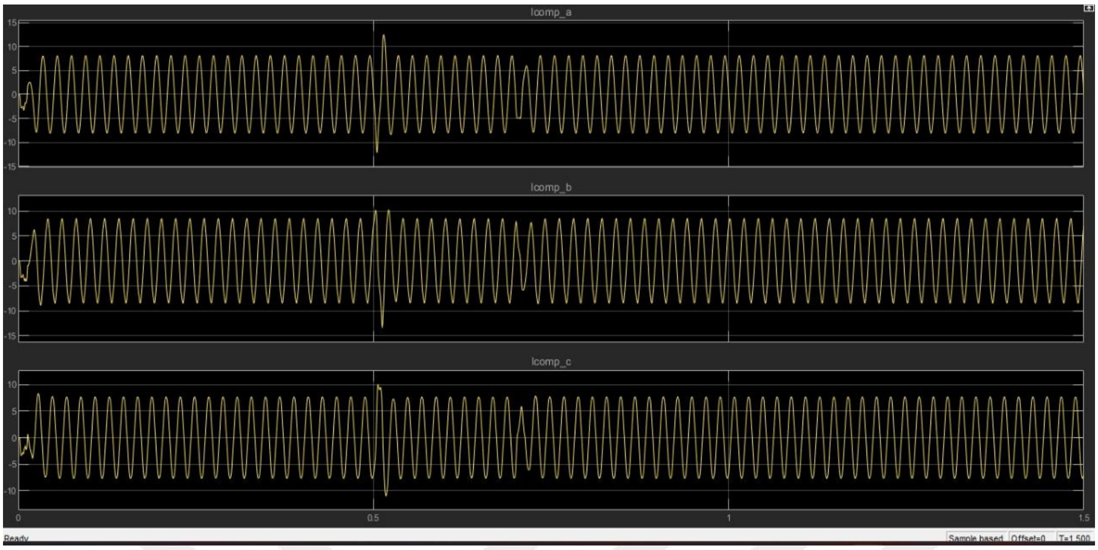

Figure 52 Current Regulation Performance

3. Active and Reactive Power Results

Active and Reactive Power Outcomes are demonstrated in the below Figure 53. The plots includes also voltages (V_{alpha}, V_{beta}), and source currents (I_{source}). Active power, which is the actual usable power supplied to the load, reaches to approximately 140 MW and indicating that the system is capable of delivering a significant amount of power efficiently during a 1000W/m2. Reactive Power also remains nearly constant and close to zero ($Q = 0$), and provides that the system is effectively compensating for reactive power. This confirms the success of the UPQC and D-STATCOM component in improving the power factor by neutralizing reactive components. The V_{alpha} and V_{beta} waveforms are clean, sinusoidal and 90° out of phase with each other which shows a balanced three-phase system. The source currents are sinusoidal and balanced across all three phases, indicating that the current drawn from the utility remains clean and free from harmonic distortion as shown in below figure 53.

