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Multi-Objective Optimization of Renewable Energy Supported UPQC for Power Quality and Reliability Improvement

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Abstract

The integration of RES into modern power systems is essential for sustainable energy generation but poses challenges such as power quality disturbances due to their intermittent and variable nature. To address these issues, the RES-UPQC emerges as an innovative solution, combining power quality improvement with renewable energy integration. The RES-UPQC is a hybrid device comprising series and shunt active power filters that simultaneously mitigate voltage sags, swells, harmonics, and reactive power imbalances while enabling the seamless incorporation of RES, such as PV, FC and wind energy, into the grid. By ensuring stable power delivery and maintaining power quality at the PCC, the system improves grid reliability and supports increased renewable penetration. Advanced control algorithms are employed for real-time compensation and efficient power management, ensuring smooth operation under dynamic grid conditions. The RES-UPQC not only enhances power quality but also maximizes the utilization of renewable energy, contributing to cleaner and more sustainable energy systems. Along with multiple renewable sources connection to the UPQC DC link energy storage elements like battery or super capacitor can also be connected for better stability. Many possible topologies of the RES-UPQC are discussed in this paper and the outcome of these topologies is discussed.

Keywords: RES (Renewable Energy Source), UPQC (Unified Power Quality Conditioner), PV (Photo Voltaic), FC (Fuel cell), PCC (Point of Common Coupling).

1. INTRODUCTION

With the growing demand for energy and the adverse environmental effects of fossil fuels, renewable energy sources (RES) like solar, wind, and biomass have gained significant attention as sustainable alternatives. However, integrating these intermittent and variable energy sources into the power grid presents challenges, such as voltage fluctuations, harmonic distortions, and other power quality issues. Unified Power Quality Conditioner (UPQC) is a powerful custom power device designed to address power quality problems [1]-[5]. It combines the functions of a series active power filter (APF) and a shunt APF in a single device to mitigate issues like voltage sags, swells, flickers, and harmonics on both the supply and load sides. By integrating renewable energy sources with UPQC, it is possible to enhance power quality while simultaneously optimizing the utilization of RES.

Renewable sources like solar and wind depend on weather conditions, leading to irregular power output. The variable nature of RES can lead to voltage fluctuations, frequency deviations, and instability in the grid. Increased penetration of RES can introduce harmonics, reactive power imbalances, and voltage distortions [5]-[13]. The series APF in UPQC helps maintain a stable voltage at the point of common coupling (PCC) by compensating for voltage sags, swells, and flickers caused by load or supply-side disturbances. The shunt APF eliminates current harmonics introduced by non-linear loads or inverter-based renewable sources. UPQC ensures optimal power factor correction by managing reactive power flow. It facilitates the smooth integration of RES into the grid by mitigating power quality issues arising from their variability [14] – [20].

Series Converter protects the load from supply-side disturbances by injecting compensating voltages. Shunt Converter maintains the grid-side current quality and manages reactive power and harmonics. Optional energy storage systems (ESS) can be included to enhance UPQC functionality during low renewable generation. Advanced control algorithms, such as synchronous reference frame (SRF) or instantaneous reactive power theory, ensure effective compensation and seamless operation of the UPQC in RES systems. The proposed structure of the RES-UPQC system with all the modules connected in presented in figure 1.

