Renewable Energy Optimization: UPQC-PI for Superior Power Delivery and Grid Stability

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Abstract

This paper argues that supplemental features in non-traditional energy systems are in high demand, especially in LV distribution networks. This is because of the meteoric rise of loads based on power electronics and alternative energy sources. These loads cause the grid to experience harmonic currents. Weak grid systems experience distortion because of this at the PCC. Voltage fluctuations happen at PCC because of the use of non-conventional energy sources like solar, wind, etc. The rising cost of repairs is directly attributable to these voltage fluctuations. Hence The combination of non-conventional energy sources with PQ improvement systems like DSTATCOM, DVR, UPQC, etc. provides the best possible power quality and clean energy solution. In this work, we propose a power quality (PQ) theory-based controller for a UPQC that is integrated into a solar PV array. To further aid in the compensation of harmonic voltages by series active filters, this paper also suggests controllers based on the Synchronous Reference Frame (SRF). Power factor is increased, and Total Harmonic Distortion (THD) is decreased when SRF is used for UPQC control.

Keywords: Generation system, UPQC-PI technique, Power quality, Voltage regulation, Current regulation, Power factor correction, Harmonics mitigation, Grid integration, Renewable energy sources, Photovoltaic (PV) systems.

I. INTRODUCTION

The necessity for eco-friendly and enduring energy solutions has prompted the assimilation of renewable energy sources like photovoltaic (PV) systems and wind turbines into the existing power grid infrastructure. Despite the benefits, the fluctuating output of these renewables introduces significant power quality and grid stability concerns that must be addressed with sophisticated control measures.

A prominent solution is the Unified Power Quality Conditioner with Proportional-Integral (UPQC-PI) control strategy, which merges the benefits of series and shunt active power filters. This approach is instrumental in ameliorating the quality of power and fortifying grid stability for systems powered by renewable energy.

The role of the UPQC-PI technique is multifaceted, targeting the enhancement of renewable energy system efficiency and ensuring grid equilibrium. It effectively tackles a variety of power disturbances, including those related to voltage, current, power factor, and harmonic distortions.

Employing power electronic mechanisms such as inverters, the UPQC-PI system regulates the interchange of electricity from renewable sources to the grid. It addresses issues like voltage dips and spikes through the series filter, and curtails harmonic and reactive power disruptions via the shunt filter. The embedded control algorithms in the UPQC-PI system are calibrated for peak performance, especially when the grid faces perturbations.

This investigation centers on the elevation of power output and stabilization of the grid in renewable energy generation setups via the UPQC-PI methodology. The primary aims are:

1. To refine power quality aspects of the electricity produced, enhancing voltage stability, current integrity, and power factor.

2. To boost grid resilience, counteracting the voltage and harmonic inconsistencies, as well as the reactive power shifts inherent in renewable energy outputs.

3. To devise and implement sophisticated control algorithms for the UPQC-PI framework to secure its steadfast and dynamic functionality across diverse grid scenarios.

4. To validate the efficacy and efficiency of the proposed system through comprehensive simulation analyses, empirical lab investigations, and practical field applications.

This research will significantly bolster the integration of renewable energy into the power grid, fostering a more robust and sustainable energy generation framework. The improved power quality and grid stabilization offered by the UPQC-PI approach are pivotal in moving towards a future powered by cleaner, renewable energysources.

