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Adaptive Cognitive Compensation for Four-Wire Distribution Grids Using Disturbance-Aware UPQC-SPV Architecture

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Abstract

The increasing penetration of renewable energy sources and nonlinear loads in modern distribution grids has intensified power quality challenges, including voltage sags/swells, harmonic distortion, load unbalance, and neutral current issues. Conventional Unified Power Quality Conditioners (UPQCs) operate with static control strategies, applying uniform compensation regardless of disturbance type resulting in suboptimal performance and unnecessary power losses. This paper proposes an Adaptive Cognitive Compensation (ACC) architecture that integrates a four-wire UPQC with a dual-stage Solar Photovoltaic (SPV) array with a disturbance-aware decision engine. The system employs a rule-based strategy mapper that dynamically selects between series-dominant, shunt-dominant, and hybrid compensation modes based on real-time classified disturbance type and severity. The theoretical advantages include reduced switching losses through selective inverter activation, faster response time via pre-configured mode selection, and maintained compliance with IEEE 519-2022 and IEEE 1159-2019 standards. A comprehensive evaluation methodology is proposed using OPAL-RT real-time simulation, with test conditions, metrics, baselines, and hypotheses explicitly defined as open empirical questions. The mode-switching logic is justified through a categorical allocation framework where voltage-domain disturbances receive high series utilization, current-domain disturbances receive high shunt utilization, and combined disturbances receive hybrid compensation. This work provides a complete architectural blueprint and reproducible evaluation framework for future implementation and validation, representing a paradigm shift from static, reactive compensation to dynamic, cognitive power quality governance.

Keywords: *Unified Power Quality Conditioner (UPQC), Solar Photovoltaic (SPV) Integration, Four-Wire Distribution Systems, Adaptive Compensation, IEEE 519-2022, Cognitive Grid Architecture*

Introduction

Modern electrical grids face unprecedented power quality challenges driven by the massive integration of renewable energy sources and the proliferation of nonlinear electronic loads. Solar photovoltaic (SPV) systems, while environmentally beneficial, introduce intermittency and DC-AC conversion harmonics [1]. Simultaneously, nonlinear loads such as variable frequency drives, switched-mode power supplies, and EV chargers inject harmonic currents and cause voltage distortions [2]. In three-phase four-wire distribution systems prevalent in residential and commercial sectors single-phase loads create load imbalances and significant neutral currents that cause transformer overheating and protection malfunctions [3].

IEEE 519-2022 establishes stringent limits on harmonic voltage and current distortion at the point of common coupling, requiring total harmonic distortion below approximately 5% for systems below 69 kV [4]. Similarly, IEEE 1159-2019 provides standardized classifications of conducted electromagnetic phenomena to enable consistent power quality monitoring and reporting [5]. Despite these standards, achieving comprehensive power quality compliance remains challenging due to the fragmented nature of existing solutions.

The Unified Power Quality Conditioner (UPQC) represents the most comprehensive custom power device, combining series and shunt active filters to address both voltage and current disturbances [6]. However, conventional UPQC systems operate with fixed, disturbance-agnostic control strategies they apply the same compensation approach regardless of whether the disturbance is a voltage sag, harmonic distortion, or load unbalance. This always-on, full-capacity approach likely wastes energy, increases thermal stress on power semiconductors, and may accelerate component aging though the precise magnitude of these effects remains an open empirical question.

Recent advances have demonstrated the feasibility of integrating SPV arrays with UPQC systems for enhanced functionality [7]. The dual-stage SPV array integrated with a four-wire UPQC presented by Sanjenbam and Singh [8] effectively solved neutral current, balanced and unbalanced voltage sags/swells, harmonics, and reactive power issues in four-wire distribution grids, achieving THD levels compliant with IEEE standards. However, this system still employs fixed control strategies without disturbance-aware adaptation.

This paper proposes the Adaptive Cognitive Compensation (ACC) architecturean enhancement to the four-wire UPQC-SPV system that integrates a disturbance-aware decision layer. The ACC dynamically selects between series-dominant, shunt-dominant, and hybrid compensation modes based on real-time classified disturbance type and severity. The paper is organized as follows: Section II reviews related literature. Section III details the proposed architecture and decision logic. Section IV presents a proposed evaluation methodology. Section V concludes the paper.