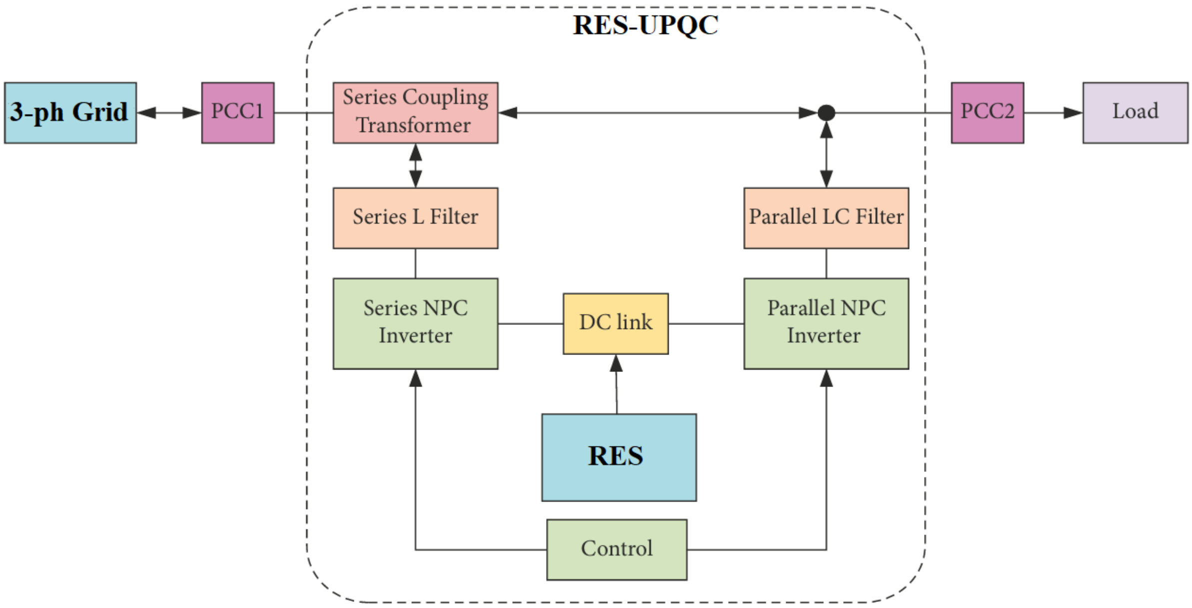

Figure 1: RES-UPQC system structure

The Unified Power Quality Conditioner (UPQC) is a versatile power electronics device designed to enhance power quality by addressing various issues such as voltage sags, swells, harmonics, and imbalances in a power distribution system. It combines the functionalities of two main components: the series active power filter (APF) and the shunt APF [21]-25]. These components work together to ensure a consistent and high-quality power supply to sensitive loads.

Series APF **is** connected in series with the supply line via a transformer. It injects compensating voltages to counteract voltage sags, swells, and flickers from the supply side. And maintains a stable and sinusoidal voltage at the load terminal. Detects supply voltage disturbances (sags, swells, flickers, or distortions). The module generates compensating voltage using pulse-width modulation (PWM) or similar techniques

[26]-[31]. Injects the compensating voltage in series with the supply through a series transformer to ensure the load voltage remains constant and sinusoidal.

Shunt APF connected in parallel with the load. Compensates for current-related issues such as harmonics, reactive power, and load current imbalances. It also maintains a sinusoidal current on the grid side. It monitors load current for harmonic components, reactive power demand, and unbalanced currents [32] – [35]. The module generates a compensating current that cancels out these undesirable components. It injects the compensating current into the system to ensure the grid current remains sinusoidal and balanced.

DC Link (Energy Storage Element) links the series and shunt APFs through a common DC capacitor. It acts as an energy storage element to support the compensation activities of both filters. The DC link capacitor serves as an energy buffer between the series and shunt APFs. It provides the energy required for compensation activities and maintains a stable DC voltage level.

Control Unit monitors voltage and current parameters in real-time. Implements control strategies to generate reference signals for series and shunt APFs. Ensures synchronization and effective operation of the UPQC.

The UPQC employs advanced control algorithms to ensure efficient compensation:

- Instantaneous Reactive Power Theory (p-q Theory): Separates active and reactive power components for precise compensation.
- Synchronous Reference Frame (SRF) Theory: Uses a rotating reference frame to extract harmonic and reactive components for compensation.
- Hysteresis or PWM Control: Generates switching signals for the power electronic converters to inject compensating voltages and currents accurately.