II. METHODOLOGY

SOLAR & WIND ENERGY SYSTEM

A hybrid renewable energy system harnesses both solar and wind power to create a more stable and efficient electricity supply. Solar panels use sunlight to produce electricity through the photovoltaic effect, while wind turbines convert wind's kinetic energy into electrical power. To be compatible with standard electrical systems, the direct current produced is converted to alternating current using power electronics like inverters. Excess energy can be stored in batteries, such as lithium-ion, for later use. These systems may be connected to the local grid, allowing for net metering and grid-supplied power during low production periods, or operate independently off-grid. This dual-source approach not only improves energy reliability but also reduces greenhouse gas emissions and fossil fuel dependency, supporting a sustainable energy future.
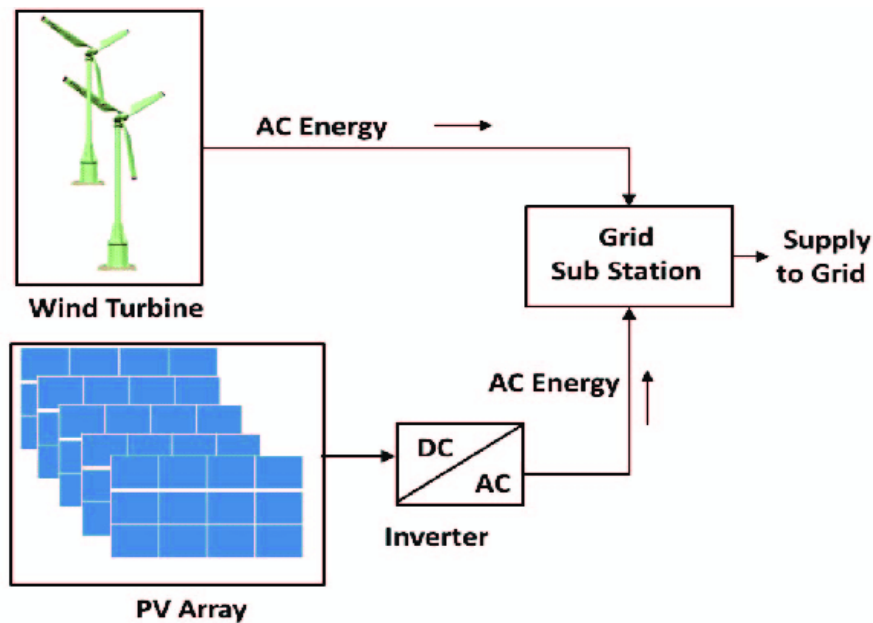

Figure 1: solar and wind energy system

GRID STABILIZATION

Grid stabilization refers to the process of maintaining the stability and reliability of an electrical grid. It involves managing and regulating various parameters of the grid, such as voltage, frequency, and power factor, within acceptable limits.

A stable grid is essential for the reliable operation of electrical power systems, as well as the efficient and safe delivery of electricity to consumers. Grid instability can lead to power outages, voltage fluctuations, frequency deviations, and other power quality issues that can disrupt operations, damage equipment, and affect the overall performance of the electrical system.

Here are some key aspects of grid stabilization:

- **Voltage Regulation:** Voltage regulation involves maintaining the grid voltage within specified limits. Fluctuations in voltage can lead to issues such as overvoltage or undervoltage, which can damage equipment and affect the performance of connected loads. Voltage regulation devices, such as voltage regulators and tap changers, are used to adjust and stabilize the grid voltage.

- **Frequency Regulation:** The frequency of an electrical grid represents the rate at which alternating current cycles occur per second. Grid frequency is typically maintained at a constant value, such as 50 or 60 Hz, depending on the region. Frequency regulation ensures that the generation and consumption of electrical power are balanced, preventing frequency deviations that can affect the operation of power-sensitive devices. Frequency control is achieved through the coordinated control of power generation and demand response.

- **Power Factor Correction:** Power factor is a measure of how efficiently electrical power is being utilized in a system. Power factor correction involves managing the reactive power component of the electrical load to achieve a power factor close to unity (1). Reactive power compensation devices, such as capacitors and synchronous condensers, are used to minimize reactive power and improve the power factor, reducing system losses and improving overall grid stability.

- **Grid Control and Monitoring:** Advanced control and monitoring systems are deployed to continuously monitor the grid conditions and ensure stability. These systems utilize real-time data from various sensors and measurement devices to detect and respond to grid disturbances promptly. Grid control mechanisms, such as load shedding, automatic generation control, and fault detection systems, are implemented to mitigate grid instability and restore stability.

- **Integration of Renewable Energy:** With the increasing penetration of renewable energy sources like solar and wind, grid stabilization becomes more challenging due to their intermittent and variable nature. Effective grid stabilization techniques, such as the use of energy storage systems, advanced power electronics devices, and intelligent control algorithms, are employed to accommodate the integration of renewable energy sources while maintaining grid stability and power quality.

Grid stabilization is a complex and dynamic process that requires careful planning, coordination, and control of various elements within an electrical grid. It ensures a reliable and efficient supply of electricity to meet the demands of consumers while minimizing the risks of power outages and system disruptions.