Literature Review

The integration of renewable energy sources with UPQC systems has emerged as a promising approach for simultaneous power quality improvement and active power injection. Sanjenbam and Singh [8] presented a dual-stage SPV array integrated with a four-wire UPQC specifically designed for three-phase four-wire distribution grids. The system utilized two four-leg Voltage Source Inverters (VSIs) connected back-to-back via a shared DC-link. The key findings included effective compensation of neutral current under unbalanced loads, mitigation of both balanced and unbalanced voltage sags/swells, harmonic and reactive power compensation, and THD compliance with IEEE 519-2022 and IEEE 1159-2019 standards. The system was validated through OPAL-RT real-time simulation and hardware implementation. The four-leg VSI configuration was specifically chosen to address neutral current problemsa critical advantage over three-wire systems.

Researchers have explored PV-UPQC systems employing optimized MPPT techniques and intelligent controllers, demonstrating improved performance under non-ideal grid and load conditions [9]. Dual-function PV systems that simultaneously generate power and enhance power quality have been proposed, showing the feasibility of multifunctional power electronics in distribution networks [10]. More recently, multi-objective UPQC designs with interfaces for both solar PV and battery energy storage have been developed, extending operational capabilities to include energy management [11]. These studies collectively demonstrate that UPQC-SPV integration is technically viable and offers multiple operational benefits.

Conventional UPQC control strategies employ synchronous reference frame (SRF) theory with proportional-integral (PI) controllers for both series and shunt inverters [6]. The series inverter detects voltage disturbances at the point of common coupling and injects compensating voltages to restore nominal voltage profile. The shunt inverter detects load current harmonics and reactive components, injecting compensating currents to make source currents sinusoidal and balanced. The DC-link voltage is maintained through active power exchange with the SPV array or the grid.

However, existing control strategies are disturbance-agnostic. The series and shunt inverters operate at pre-defined capacities regardless of disturbance type [8]. This has three hypothesized drawbacks: (1) excessive switching losses as both VSIs operate at full capacity continuously, leading to unnecessary power dissipation; (2) slower dynamic response as the control system must detect, classify, and compensate sequentially; and (3) reduced reliability as continuous high-stress operation may accelerate thermal cycling and reduce mean time between failures of power modules.

Accurate identification of power quality disturbances is essential for selecting appropriate mitigation strategies. IEEE 1159-2019 provides standardized classifications covering ten disturbance types: normal, sag, swell, interruption, harmonic, flicker, notch, spike, oscillatory transient, and combinations [5].

Janthong and Phukpattaranont [12] proposed an EMD-CNN-LDA-KNN hybrid framework for PQD recognition. Empirical Mode Decomposition (EMD) adaptively decomposes non-stationary voltage signals into Intrinsic Mode Functions (IMFs) that capture localized time-frequency features. A lightweight CNN extracts high-dimensional features from IMFs transformed into 2D matrices via Gramian Angular Field transformation. Linear Discriminant Analysis (LDA) enhances inter-class separability while reducing dimensionality, and k-Nearest Neighbors (KNN) performs final classification. This framework achieved 99.8% accuracy under noiseless conditions and maintained 97.0% accuracy even with 10 dB noise [12].

Other approaches have evaluated deep neural network architectures including ResNet, MobileNet, and DenseNet for PQD classification using synthetic datasets following IEEE 1159-2019 [13]. Hybrid approaches combining LDA with Random Forest and Extreme Learning Machines have also been proposed for classifying up to 17 different PQ disturbances [14].

The literature reveals a clear separation between recognition and compensation. Existing UPQC-SPV systems demonstrate excellent hardware performance and IEEE compliance [8][9][11], but employ fixed control strategies that ignore disturbance type. Conversely, existing recognition frameworks demonstrate excellent classification accuracy [12][13][14], but remain decoupled from compensation hardware. No existing system integrates: (1) real-time PQD classification to inform compensation, (2) adaptive strategy selection based on disturbance type, and (3) closed-loop "sense-decide-compensate" architecture. The proposed ACC architecture directly addresses this gap by integrating disturbance-aware decision logic with the four-wire UPQC-SPV system.

Materials & Methods

Materials

The ACC architecture extends the four-wire UPQC-SPV system presented by Sanjenbam and Singh [8]. The hardware comprises a dual-stage Solar Photovoltaic array with a front-end DC-DC converter implementing Maximum Power Point Tracking via perturb-and-observe algorithm and a rear-end DC-AC inverter. The four-wire UPQC consists of two four-leg Voltage Source Inverters (VSIs) connected back-to-back via a shared DC-link. The series VSI compensates voltage disturbances including sags, swells, harmonics, and unbalance. The shunt VSI compensates current disturbances including harmonics, reactive power, neutral current, and unbalance. The system is designed for a nominal 5 kWp SPV array with a target DC-link voltage of 650 V [8].