The series APF ensures the load receives a stable voltage by compensating for supply-side disturbances [36]-[40]. The shunt APF maintains grid-side current quality by neutralizing load-induced distortions. The DC link capacitor facilitates energy exchange between the series and shunt APFs, ensuring seamless operation. A control unit continuously monitors and adjusts the operation of the UPQC to achieve desired power quality standards.

2. RES

2.1 PV system

Photovoltaic (PV) Boost Converter with Maximum Power Point Tracking (MPPT) is a critical component in solar energy systems. It ensures that solar panels operate efficiently, maximizing the energy harvested and delivered to a load or storage system, such as a battery. PV cells convert sunlight into electrical energy through the photovoltaic effect. The power output of a PV cell depends on factors like solar irradiance, temperature, and load conditions [41]-[47].

The MPP is the point on the PV panel's power curve where the product of current and voltage is maximum. Due to variations in sunlight and temperature, the MPP shifts dynamically. MPPT algorithms are used to continuously adjust the operating point of the PV panel to maintain it at the MPP. Popular algorithms include Perturb and Observe (P&O), Incremental Conductance, and others.

A boost converter is a DC-DC converter that steps up the input voltage from the PV panel to a higher output voltage suitable for the load or battery. It operates using components like an inductor, switch (typically a MOSFET), diode, and capacitor. The duty cycle of the switch is controlled to regulate the output voltage and current [48] [49] [50]. The PV panel generates DC electricity at a voltage and current determined by the load and environmental conditions.

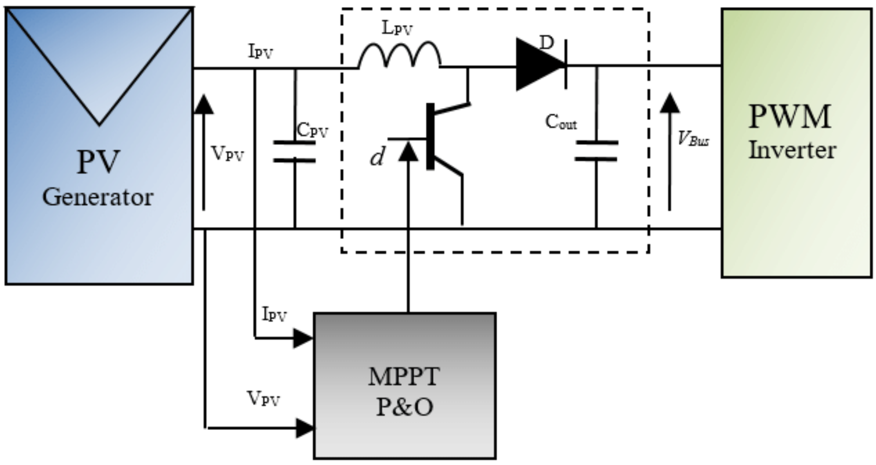

Figure 2: PV connected boost converter topology

The boost converter increases the PV panel's voltage to a desired level. This is essential when the load or battery requires a voltage higher than the PV panel's output [51] – [56]. The MPPT controller monitors the PV panel's voltage and current to calculate its power output. Based on the MPPT algorithm, it adjusts the boost converter's duty cycle to align the PV panel's operating point with the MPP. The energy harvested at the MPP is efficiently transferred to the load or battery.

Ensures that the PV panel operates at its optimal power point, maximizing energy harvest. Can handle varying load and environmental conditions, such as changing sunlight intensity. Suitable for small-scale systems (e.g., portable solar chargers) and large-scale systems (e.g., solar farms). Provides a stable output voltage to the load or storage system.

2.2 Wind farm

A wind farm is a collection of wind turbines in a specific geographic area that work together to harness the kinetic energy of the wind and convert it into electrical energy. Wind farms are a sustainable and environmentally friendly method of generating electricity, contributing significantly to the global shift toward renewable energy. The primary energy-harvesting devices, consisting of blades, a rotor, a generator, and a tower [57]-[62]. The blades capture wind energy, turning the rotor connected to a generator that produces electricity.