POWER QUALITY PROBLEMS

Power quality problems refer to various disturbances and issues that affect the quality of electrical power supplied to consumers. These problems can arise from various sources, including the power grid, electrical equipment, and environmental factors. Here are some common power quality problems:

- ❖ **Voltage Fluctuations:** Voltage fluctuations occur when the amplitude of the voltage deviates from the nominal value. These fluctuations can manifest as voltage sags (short-term voltage reduction), voltage swells (short-term voltage increase), or voltage flicker (rapid voltage changes). Voltage fluctuations can cause equipment malfunction, data loss, or flickering of lights.

- ❖ **Harmonic Distortion:** Harmonic distortion is the presence of unwanted harmonic frequencies in the power system. Harmonics result from non-linear loads such as computers, electronic devices, and variable speed drives. They can cause overheating in equipment, reduce power system efficiency, and disrupt communication systems.

- ❖ **Voltage Unbalance:** Voltage unbalance occurs when the voltages in a three-phase system are not equal. This can lead to unequal distribution of power among phases, motor overheating, increased losses, and reduced equipment lifespan.

- ❖ **Power Factor:** Power factor is a measure of how efficiently electrical power is being utilized. A low power factor occurs when reactive power is present due to inductive loads. This can result in increased energy costs, reduced system capacity, and voltage drop.

❖ **Transients:** Transients, also known as voltage spikes or surges, are brief and rapid changes in voltage. They can be caused by lightning strikes, switching operations, or equipment faults. Transients can damage sensitive electronics and result in equipment failure.

❖ **Frequency Variations:** Frequency variations occur when the power system deviates from the standard frequency (50 or 60 Hz). Frequency variations can cause clocks to run fast or slow, affect motor performance, and disrupt timing-sensitive equipment.

❖ **Voltage Dips and Interruptions:** Voltage dips are short-duration reductions in voltage, while voltage interruptions are complete losses of voltage. These events can disrupt equipment operation, lead to data loss, and affect sensitive processes.

PI CONTROLLER

A PI controller, also known as a proportional-integral controller, is a widely used control algorithm in various control systems, including power electronics, process control, and robotics. It is a feedback control mechanism that aims to regulate a system's output based on the difference between the desired setpoint and the actual measured value.

The formula for a PI controller can be expressed mathematically as follows:

$$u(t) = Kp * e(t) + Ki * \int e(t) \, dt \qquad\qquad (1)$$

Where:

➢ u(t) is the control output or the manipulated variable at time t.

➢ Kp is the proportional gain, which determines the proportional response of the controller to the error.

➢ Ki is the integral gain, which determines the integral response of the controller to the error.

➢ e(t) is the error signal at time t, calculated as the difference between the desired setpoint and the measured value.

The proportional term, $Kp * e(t)$, provides an immediate response to the present error, adjusting the control output in proportion to the error. The integral term, $Ki * \int e(t) \, dt$, accumulates the error over time and provides a corrective action to eliminate steady-state errors.

The integral term involves integrating the error signal with respect to time ($\int e(t) \, dt$). This integration can be performed using numerical integration techniques, such as the trapezoidal rule or Euler's method, in discrete-time systems. In continuous-time systems, the integration is represented by the integral sign.
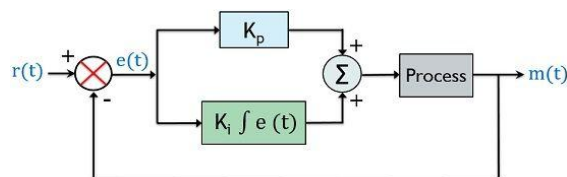

Figure 2: Block diagram PI controller

UPQC

UPQC stands for Unified Power Quality Conditioner. It is a power electronic device used to mitigate power quality issues in electrical distribution systems. The main purpose of UPQC is to regulate and improve the quality of electrical power supplied to sensitive loads, such as industrial equipment, computers, and other electronic devices.

The UPQC combines the functionalities of two power conditioning devices: the Active Power Filter (APF) and the Voltage Source Inverter (VSI). The APF is responsible for compensating for current-related power quality problems, such as harmonics and reactive power, while the VSI is used to regulate voltage-related power quality issues, such as voltage sags, swells, and interruptions.