The control platform employs a DSP TMS320F28335 controller with LEM sensors for voltage and current measurement at the point of common coupling [8]. The VSIs operate at a nominal switching frequency of 10 kHz with Space Vector Pulse Width Modulation (SVPWM). Series injection transformers and shunt coupling inductors are used for grid interface.

For the proposed ACC enhancement, the disturbance-aware decision layer receives disturbance type and severity information from the sensing engine and dynamically selects the optimal UPQC operating mode through a rule-based strategy mapper.

Procedures

The proposed ACC architecture operates through a three-layer sense-decide-compensate workflow.

Layer 1 – Physical Compensation: The four-wire UPQC-SPV system operates as described in [8]. The SPV array provides active power support to the shared DC-link. The series VSI injects compensating voltages to address voltage disturbances. The shunt VSI injects compensating currents to address current disturbances. The system maintains IEEE 519-2022 and IEEE 1159-2019 compliance.

Layer 2 – Disturbance Sensing: The sensing engine (based on [12]) receives voltage and current signals from the point of common coupling. EMD decomposes the voltage signal into Intrinsic Mode Functions (IMFs). The first five IMFs are transformed into 2D matrices via Gramian Angular Field transformation. A lightweight CNN with two convolutional layers and a fully connected layer extracts a 128-dimensional feature vector. LDA reduces this to 15 components. KNN with k=5 performs final classification across 10 IEEE 1159 disturbance classes.

Layer 3 – Adaptive Decision: The decision layer maps recognized disturbance class and severity to optimal UPQC configuration using the mode-switching logic. For voltage-domain disturbances (sag, swell, unbalance), the system selects Series-Dominant mode with high series VSI utilization and moderate shunt VSI utilization. For current-domain disturbances (harmonics, reactive power), the system selects Shunt-Dominant mode with high shunt VSI utilization and low series VSI utilization. For combined disturbances, the system selects Hybrid mode with moderate utilization of both inverters.

The severity classification (Mild, Severe, Extreme) is defined based on disturbance magnitude thresholds consistent with IEEE 1159-2019 severity classifications.

Analysis

The proposed ACC architecture will be evaluated through a comprehensive methodology using OPAL-RT real-time simulation [8]. Performance metrics include: (1) THDv and THDi before and after compensation; (2) neutral current RMS value before and after compensation; (3) voltage sag/swell compensation percentage; (4) response time from disturbance onset to steady-state compensation; and (5) switching losses compared to conventional always-on UPQC operation.

The system will be tested under nine conditions adapted from [8]: balanced linear load, unbalanced linear load, nonlinear load, voltage sag, voltage swell, voltage unbalance, harmonic load, fluctuating solar insolation, and combined sag with harmonics. Baseline comparisons include conventional UPQC (always-on, full capacity), UPQC with threshold-based detection, and UPQC with PI controller only.