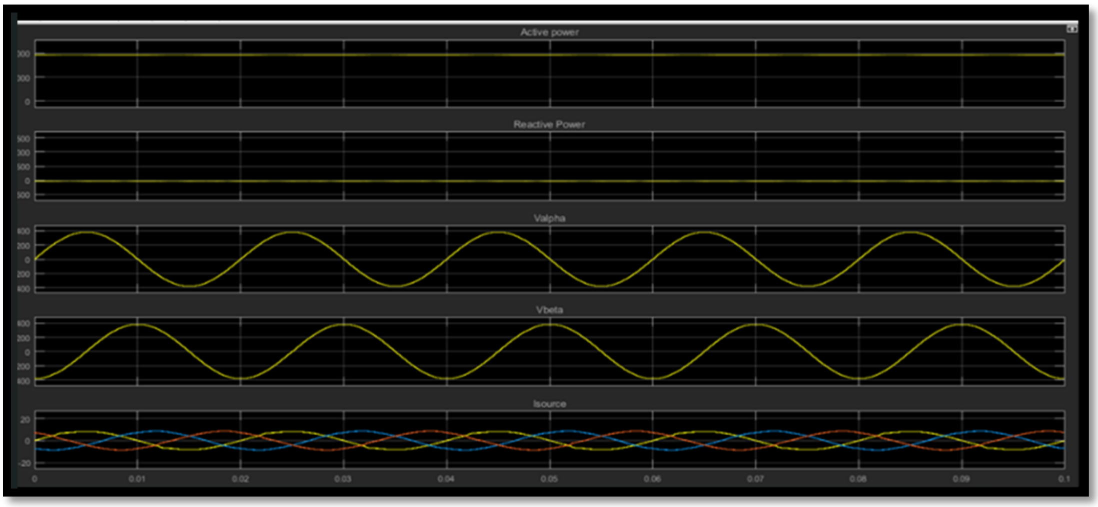

Figure 53 Active and Reactive Power Performance

4. Total Harmonic Distortion Results

THD analysis in below figure 54 demonstrate the effectiveness of harmonic mitigation with a corresponding magnitude of 310.2 units and the THD is 0.79%. THD of the fundamental frequency signal voltage and load voltage is measured at 0.79% which indicates that the signal is very close to a pure sine wave with minimal harmonic distortion that is within IEC/IEEE standards which is highlighting the crucial role of APF and D-STATCOM.

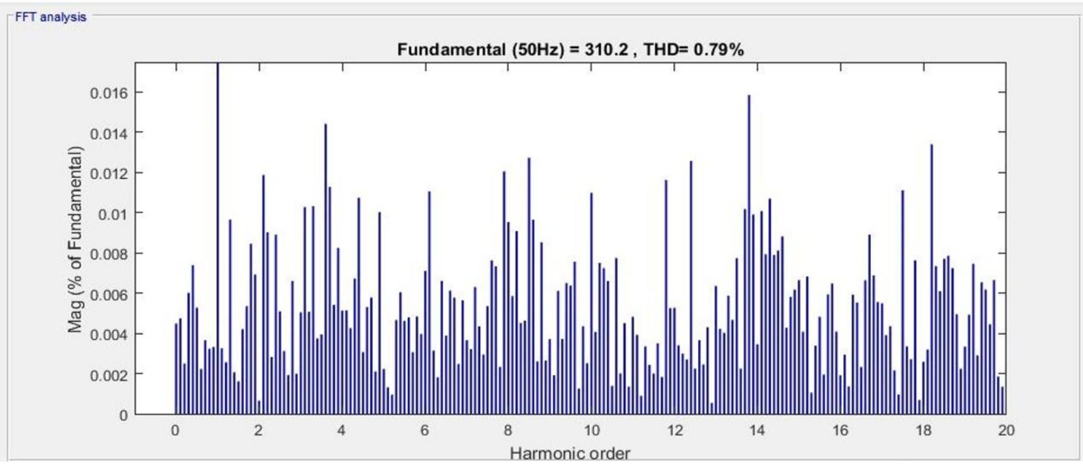

Figure 54 Total Harmonic Distortion Results of the System

The Figure 54 above shows smooth and symmetrical sinusoidal waveforms for the grid and load voltage that indicating effective filtering of harmonic components. The substantial reduction in THD suggests that high-order harmonics, which can negatively impact system stability, have been successfully suppressed in the MATLAB/Simulink results. The clear and undistorted waveforms confirm improved voltage regulation and reduced power losses.

5. PV and Wind Power Results

The Figure 55 illustrates the relationship between irradiance, DC voltage and DC power in response to changes in solar input. Initially, the irradiance is stable at around 1000 W/m², but it drops to 800 W/m² at t ≈ 0.5s, causing a reduction in power output. The DC voltage remains relatively stable with very minor fluctuations, reflecting effective voltage regulation. As the irradiance returns to its original level at t ≈ 1s, the power output recovers accordingly. This result confirms that the simulation in this hybrid system, PV output dynamically adjusts power generation based on available solar energy while maintaining voltage stability.