By integrating these two functions into a single device, the UPQC can simultaneously regulate both the current and voltage at a specific point in the electrical system. It achieves this by injecting compensating currents and voltages into the system to counteract the unwanted disturbances and maintain the desired power quality levels.

The UPQC typically consists of power electronic converters, control circuits, and energy storage elements. It continuously monitors the electrical signals at its input and output terminals and generates appropriate compensating currents and voltages to mitigate power quality problems. The device can be installed at various points in the distribution system, such as at the grid interface or closer to the sensitive loads.
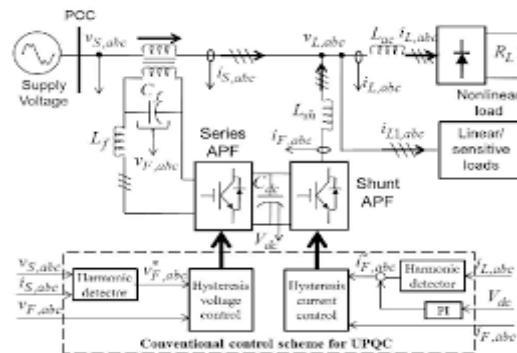

Figure 3: Block diagram UPQC

UPQC-PI TECHNIQUE

The UPQC-PI technique refers to the control strategy used in a Unified Power Quality Conditioner (UPQC) for power enhancement and grid stabilization in renewable energy-based generation systems.

Renewable energy sources, such as solar and wind, are known to have intermittent and variable power outputs. This variability can cause power quality issues and instability in the electrical grid. The UPQC-PI technique aims to address these challenges by combining the UPQC device with a proportional-integral (PI) controller.

The PI controller is a common control algorithm used in power electronics systems to regulate and stabilize various parameters. In the context of UPQC, the PI controller is used to regulate the compensating currents and voltages injected by the UPQC into the grid.

The UPQC-PI technique employs a feedback loop that continuously monitors the grid conditions and generates appropriate control signals for the UPQC. The PI controller compares the desired grid parameters (e.g., voltage, frequency, power factor) with the actual grid measurements and adjusts the control signals to minimize the deviations and maintain stable operation.

By using the UPQC-PI technique, the renewable energy-based generation system can achieve several objectives:

➤ **Power Enhancement:** The UPQC compensates for voltage sags, swells, and interruptions caused by fluctuations in renewable energy generation. It injects compensating voltages to regulate and improve the grid voltage profile, thereby enhancing the power quality and stability.

➤ **Harmonic Mitigation:** The UPQC-PI technique also addresses harmonics generated by the renewable energy generation system. The UPQC injects compensating currents to cancel out the harmonics, resulting in a cleaner power supply to the grid.

➤ **Grid Stabilization:** The PI controller in the UPQC-PI technique helps in grid stabilization by regulating the active and reactive power flow. It ensures that the renewable energy-based generation system operates in synchronization with the grid, maintaining voltage and frequency within acceptable limits.

Overall, the UPQC-PI technique combines the capabilities of the UPQC device, and the control strategy provided by the PI controller to enhance power quality, mitigate harmonics, and stabilize the grid in renewable energy-based generation systems. It enables the seamless integration of renewable energy sources into the electrical grid while maintaining a reliable and stable power supply.

ADVANTAGES

- **Improved Power Quality:** The UPQC-PI technique addresses power quality issues such as voltage fluctuations, harmonics, and reactive power problems associated with renewable energy sources. It injects compensating currents and voltages to regulate the grid voltage profile, reduce harmonics, and maintain power factor close to unity. This results in cleaner and more stable power supply, ensuring optimal performance of connected loads and reducing the risk of equipment damage.

- **Grid Stability:** The PI controller component of the UPQC-PI technique plays a crucial role in maintaining grid stability. It continuously monitors grid conditions and adjusts compensating signals to ensure stable voltage and frequency levels. By providing real-time control and stability enhancement, the UPQC-PI technique enables reliable integration of renewable energy sources into the grid.