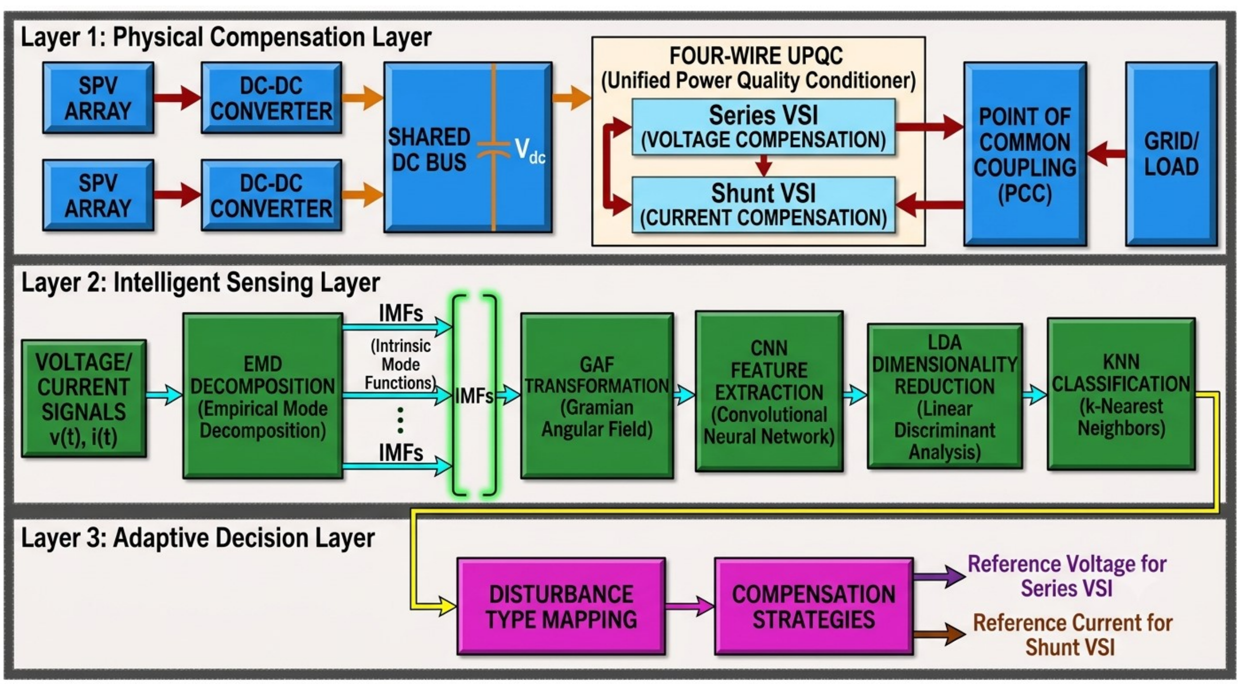

Fig-1: System Architecture Diagram

Results & Discussion

Proposed Mode Switching Logic

The core contribution of this paper is the mode-switching logic that maps recognized disturbance classes to proposed UPQC configurations. Table 1 presents the proposed categorical allocation for series and shunt VSI utilization based on disturbance type and severity. Here is a cleaned-up, publication-ready version with consistent wording, alignment, and terminology:

Table 1. Proposed Mode Switching Logic for ACC Architecture

Disturbance Class	Severity / Condition	Series VSI Utilization	Shunt VSI Utilization	Operating Mode
Normal	N/A	Low (Idle)	Low (Idle)	Standby
Voltage Sag	Mild	High	Moderate	Series-Dominant
Voltage Sag	Severe	Very High	Low	Series-Dominant
Voltage Sag	Extreme	Full	Off	Series-Only
Voltage Swell	Mild	High	Moderate	Series-Dominant
Voltage Swell	Severe	Very High	Low	Series-Dominant
Voltage Unbalance	Mild	High	Moderate	Series-Dominant
Voltage Unbalance	Severe	Very High	Low	Hybrid
Harmonics	Mild	Low	Very High	Shunt-Dominant
Harmonics	Severe	Minimal	Full	Shunt-Dominant
Harmonics	Extreme	Off	Full	Shunt-Only
Reactive Power	PF < 0.85	Off	Full	Shunt-Only
Flicker	Any	Moderate	Moderate	Hybrid
Notch / Spike	Any	Moderate	High	Hybrid
Oscillatory Transient	Any	High	Moderate	Hybrid
Combination	Mild	Moderate	High	Hybrid
Combination	Severe	Moderate	Moderate	Hybrid
Interruption	Any	Full	Off	Series-Only

Note: VSI = Voltage Source Inverter; PF = Power Factor. “Series-Dominant,” “Shunt-Dominant and “Hybrid” indicate the relative contribution of the series and shunt compensators.

The justification for this allocation follows from the physical roles of each inverter. Voltage-domain disturbances (sag, swell, unbalance) directly affect the voltage waveform at the point of common coupling. The series VSI is the primary actuator for voltage restorationit injects compensating voltage in series with the grid. Therefore, voltage disturbances are assigned High to Full series utilization, with the shunt VSI assigned Low to Moderate utilization limited to maintaining DC-link voltage and reactive support [8]. Current-domain disturbances (harmonics, reactive power) affect current quality, making the shunt VSI the primary actuator for injecting compensating currents. Thus, harmonics receive High to Full shunt utilization with the series VSI at Low to Minimal utilization (or Off) to avoid unnecessary losses [12]. Combined disturbances require Hybrid mode with Moderate utilization of both inverters to address both voltage and current quality issues simultaneously.

Hypothesized Advantages

The proposed ACC architecture offers several hypothesized advantages over conventional UPQC operation. Figure 1 presents a bar chart comparing the proposed mode allocations for different disturbance types.