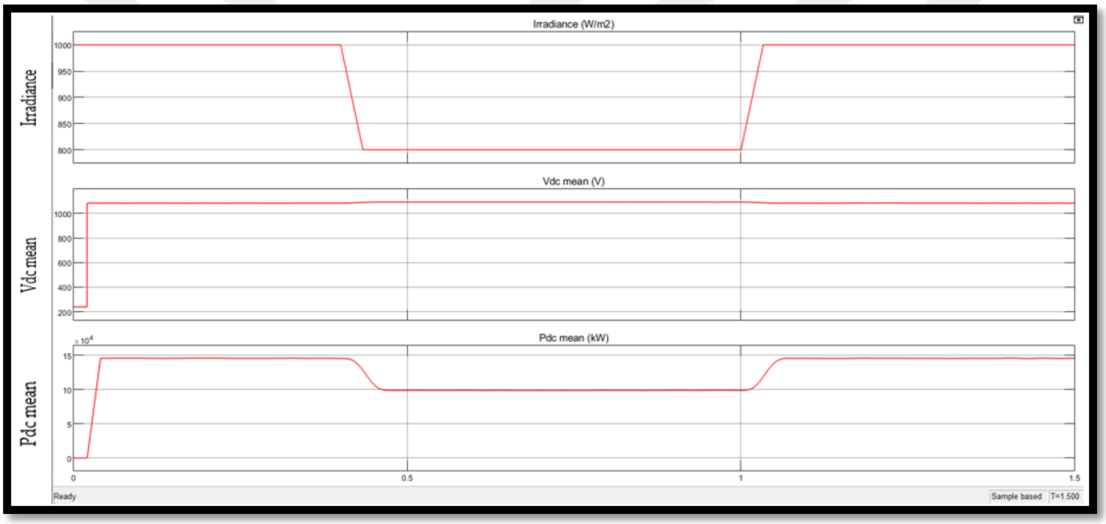

Figure 55 PV Output

Below three graphs in Figure 56 represent the simulation results of a wind turbine system modelled in Simulink. Wind Current (Top left graph) shows the wind turbine-generated current over time. The current exhibits oscillations that gradually stabilize, indicating the system's transient response before reaching a steady state. Wind Voltage (Top right graph), represents the voltage output of the wind turbine system. The voltage initially experiences large oscillations before settling, demonstrating how the system stabilizes after an initial transient phase. Wind Power (Bottom Graph) demonstrates power output of the wind turbine increases sharply, reaching a peak before gradually stabilizing. The fluctuations in power reflect dynamic changes in wind energy conversion and system stabilization.

