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Unified Power Quality Conditioner (UPQC) for Harmonic Suppression and Voltage Stabilization: A Control Strategy Approach Validated through MATLAB Simulation

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Abstract: *The rapid evolution of communication technologies, digital electronics, and control systems has amplified the reliance on sensitive loads that demand a stable sinusoidal voltage supply for optimal functionality. Consequently, adherence to power quality standards necessitates the implementation of advanced compensation strategies. This research addresses prevalent power quality challenges—including voltage fluctuations, harmonic distortions, transient disturbances, and reactive power imbalances—by proposing a Unified Power Quality Conditioner (UPQC). The UPQC integrates series and shunt active power filters (APFs) in a back-to-back configuration, interconnected via a shared DC-link capacitor, to simultaneously mitigate grid-side and load-side disturbances. While the series APF compensates for voltage-related anomalies, the shunt APF alleviates current-related distortions, ensuring compliance with regulatory frameworks. The growing complexity of power demand patterns, driven by non-linear and dynamic loads, underscores the urgency for such hybrid solutions. This study evaluates the proposed UPQC topology through MATLAB Simulink-based simulations, demonstrating its efficacy in stabilizing voltage profiles, suppressing harmonics, and balancing reactive power under varying load conditions. The results validate the UPQC's ability to enhance grid reliability, offering a robust solution for modern power systems grappling with escalating quality and stability demands.*

Keywords: Power Quality, UPQC, Power Distribution system etc

I. INTRODUCTION

In contemporary power systems, the demand extends beyond mere continuity of supply to encompass stringent quality standards. Modern electrical networks face escalating challenges in maintaining sinusoidal voltage waveforms and stable frequencies, primarily due to the proliferation of non-linear loads, power electronic devices, and dynamic industrial applications[5]. These disturbances—manifested as voltage fluctuations, harmonic distortions, transient surges, and reactive power imbalances—compromise the performance of protection systems, control equipment, and metering infrastructure, necessitating robust solutions to uphold regulatory power quality benchmarks.

To address these challenges, advanced compensation technologies such as Custom Power Devices (CPDs) and Flexible AC Transmission Systems (FACTS) have gained prominence[6]. Devices like Distribution Static Synchronous Compensators (DSTATCOMs), Dynamic Voltage Restorers (DVRs), and Active Power Filters (APFs) are deployed to mitigate voltage and current distortions. APFs, categorized into series and shunt configurations, correct supply-side voltage irregularities and load-side current distortions, respectively. However, the growing complexity of modern grids, driven by sensitive loads and renewable integrations, demands integrated solutions capable of simultaneous voltage and current compensation.

The Unified Power Quality Conditioner (UPQC) emerges as a holistic approach, combining a shunt APF and a series APF through a shared DC-link capacitor[7],[8]. The shunt APF, connected in parallel with the load, suppresses harmonic currents, compensates reactive power, and regulates the DC-link voltage. Conversely, the series APF, interfaced via a coupling transformer, ensures sinusoidal load voltage by neutralizing grid-side voltage disturbances.

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This dual functionality enables the UPQC to address both source voltage anomalies and load current distortions concurrently, offering comprehensive power quality enhancement.

This study explores the UPQC's efficacy in resolving multifactorial power quality issues, emphasizing its role in harmonizing grid performance with the precision required by modern sensitive equipment. By integrating theoretical analysis with simulation-based validation [9], the research underscores the UPQC's potential [10] as a critical enabler of reliable, high-quality power delivery in evolving electrical networks.

II. DISTRIBUTION SYSTEM

The distribution substation acts as the critical interface connecting the distribution system to the upstream power delivery network. At this substation, a step-down transformer (HV/MV) lowers the sub-transmission voltage to a level suitable for primary distribution lines. To ensure operational safety[11] and reliability, the substation is equipped with protective devices, switching mechanisms, and monitoring systems.