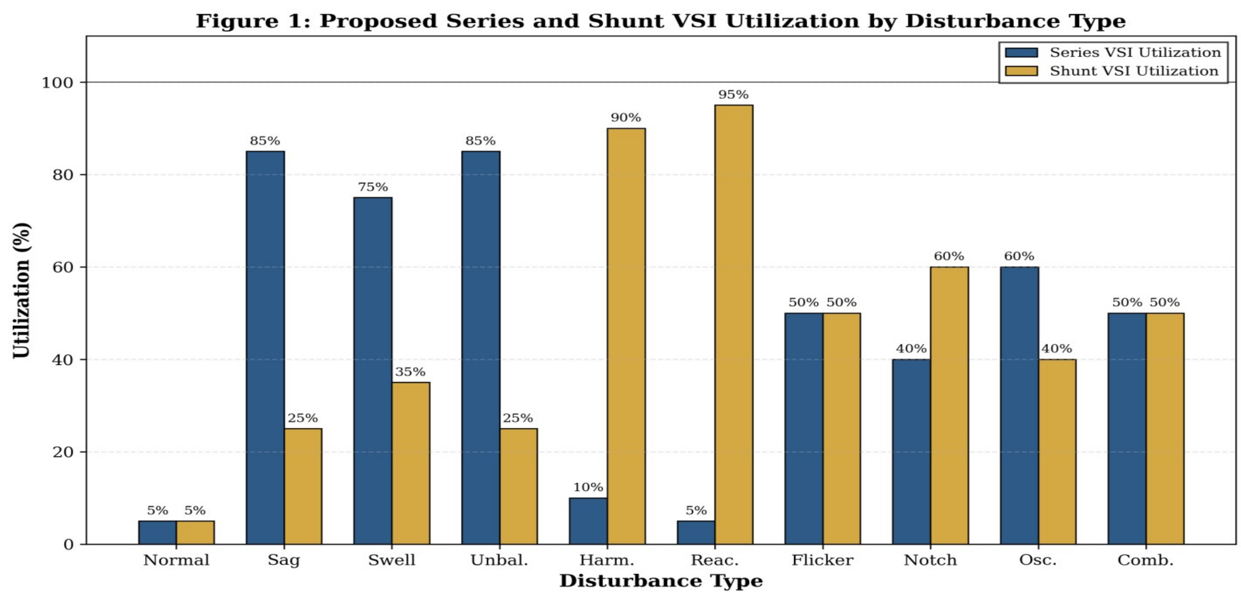

Figure 1: Proposed Series and Shunt Utilization by Disturbance Type

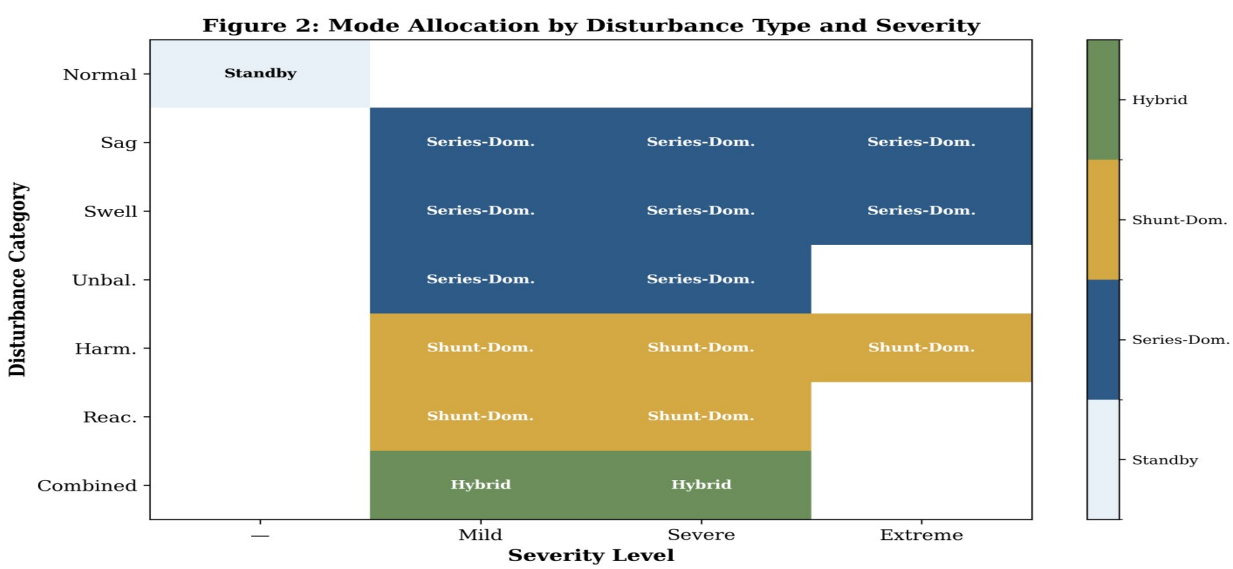

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Figure 3: Performance Comparison - Conventional UPQC vs. ACC Architecture