A Permanent Magnet Synchronous Generator (PMSG) wind farm uses wind turbines equipped with PMSGs to convert wind energy into electrical energy. PMSG technology is widely adopted due to its high efficiency, compact design, and suitability for direct-drive systems, which eliminate the need for a gearbox. A wind farm utilizing Permanent Magnet Synchronous Generators (PMSGs) combined with Buck-Boost Converters enhances the efficiency and adaptability of power generation, ensuring stable and optimized energy delivery to the grid or storage systems [63] – [67]. This setup addresses the challenges of variable wind speeds and provides robust power management.

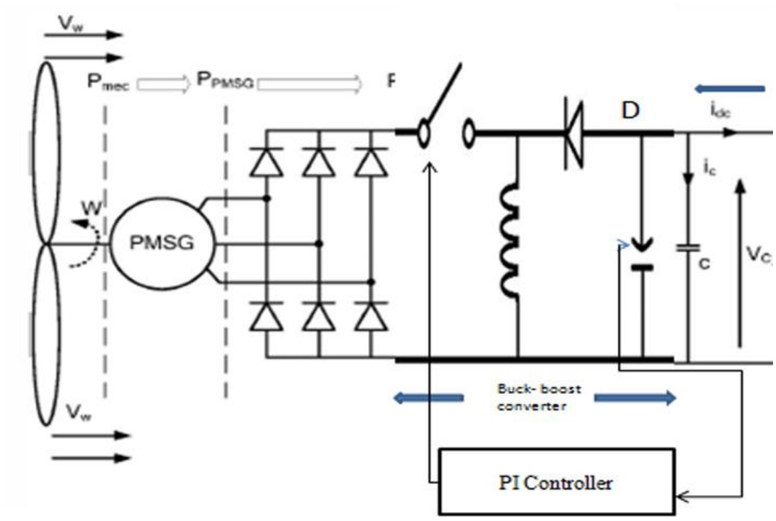

Figure 3: PMSG wind farm structure

A DC-DC converter that can step up (boost) or step down (buck) the input voltage to a desired level. Adjusts the DC voltage from the rectifier to match grid requirements or charging systems. The controller implements Maximum Power Point Tracking (MPPT) algorithms to maximize power extraction under varying wind speeds. Controls the duty cycle of the buck-boost converter to achieve the desired voltage regulation.

Integrating a PMSG with a Buck-Boost Converter in a wind farm enhances the system's ability to handle varying wind conditions while maintaining efficient and reliable power output [68]-[70]. This technology is pivotal in advancing the global adoption of clean, renewable energy and ensuring stable electricity generation in both large-scale and localized applications.

2.3: Fuel cell system

A fuel cell connected to a boost converter with voltage feedback control is an advanced energy system designed to efficiently manage the power generated by the fuel cell and ensure stable output voltage for various applications. The boost converter steps up the relatively low and variable output voltage of the fuel cell to a higher, regulated level suitable for the load or further processing.

Converts chemical energy (from hydrogen or other fuels) into electrical energy via an electrochemical reaction. Provides a DC output voltage that can vary depending on load conditions and fuel supply. A DC-DC converter that steps up the input voltage from the fuel cell to a desired higher level. Includes components like an inductor, diode, switch (typically a MOSFET or IGBT), and a capacitor [71]-[73].