- **Cost Savings:** By mitigating power quality issues and stabilizing the grid, the UPQC-PI technique helps reduce maintenance costs. Voltage fluctuations, harmonics, and reactive power problems can lead to increased equipment wear and tear, malfunctions, and downtime. Implementing the UPQC-PI technique helps minimize such issues, extending the lifespan of electrical equipment and reducing maintenance and replacement expenses.

- **Efficient Renewable Energy Integration:** Renewable energy sources, such as solar and wind, are intermittent and variable in nature. The UPQC-PI technique enables efficient integration of these sources into the grid by compensating for fluctuations and ensuring a smooth transition of power. This allows for optimal utilization of renewable energy resources and reduces dependence on conventional power generation, leading to a more sustainable and environmentally friendly energy system.

- **Flexibility and Scalability:** The UPQC-PI technique is a flexible and scalable solution that can be customized to different system configurations and renewable energy sources. It can be applied to both small-scale and large-scale renewable energy systems, making it suitable for various applications, including residential, commercial, and industrial sectors.

- Compliance with Grid Standards: Power utilities often have strict power quality requirements and grid standards that need to be met. The UPQC-PI technique enables compliance with these standards by actively regulating voltage, power factor, and harmonic distortion levels. This ensures smooth grid integration and reduces the risk of penalties or non-compliance issues.

III. RESULTS & DISCUSSION

The UPQC-PI technique combines the capabilities of the Unified Power Quality Conditioner (UPQC) and the PI controller to enhance power quality and stabilize the grid in renewable energy-based generation systems.
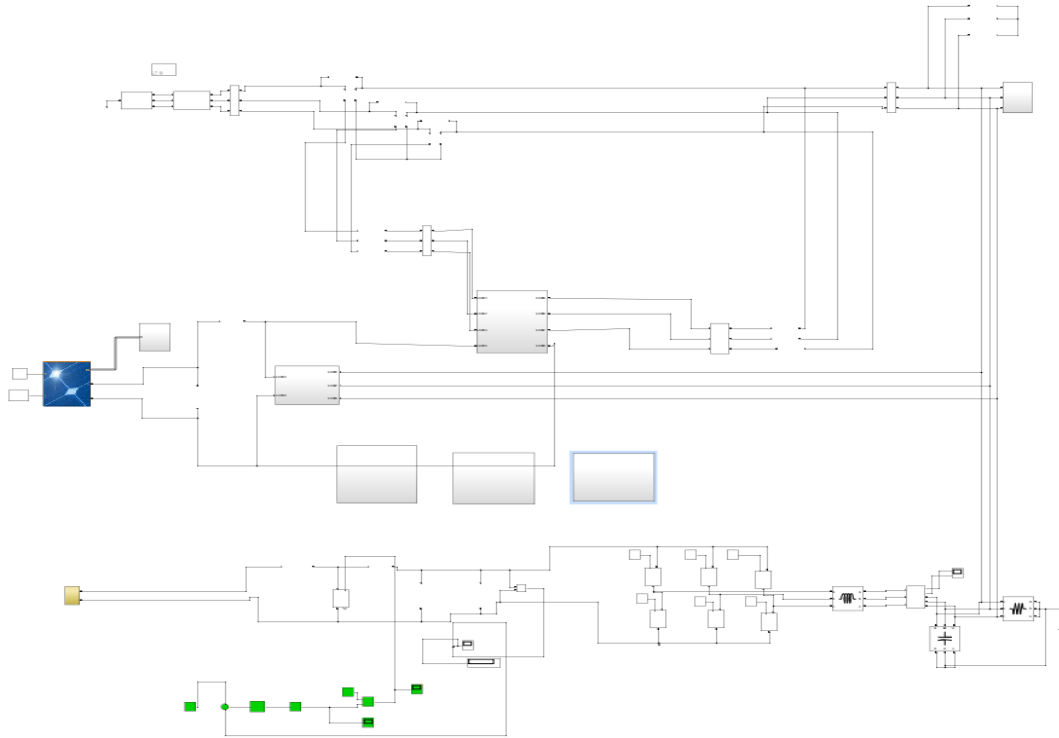
Proposed Simulink:

Figure 4: Proposed Simulink using UPQC-PI technique.