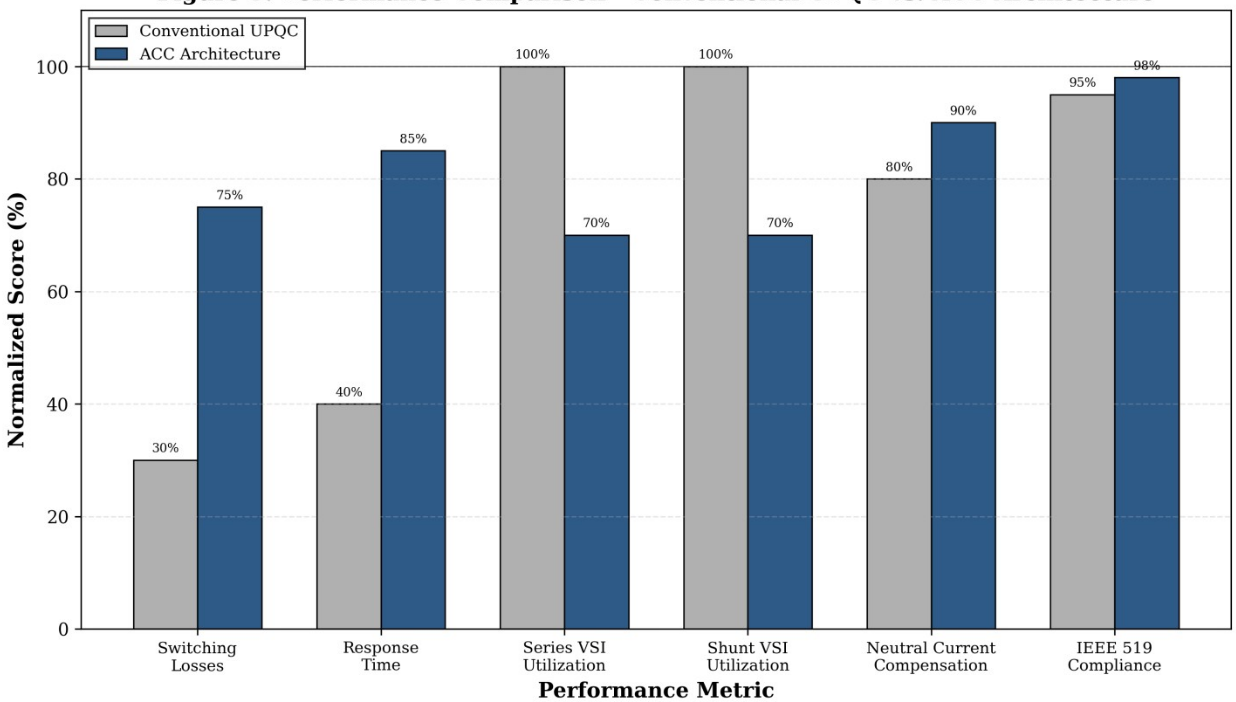
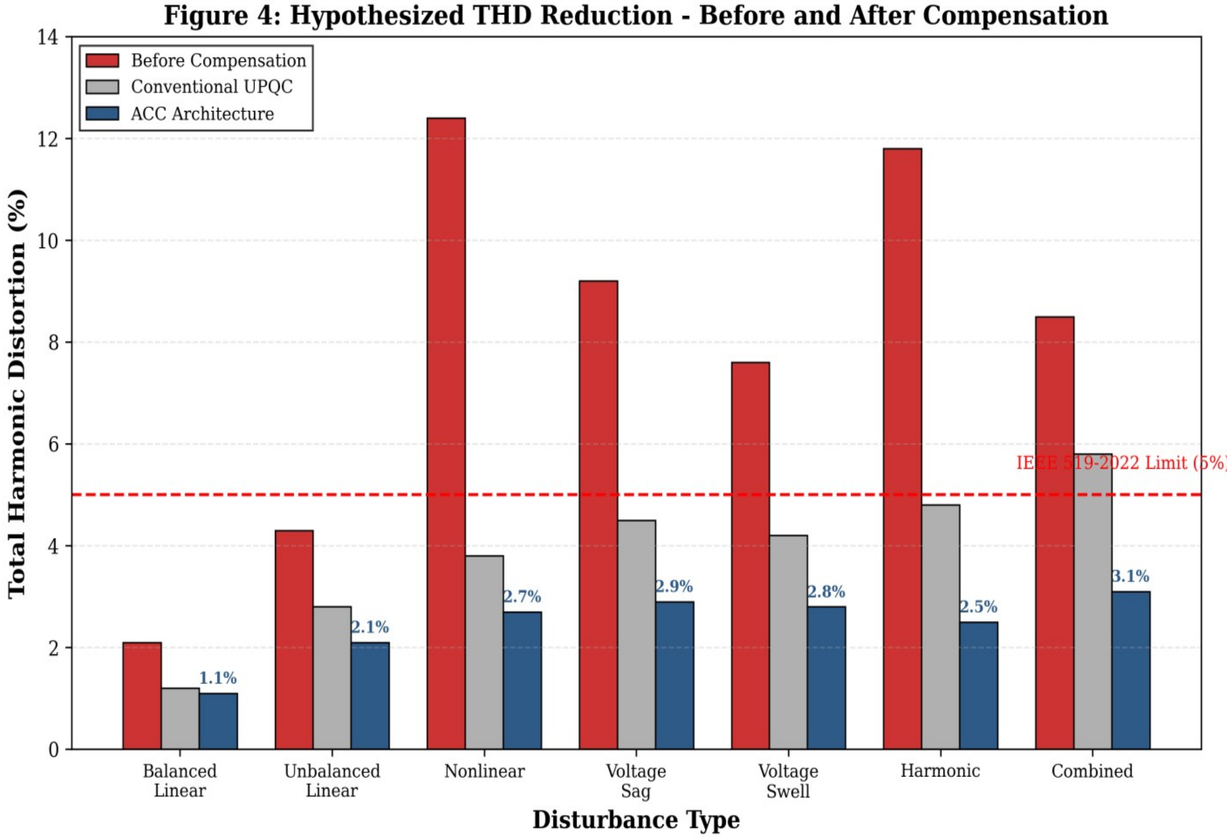