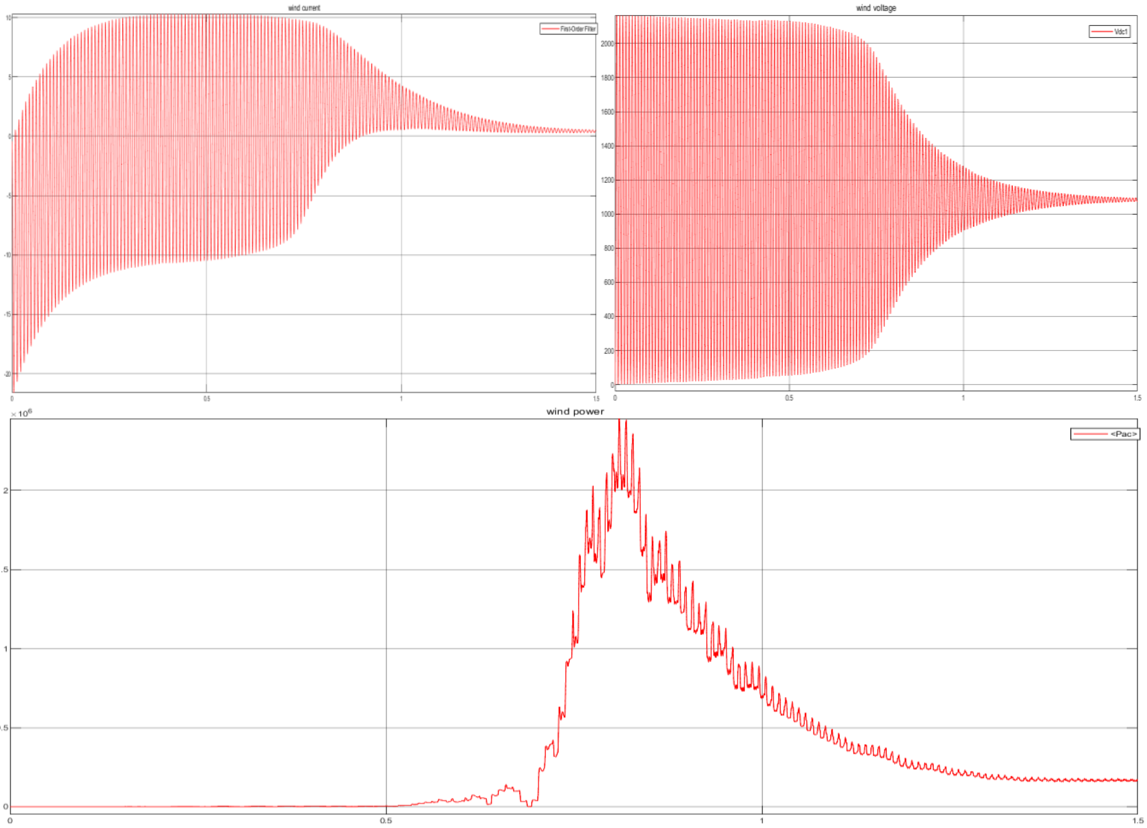

Figure 56 Wind Turbine System Response: Current, Voltage and Power Dynamics

6. Power Factor Correction Results

Power Factor Correction results are provided in below Figure 57 for the system performance that is analysed through frequency domain representation using FFT analysis.