From the substation, primary distribution lines (feeders) extend outward across the service area. These feeders branch into smaller lateral lines, which eventually connect to step-down transformers (MV/LV)[12]. These transformers perform the final voltage reduction, adjusting it to levels safe for consumer use (e.g., 400 V or 230 V).

The secondary distribution lines, operating at low voltage, then deliver power directly to end users' connection points. While most secondary lines are single-phase, three-phase circuits may also be utilized to meet higher power demands**.**

III. POWER QUALITY AND ITS EFFECT ON DISTRIBUTION SYSTEM

Definition and Scope

As per IEEE standards, power quality[13] refers to the methods of grounding and delivering electrical power to sensitive equipment to ensure reliable and consistent performance[11].It is defined by the combined quality of voltage (managed by the network operator at the connection point) and current (determined by the consumer's load characteristics).

Standards and Measurement Guidelines

The International Electrotechnical Commission (IEC), in partnership with Technical Committee 88 (TC-88), develops standardized methodologies [14] for assessing power quality in distribution systems. These guidelines detail procedures for evaluating critical parameters such as waveform stability, voltage consistency, and harmonic distortion. [15]

Characteristics of Ideal Power Quality

- Continuous sinusoidal voltage with stable amplitude and frequency.
- Compliance with national and international standards for voltage specifications.
- Minimal interruptions, quantified through metrics like voltage stability, frequency accuracy, and supply continuity.

Voltage Disturbances and Their Categories

Voltage deviations are classified into four primary types under most regulatory frameworks:

1. Voltage variations: Temporary sags, swells, or imbalances.
2. Flicker: Rapid, perceptible fluctuations in voltage levels.
3. Transients: Short-duration, high-magnitude voltage spikes.
4. Harmonic distortion: Waveform irregularities caused by non-linear loads [(e.g., industrial machinery)[16].

IV. UNIFIED POWER QUALITY CONDITIONER (UPQC)

Overview of UPQC

The **Unified Power Quality Conditioner (UPQC)** is an advanced solution designed to address both *current-related* and *voltage-related* power quality (PQ) issues in electrical systems. It combines two critical components:

a. Shunt Active Power Filter (APF):[17]
   - Mitigates **current disturbances** such as load imbalance, reactive power demand, and harmonic distortions.

b. Series Active Power Filter (APF):[17]
   - Corrects **voltage disturbances** like sags, swells, transients, and harmonics.

These components are interconnected via a **shared DC link capacitor**, enabling synchronized operation to stabilize both current and voltage waveforms.

Key Features and Applications

- **Structural Similarity to UPFC**: While the UPQC shares design similarities with the **Unified Power Flow Controller (UPFC)**, its primary focus is on PQ enhancement rather than power flow control[21].
- **Disturbance Elimination**: Actively suppresses grid disturbances to ensure stable power delivery, protecting sensitive loads.
- **Localized Power Quality Improvement**: Installed at strategic points in distribution networks to enhance reliability at the point of use[20].

Factors Influencing Power Quality Events

The severity of PQ issues depends on:

- **Event Characteristics**: Nature (e.g., sag, harmonic), magnitude, and duration.
- **Frequency of Occurrence**: How often disturbances occur.
- **Component Sensitivity**: Vulnerability of equipment to PQ deviations.
- **Equipment Location**: Position within the customer's facility.
- **Component Age**: Older equipment may be less resilient.

Consequences of Power Loss

Power interruptions lead to:

- **Operational Disruptions**: Downtime for consumers, especially critical in industries like manufacturing.
- **Financial Losses**:
  - For **consumers**: Costs from halted production and unsupplied energy.
  - For **utilities**: Penalties and reputational damage.
- **Industrial Impact**: The cost of unscheduled outages often far exceeds the expense of supplied energy.

Role of UPQC in Mitigation

By addressing PQ issues proactively, the UPQC:

- Reduces downtime and associated financial losses.
- Enhances equipment lifespan by minimizing stress from disturbances.
- Ensures compliance with power quality standards, improving grid reliability.