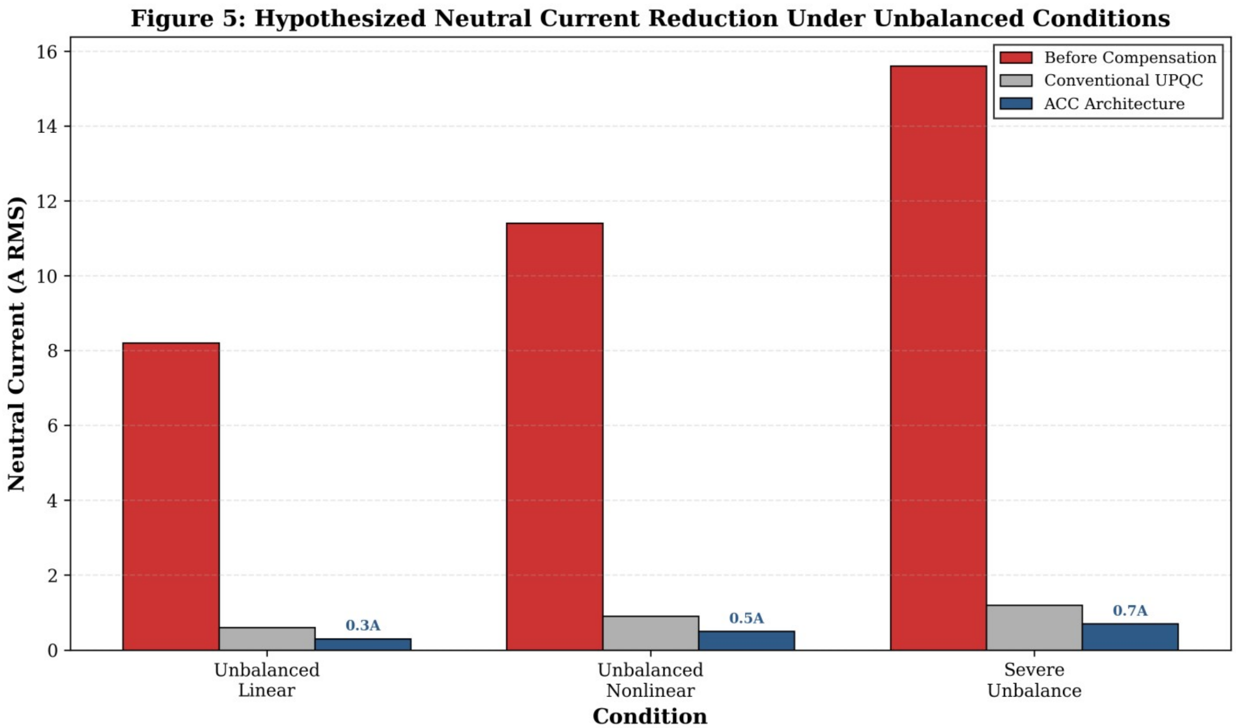