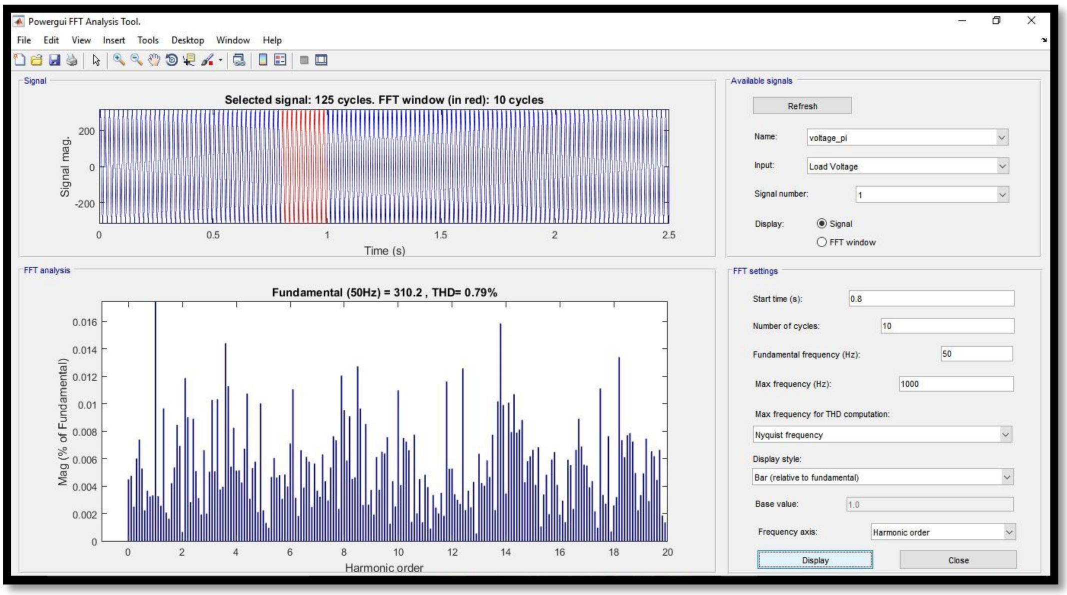

Figure 57 Voltage Regulation Performance of the System

The first section of the figure presents the time-domain signal of the load voltage where a specific FFT window (highlighted in red) is selected for spectral analysis. The selection of 10 cycles within 125 total cycles ensures a focused examination of the harmonic and power quality.

The second section displays the harmonic spectrum is the analysed voltage waveform where the fundamental frequency is identified at 50 Hz with a magnitude of approximately 310.2. The THD is measured at 0.79%, indicating a relatively low presence of harmonic distortions in the system. A low THD value signifies that the applied control mechanisms and power electronic components are effectively mitigating distortions and improving the waveform quality. The presence of minimal harmonics ensures that reactive power components are minimized to increase overall system efficiency. The voltage regulation performance, as depicted in the figure, confirms that the control strategies successfully maintain voltage stability while reducing harmonics.

7. Frequency Control Results

The simulation results in below Figure 58 show that the grid frequency control outcome is well managed as the frequency fluctuates around the desired range mainly due to changes in power generation and load demand. The management of the frequency modulation in the generation of the three-phase voltage is done in a coordinated manner by the inverters, PWM system and other related sub systems making the operation reliable. The frequency oscillates around 50 Hz, with a very minor deviations primarily between 49.9 Hz and 50 Hz. This range variations indicate a well-regulated system where power generation and demand are balanced effectively.