The proposed Simulink model allows for the analysis and evaluation of the power enhancement and grid stabilization capabilities of the UPQC-PI technique. Through simulations, it enables the assessment of various system parameters, control strategies, and performance indicators such as voltage regulation, harmonic compensation, and power factor improvement. By studying the model's response under different operating conditions, it becomes possible to optimize the UPQC-PI system configuration and control parameters for specific renewable energy-based generation systems.

It's important to note that the actual implementation and customization of the Simulink model would depend on the specific requirements, system configuration, and control algorithm chosen for the UPQC-PI technique. Detailed research papers, technical articles, or publications can provide specific guidance and examples to develop an accurate and comprehensive Simulink model for the intended study or application.
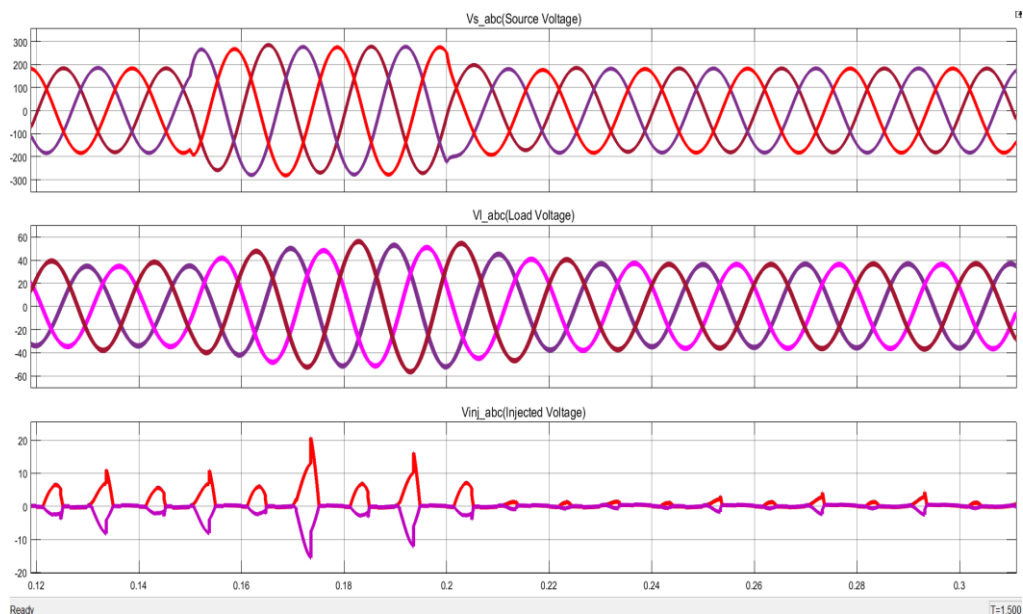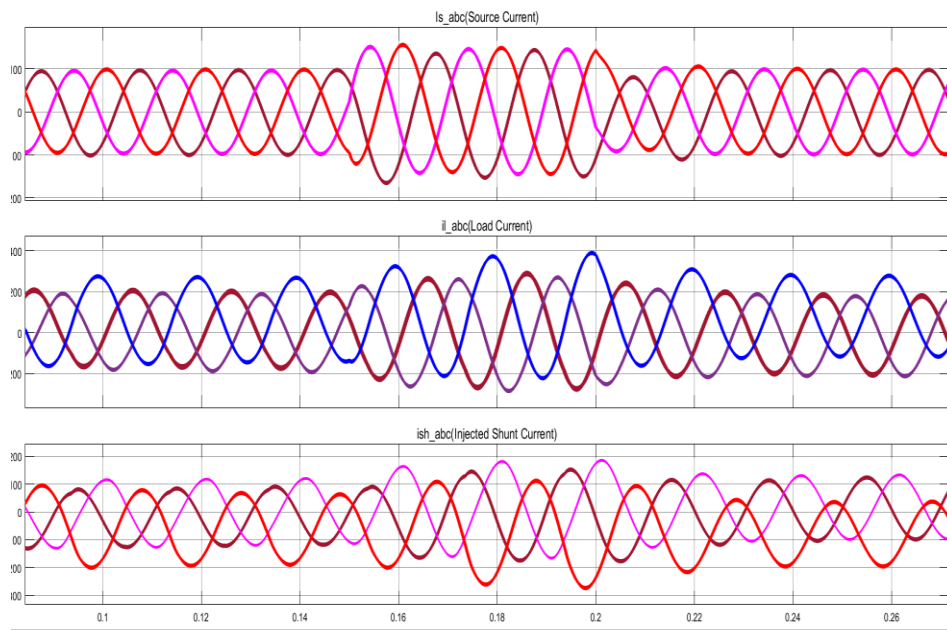
Output Response:

Figure 5: Output Response for Source, Load & Injected voltage

The output response of the UPQC-PI technique in power enhancement with grid stabilization of renewable energy-based generation systems can be analyzed by examining the behavior of the source voltage, load voltage, and injected voltage by the UPQC. Here is a description of the output response for each of these components:

➢ **Source Voltage:** The source voltage represents the voltage at the connection point between the renewable energy-based generation system and the electrical grid. The UPQC-PI technique aims to regulate and enhance the source voltage to ensure optimal power quality. By injecting compensating voltages and currents, the UPQC adjusts the source voltage to mitigate voltage fluctuations, sags, swells, and other disturbances caused by the renewable energy sources or grid conditions. The output response of the source voltage can be analyzed to assess the effectiveness of the UPQC-PI technique in maintaining a stable and reliable voltage supply to the grid.

➢ **Load Voltage:** The load voltage represents the voltage at the electrical load connected to the grid. The UPQC-PI technique works to ensure that the load voltage remains within acceptable limits and free from disturbances. By regulating the source voltage and compensating for reactive power, harmonics, and voltage variations, the UPQC helps maintain a stable load voltage. The output response of the load voltage can be evaluated to determine the impact of the UPQC-PI technique in improving power quality and minimizing voltage fluctuations at the load.

➢ **Injected Voltage by UPQC:** The UPQC injects compensating voltages and currents into the grid to mitigate power quality issues. The injected voltage by the UPQC represents the compensating voltages added to the grid to regulate voltage profile, compensate for reactive power, and reduce harmonics. The output response of the injected voltage can be analyzed to assess the effectiveness of the UPQC in mitigating power quality problems and stabilizing the grid.

Figure 6: Output Response for Source, Load & Injected Current

The output response of the UPQC-PI technique in power enhancement with grid stabilization of renewable energy-based generation systems can also be analyzed by examining the behavior of the source current, load current, and injected current by the UPQC. Here is a description of the output response for each of these components:

✓ **Source Current:** The source current represents the current flowing from the renewable energy-based generation system to the electrical grid. The UPQC-PI technique aims to regulate and enhance the source current to ensure optimal power quality. By injecting compensating currents, the UPQC adjusts the source

current to mitigate current harmonics, balance the load currents, and minimize the reactive power flow. The output response of the source current can be analyzed to assess the effectiveness of the UPQC-PI technique in maintaining a balanced and high-quality current supply to the grid.

- ✓ **Load Current:** The load current represents the current consumed by the electrical load connected to the grid. The UPQC-PI technique works to ensure that the load current remains within acceptable limits and free from distortions. By regulating the source current and compensating for current harmonics and imbalances, the UPQC helps maintain a stable load current. The output response of the load current can be evaluated to determine the impact of the UPQC-PI technique in improving power quality and minimizing current harmonics at the load.

- ✓ **Injected Current by UPQC:** The UPQC injects compensating currents into the grid to mitigate power quality issues. The injected current by the UPQC represents the compensating currents added to the grid to regulate the load currents, reduce harmonics, and balance the power flow. The output response of the injected current can be analyzed to assess the effectiveness of the UPQC in mitigating power quality problems and stabilizing the grid.

IV. CONCLUSION

The UPQC-PI method is highly beneficial for augmenting power quality and grid stability in systems powered by renewable energy. It utilizes the Unified Power Quality Conditioner (UPQC) combined with a PI (Proportional-Integral) controller to not only refine power quality but also to stabilize the grid and seamlessly incorporate renewable sources. By deploying UPQC, voltage and current harmonics can be regulated—series converters tackle voltage sags, while shunt converters address current harmonics. This integration is a dependable and effective strategy for enhancing power quality, particularly in renewable energy systems like wind and solar, where power generation can be unpredictable.

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