4.1 UPQC Configuration: Core Components

The **Unified Power Quality Conditioner (UPQC)** integrates several critical components to address power quality issues. Below is a breakdown of its primary elements:

a.. Shunt Inverter

- **Function**: Connected in *parallel* with the load.
- **Role**: Compensates for **current-related disturbances** such as harmonic currents, reactive power imbalance, and load unbalance.
- **Key Action**: Injects corrective currents to maintain sinusoidal and balanced supply currents.

b. Series Inverter

- **Function**: Connected in *series* with the supply line.
- **Role**: Mitigates **voltage-related disturbances** like sags, swells, flicker, and voltage harmonics.
- **Key Action**: Injects compensating voltages to stabilize the load-side voltage waveform.

c. LC Filter

- **Purpose**: Smooths the output of the inverters by filtering high-frequency switching noise (e.g., from PWM operations).
- **Design**: Combines inductors (L) and capacitors (C) to attenuate unwanted harmonics.

d. Transformer

- **Role in Series Path**: Steps up/down the voltage injected by the series inverter to match grid requirements.
- **Isolation**: Provides galvanic isolation between the UPQC and the grid, enhancing safety.

e. Coupling Devices

- **Examples**: Coupling transformers or inductors.
- **Function**: Facilitate seamless integration of the series and shunt inverters into the power network.

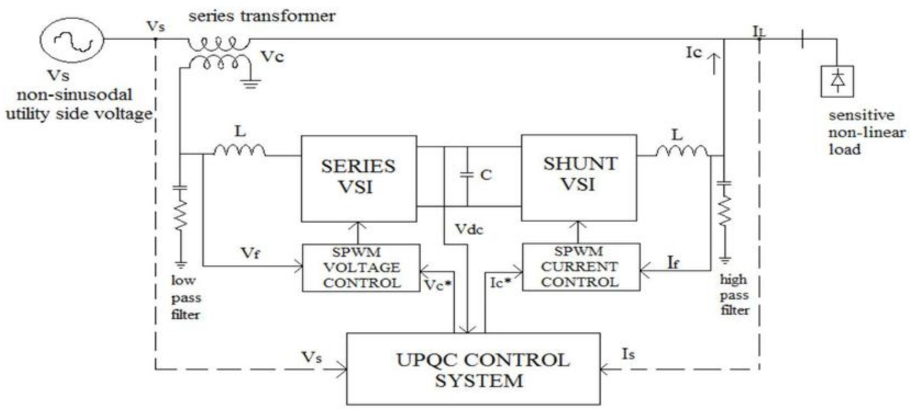

Figure1. Basic Block diagram of UPQC

4.2. UPQC Controlling Technique

Control Techniques for UPQC in Harmonic Mitigation

The **Unified Power Quality Conditioner (UPQC)** employs advanced control strategies to suppress voltage and current harmonics. Two widely used methodologies are outlined below:

1. Unit Vector Template Generation

- **Principle**: Generates reference signals using unit vectors derived from the grid voltage to synchronize compensation.
- **Function**:
  - Creates a sinusoidal template aligned with the grid's phase angle.
  - Ensures accurate injection of compensating voltages/currents to neutralize harmonics.
- **Application**: Effective for balancing loads and mitigating voltage sags/swells.

2. Synchronous Reference Frame (SRF) and P-Q Theory

- **SRF Method**:
  - Transforms grid currents into a rotating reference frame (d-q axis) to isolate harmonic components.
  - Enables precise detection of active and reactive power distortions.
- **P-Q Theory**:[20]
  - Calculates instantaneous active (P) and reactive (Q) power to derive compensation signals.
  - Targets harmonic elimination and power factor correction.
- **Advantage**: Adaptable to dynamic grid conditions, ensuring robust harmonic suppression.

Impact of Voltage Sags on Households

- **Disruption**: Voltage sags (temporary drops in voltage magnitude) can interrupt daily activities by causing appliance malfunctions.