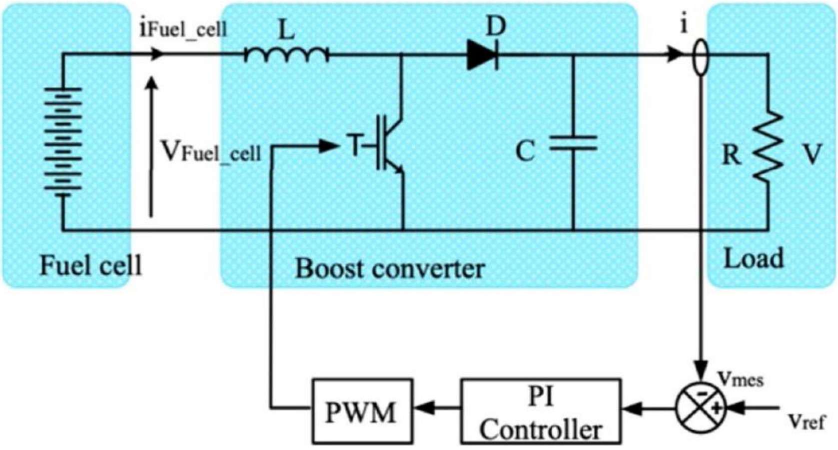

Figure 4: Fuel cell topology

The fuel cell generates DC voltage, but the output is often variable and lower than required for most applications. The boost converter steps up the fuel cell's output voltage to meet the desired level. The energy storage components (inductor and capacitor) temporarily store and release energy to achieve the voltage boost. The voltage sensor monitors the output voltage of the boost converter in real-time. The error amplifier compares the sensed voltage to a predefined reference voltage and calculates the error.

The controller adjusts the duty cycle of the switching element to minimize the error, ensuring the output voltage remains constant despite changes in load or fuel cell output. The regulated voltage from the boost converter is supplied to the load, ensuring stable and efficient operation. Maintains a constant voltage, essential for sensitive electronic devices and grid integration. Optimizes the performance of the boost converter by dynamically adjusting the duty cycle. Handles varying load demands without compromising output voltage quality. Reduces stress on the fuel cell by managing fluctuations in load and voltage demand effectively.

3. METHODOLOGY OF DIFFERENT CONTROLLER REGULATORS

3.1: Instantaneous Reactive Power Theory

The Instantaneous Reactive Power Theory (also known as the p-q Theory) is a mathematical framework used primarily in power electronics and electrical engineering to analyze and control power systems, particularly in the context of three-phase systems. It was introduced to address challenges in reactive power compensation, harmonic mitigation, and power quality improvement in electrical networks.

Unlike traditional methods that deal with average power over a cycle, the p-q theory focuses on instantaneous values of voltage and current. It decomposes the instantaneous power into: Instantaneous active power (p): Represents the real power being delivered to the load at any instant. Instantaneous reactive power (q): Represents the oscillatory power exchange between the source and the load, which does not contribute to real energy transfer [74].

The theory uses a mathematical transformation called the Clark Transformation or α-β Transformation, which converts three-phase voltages and currents (a, b, c) into two orthogonal components (α, β) in a stationary reference frame. This transformation simplifies the analysis of three-phase systems, especially for unbalanced or non-sinusoidal conditions. Reactive Power Compensation: By analyzing the instantaneous reactive power, compensators like shunt active power filters can inject the required current to cancel out reactive power, improving power factor and voltage stability [75].

The theory helps identify and mitigate harmonic components in the system. Load Balancing: It can be used to equalize unbalanced load currents in three-phase systems. Power Quality Enhancement: The p-q theory provides tools for improving overall system performance, especially under distorted or unbalanced conditions.

Advantages of the p-q Theory is the effective for real-time control and analysis. Applicable to both sinusoidal and non-sinusoidal systems. Handles unbalanced loads and systems efficiently. Provides a unified approach to tackle various power quality issues. Limitations of the theory assumes an idealized, lossless system, which may not fully represent practical systems. Implementation requires precise real-time measurement and control, which can be technically demanding.

3.2 Synchronous Reference Frame

The SRF Theory involves transforming three-phase quantities (voltages or currents) from their natural stationary reference frame (aaa, bbb, ccc) into a rotating reference frame (ddd, qqq) that is synchronized with the system frequency. The transformation is typically done using the Park Transformation, which converts three-phase quantities into two orthogonal components (d-axis and q-axis).