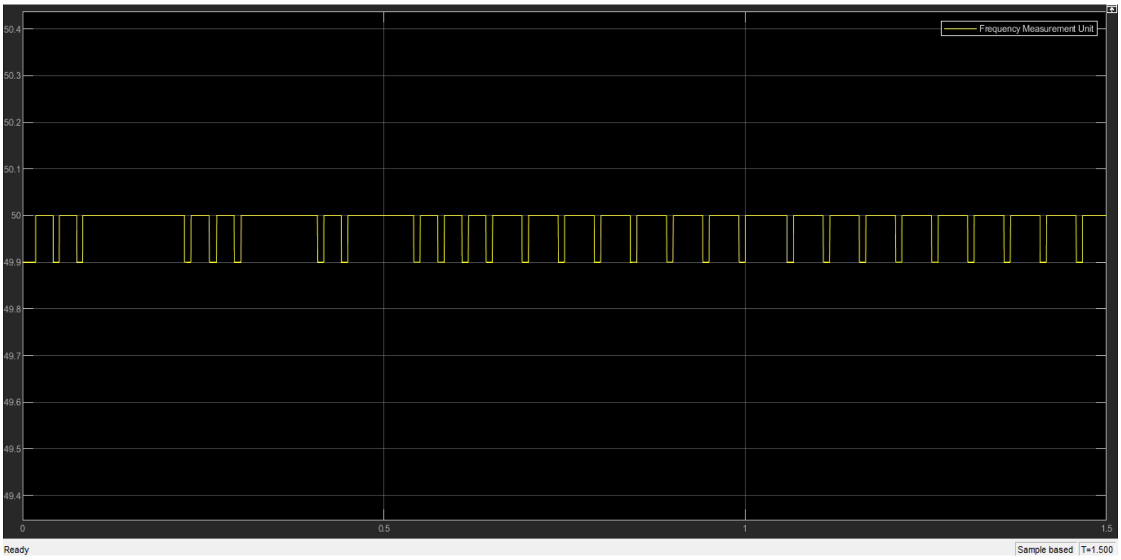

Figure 58 Frequency Regulation Performance

VI. CONCLUSIONS

This thesis has introduced and validated new control methods for power quality control in hybrid electrical energy systems, integrating PV and wind power sources. A comprehensive MATLAB/Simulink-based experimental control method setup was developed with integrated the effectiveness of advanced control algorithms, power filters and modulation techniques in improving power quality. The findings highlight key improvements in voltage regulation, power factor correction, harmonic distortion minimization and frequency stability under dynamic load and generation conditions which are key issues in power quality.

A dedicated power quality control framework was implemented with integrating advanced filtering techniques, inverter control strategies and compensation devices. This framework effectively mitigated power fluctuations arising from hybrid renewable energy sources. The developed hybrid electrical energy system model in MATLAB/Simulink successfully simulated real-world operating conditions, including irradiance and load changes, temperature changes and grid-connected scenario. The model demonstrated the interplay between PV, wind power and power electronic components while validating the proposed control methodologies.

Accurate mathematical models for PV and wind power were formulated to capture dynamic responses under varying environmental conditions. These models served as the basis for optimizing MPPT strategies and inverter controls. The implementation of robust DC-AC controllers ensured stable voltage and frequency regulation while improving waveform quality. The P&O algorithm was optimized to enhance energy extraction efficiency, achieving higher power conversion rates with reduced oscillations. Additionally, UPQC and LCL filters significantly reduced voltage sags and improved the overall harmonic profile of the system.

The proposed control strategies demonstrated notable improvements in system stability and power quality. Voltage regulation was maintained within to ensuring smooth operation of loads and minimizing fluctuations caused by renewable energy intermittency. The frequency stability was well-maintained, consistently operating within the range of 49.9 Hz to 50 Hz, which meets grid compliance standards and ensures seamless integration with the power network. THD was reduced to 0.79%, significantly improving waveform quality and maintaining compatibility with IEEE and IEC standards. The reactive power compensation achieved through D-STATCOM and inverter-based control methods maintained power factor levels above 0.98, minimizing reactive power exchange with the grid and enhancing system efficiency. This was another great validated part of the simulation.

Further analysis revealed that the active power filters effectively mitigated harmonic distortion while ensuring fast dynamic response times. The three-phase inverter control system contributed to improved reactive power support, helping to stabilize voltage variations and maintain grid reliability. The PWM control system optimized switching techniques, reducing losses and improving power conversion efficiency and ensuring a stable and flexible operation even under fluctuating generation conditions.

In conclusion, this research has provided a robust framework for improving power quality in hybrid electrical systems, demonstrating the effectiveness of advanced control strategies and validating their performance through MATLAB/Simulink simulations. The findings contribute to the ongoing development of sustainable, efficient and resilient power systems, paving the way for smarter grid integration and renewable energy utilization. The future of hybrid electrical energy systems lies in the seamless integration of intelligent control systems, predictive analytics and adaptive grid management solutions, ensuring enhanced performance, reliability and long-term sustainability.

Future research on power quality control in hybrid electrical systems should focus on the practical implementation of advanced control strategies through real-world hardware validation and testing to ensure scalability and robustness. More predictive and self-learning controllers can significantly enhance system responsiveness by dynamically adapting to fluctuating grid conditions in real time. The integration of battery storage and EV systems will further improve grid flexibility and resilience against demand fluctuations. Additionally, advanced monitoring control systems which is integrated with ML and AI could enable decentralized and efficient energy exchange between hybrid system components. As hybrid grids become more interconnected, the impact of cybersecurity threats on power quality control should be assessed to ensure the resilience of smart energy networks. Finally, adopting multi-objective optimization techniques that balance economic feasibility, energy efficiency and environmental impact will be essential for developing next-generation hybrid electrical energy systems that are more stable, efficient and sustainable.

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