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- **Measurement**:
  - **Magnitude**: Severity of voltage drop (e.g., 20% below nominal).
  - **Duration**: Typically lasts from milliseconds to a few seconds.
- **Device Sensitivity**:
  - Equipment vulnerability is defined by **voltage tolerance curves**, which specify thresholds for safe operation.
  - Example: Computers may shut down at 70% nominal voltage, while motors tolerate deeper sags.

Role of UPQC in Mitigation

- **Voltage Stabilization**: Compensates sags/swells in real-time, maintaining stable voltage at load terminals.
- **Harmonic Filtering**: Reduces waveform distortion caused by non-linear loads (e.g., inverters, LEDs).
- **Enhanced Reliability**: Minimizes operational disruptions and protects sensitive household devices.

V. MATLAB MODEL AND RESULT

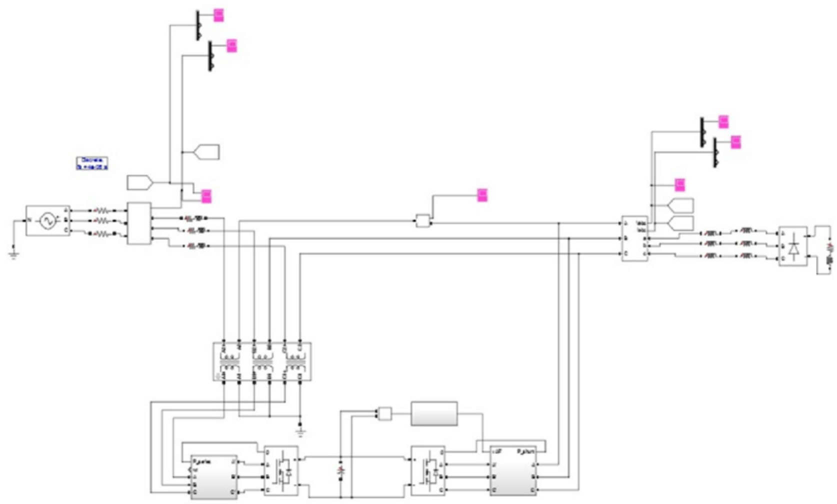

Figure 2: Matlab Simulink Model of UPQC

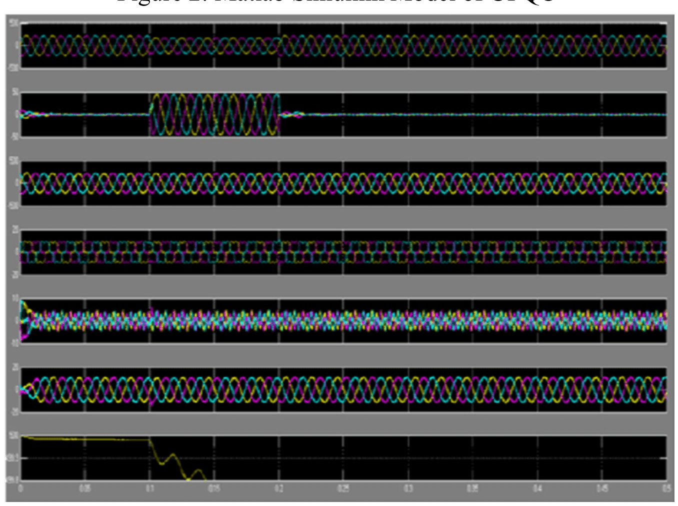

Figure 3: Simulation Results of UPQC for voltage swell condition a) Source voltage b) Series injected voltage c) Load voltage d) Load current e) Injected current f) Source current g) DC Capacitor voltage

VI. CONCLUSION

A simplified control approach for the Unified Power Quality Conditioner (UPQC) has been presented, utilizing unit vector template generation and a synchronous reference frame (SRF) based P-Q control technique. Both strategies offer efficient solutions for enhancing power quality by addressing voltage and current-related issues and effectively mitigating harmonic distortions. A Simulink-based simulation model was developed to validate the performance. The simulation outcomes demonstrate that the proposed SRF control method can effectively compensate for current harmonics introduced by non-linear loads.

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