The rotating reference frame aligns with the instantaneous voltage or current phasor in the system. The ddd-axis often represents the direct (active) component, while the qqq-axis represents the quadrature (reactive) component of the signal. By aligning the reference frame with the rotating phasor, time-varying quantities can be analyzed as DC-like quantities, simplifying their control. In the synchronous reference frame, sinusoidal signals in the original stationary frame are transformed into nearly constant (DC) values under steady-state conditions, making it easier to design controllers and analyze system performance [76].

The theory is extensively used in vector control (field-oriented control) of AC motors like induction motors and permanent magnet synchronous motors (PMSMs). It enables independent control of torque and flux, similar to DC motors. The SRF theory is used to detect and compensate for harmonics and reactive power in power systems. Harmonic currents are identified as oscillatory components in the ddd-qqq frame and can be filtered out.

Inverters for photovoltaic (PV) systems and wind turbines use SRF theory to synchronize output voltages with the grid. The SRF theory provides tools for analyzing and mitigating imbalances and distortions in power systems.

Advantages of the SRF theory are time-varying signals become DC-like in the d-q frame, enabling simpler control algorithms. Works well for both balanced and unbalanced systems. Improves system dynamics and enables precise control of power converters and machines. Limitations of SRF Theory are Implementation requires accurate transformations, including real-time computation of system angles (e.g., using phase-locked loops, or PLLs) [77]. Any error in synchronization (PLL errors) can degrade performance.

3.3 Hysteresis or PWM Control

The pulse width modulation technique is generally used for the conversion of DC to AC waveforms. A full bridge inverter with six IGBTs can be used to convert DC to three phase AC. Each phase has to be phase shifted to each other by 120^0 and has to be in synchronization with the grid to which it is being connected. The pulses are to be given to the IGBTs are generated with a reference or fundamental waveform compared with a triangular waveform. The fundamental waveform has the frequency of the grid and the triangular or carrier waveform has higher frequency to create a modulation signal. The diagram of the fundamental and the carrier waveform are shown below in fig. 4. Six pulses are formed by applying NOT gates to the three pulses produced by the comparison of the fundamental and carrier waveforms. The generated pulses are fed to the VSI (Voltage source Inverter) with G1 G2 G3 G4 G5 and G6 switches. A simple construction of VSI is shown in fig. 2

The rating of IGBT is taken as

Internal resistance Ron = 0.001 ohms

Snubber resistance Rs = 100 kohms

Snubber capacitance Cs = 1F

Due to the impedance load the load current gets ceased during sudden switch OFF of the IGBT switch and generate high voltage peaks in the output voltage. To avoid this an anti-parallel diode is attached to the switch (IGBT) so that the inductor current from the impedance load can pass through the diode.