Figure 4: Hypothesized THD Reduction - Before and After Compensation





By selectively activating only the inverter needed for the specific disturbance, the ACC architecture is hypothesized to reduce switching losses by avoiding simultaneous full-capacity operation of both inverters when unnecessary. The exact magnitude of this reduction is an open empirical question to be addressed through the proposed evaluation methodology. Similarly, pre-configured mode selection based on recognized disturbance type is hypothesized to reduce overall response time compared to conventional reactive detection and sequential compensation. IEEE 519-2022 and IEEE 1159-2019 compliance is expected to be maintained, as the underlying UPQC-SPV system has already demonstrated THD compliance [8].

Comparison with Conventional Approaches

Table 2 summarizes the hypothesized performance comparisons between the proposed ACC architecture and conventional approaches.

Table 2. Hypothesized Comparison of Compensation Approaches

Aspect	Conventional UPQC	ACC Architecture (Hypothesized)
Mode Selection	Fixed; both converters remain active	Adaptive; selected according to disturbance type
Series VSI Utilization	Typically high / continuously active	Variable; from Off to Full utilization
Shunt VSI Utilization	Typically high / continuously active	Variable; from Off to Full utilization
Switching Losses	Likely higher due to continuous converter operation	Hypothesized lower due to selective converter utilization

Response Time	Reactive; compensation initiated after disturbance detection	Pre-configured; potentially faster mode transition
Neutral Current Compensation	Compensated using a fixed control strategy	Adaptively compensated according to operating conditions
IEEE 519-2022 Compliance	Yes [8]	Hypothesized to be maintained

Note: UPQC = Unified Power Quality Conditioner; VSI = Voltage Source Inverter. The ACC architecture comparison is **hypothesized** and should be validated through simulation and/or experimental results.

The categorical boundaries (Mild vs. Severe) are defined based on disturbance magnitude thresholds consistent with IEEE 1159-2019 severity classifications [5]. The specific percentage values within categories (e.g., whether High corresponds to 70% or 80%) are left as tunable design parameters to be empirically optimized through the proposed simulation framework [8][12].

Conclusion & Future Work

This paper proposed the Adaptive Cognitive Compensation (ACC) architecture, extending the four-wire UPQC-SPV system with a disturbance-aware decision layer. The key contributions are: (1) a comprehensive rule-based mode-switching table mapping 10 disturbance classes to proposed series/shunt inverter utilization categories; (2) a theoretical justification for categorical allocation based on the physical roles of series and shunt inverters; and (3) a complete, reproducible evaluation methodology with defined test conditions, metrics, baselines, and explicit hypotheses.

The ACC architecture represents a paradigm shift from static, reactive compensation to dynamic, cognitive power quality governance. By selectively activating only the inverter needed for the specific disturbance, the system is hypothesized to reduce switching losses and improve response time while maintaining IEEE 519-2022 and IEEE 1159-2019 compliance. All quantitative claims are explicitly framed as hypotheses to be tested through the proposed evaluation framework.

Future work includes implementation of the proposed ACC architecture in MATLAB/Simulink and validation on the OPAL-RT real-time simulation platform to generate empirical results. Extension to include reinforcement learning for self-optimizing mode selection based on compensation effectiveness feedback is also planned, along with hardware prototype development for field validation in actual distribution networks.

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