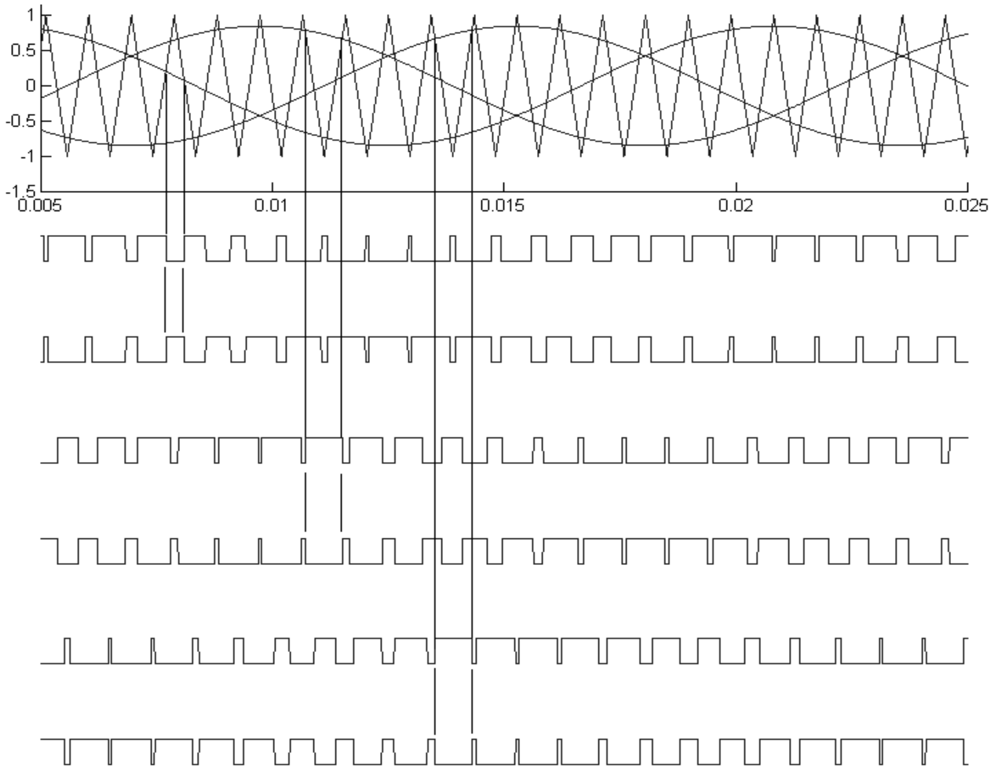

Figure 5: Generation of pulses with respect to reference fundamental waveforms

Compared to traditional PWM techniques the hysteresis loop controller is flexible and easy to control. The operation of the this control is simple and fast in response. The pulses in hysteresis control are generated by comparing the source current to the reference current generated by the unit vector templates [78]. The unit vector templates with PLL reference 'wt' are give as

Ua= Vm Sin(wt) (1)

Ub= Vm Sin(wt+2pi/3) (2)

Uc= Vm Sin (wt-2pi/3) (3)

The comparison output of the two currents (reference current & measured current) is given to relay which has a hysteresis band [79]. The upper limit and the lower limit of the hysteresis controller is manually set to a certain value which can be +h & -h. When the error value is more than the upper limit, HIGH signal is produced ie., '1' and when the error value goes below the lower limit, LOW signal is generated ie., '0' [80].

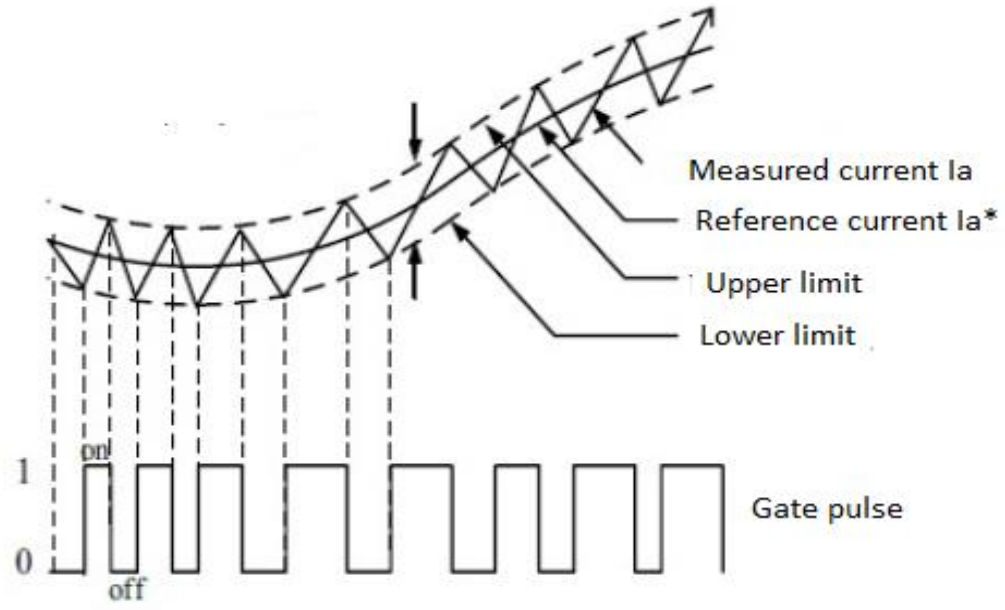

Figure 6: Hysteresis band

3.4 Mathematical Modeling

(a) Renewable Source Model

The PV output power:

$$P_{PV} = V_{PV} I_{PV} \tag{4}$$

MPPT (e.g., P&O or Incremental Conductance) is used to extract maximum power.

(b) UPQC Model

The UPQC consists of:

Series Active Filter → Voltage compensation

Shunt Active Filter → Current harmonic elimination and reactive power support
In dq-frame:

$$i_d = \frac{2}{3}(i_a \cos\theta + i_b \cos(\theta - 120°) + i_c \cos(\theta + 120°))$$
$$i_q = \frac{2}{3}(i_a \sin\theta + i_b \sin(\theta - 120°) + i_c \sin(\theta + 120°)) \quad (5\&6)$$

Reference currents are generated using:

Instantaneous p–q theory
or
Synchronous Reference Frame (SRF) control

3.5 Multi-Objective Optimization Formulation

The optimization aims to simultaneously minimize:

F_1 = THD
F_2 = Voltage Deviation
F_3 = Power Loss
F_4 = Reliability Index (SAIFI/SAIDI improvement)

Overall objective:

$$\text{Minimize } F = w_1F_1 + w_2F_2 + w_3F_3 + w_4F_4 \tag{7}$$

Subject to:

DC-link voltage constraint

Converter rating limits
Grid voltage limits
Current limits

4. RESULTS AND DISCUSSION

4.1 Harmonic Reduction

Table 1 Representation of harmonic spectrums

Case	THD (%))
Without UPQC	24.8%
Conventional UPQC	5.2%
Conventional UPQC	2.1%

THD reduced below IEEE 519 standard (5%).

4.2 Voltage Sag Compensation

A 30% voltage sag was introduced at 0.3 s.

Without UPQC → Voltage dropped to 0.7 pu

With proposed system → Maintained at 0.98 pu

Improvement ≈ **40% enhancement in voltage stability**

4.3 Reactive Power Compensation

Reactive power demand reduced from:

18 kVAR → 2 kVAR

Power factor improved from:

$$0.82 \rightarrow 0.99$$

4.4 Reliability Improvement

Due to RES integration:

Reduced feeder loading

Improved voltage profile

Reduced outage probability

Reliability indices improved:

SAIFI reduced by 18%

SAIDI reduced by 22%

4.5 Optimization Performance

Algorithm convergence achieved within 35 iterations

Fitness function minimized by 42%

Faster dynamic response compared to conventional tuning

5. CONCLUSION

The proposed Multi-Objective Optimized Renewable Energy Supported UPQC:
Reduces harmonics significantly
Improves voltage regulation
Enhances power factor
Improves system reliability

Reduces power losses
Hence, the system is suitable for modern smart grid applications.
The RES-UPQC represents a significant advancement in power quality management and renewable energy integration. By combining the functionalities of a traditional UPQC with the ability to manage power from renewable sources, it addresses multiple challenges in modern power systems, including power quality issues, grid stability, and the efficient utilization of renewable energy. The RES-UPQC effectively mitigates voltage sags, swells, and harmonics, ensuring a stable and reliable supply to sensitive loads. It also compensates for current-related issues like harmonics and imbalances. The system seamlessly integrates renewable energy sources (e.g., solar or wind) into the grid or directly to local loads. It optimizes renewable energy utilization, reducing dependence on conventional power generation. The RES-UPQC serves both as a power quality conditioner and a renewable energy interface, minimizing the need for additional infrastructure. It provides uninterrupted power supply to critical loads by combining renewable generation with power conditioning. By utilizing the renewable energy source to compensate for reactive power and harmonics, the RES-UPQC improves the overall efficiency of the system.

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