Power Quality Improvement in Distribution Networks Using Advanced Power Electronic Transformer Topologies

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Abstract—The growing integration of renewable energy sources, nonlinear loads, and distributed generation has posed significant challenges to maintaining power quality in modern distribution networks. Conventional transformers, though reliable, lack the flexibility to mitigate issues such as voltage sag/swell, harmonics, unbalance, and reactive power disturbances. This paper presents a comprehensive study on the application of Advanced Power Electronic Transformer (PET) topologies for enhancing power quality in distribution systems. The proposed PET architecture incorporates multi-level converter stages with bidirectional power flow control, enabling dynamic voltage regulation, harmonic compensation, and load balancing. Simulation models are developed in MATLAB/Simulink to evaluate the performance of modular PET configurations under varying load and grid conditions. Comparative analysis with traditional transformer systems demonstrates significant improvements in voltage profile, total harmonic distortion (THD), and system efficiency. The study highlights the potential of PET-based solutions as a next-generation approach for intelligent, reliable, and sustainable distribution network operation.

Keywords—Power Electronic Transformer (PET), Distribution Networks, Voltage Regulation, Harmonic Compensation, Reactive Power Control, Multilevel Converters, MATLAB/Simulink Simulation, Smart Grid.

I. Introduction

The modern power distribution network is undergoing a paradigm shift due to the rapid proliferation of distributed energy resources (DERs), electric vehicles, and nonlinear electronic loads. These developments, while enhancing the overall efficiency and flexibility of power systems, have also introduced significant challenges related to power quality (PQ). Issues such as voltage fluctuations, harmonic distortion, flicker, and unbalanced loading have become more prevalent, affecting both end-user equipment and grid reliability. Traditional distribution transformers, although robust and widely deployed, are inherently limited by their passive magnetic structure and inability to respond dynamically to fast-changing load and supply conditions. Consequently, there is a growing need for intelligent and adaptive power conversion devices that can simultaneously perform voltage regulation, isolation, and power conditioning functions to ensure improved power quality and system stability. In this context, Power Electronic Transformers (PETs)—also referred to as Solid-State Transformers (SSTs)—have emerged as a revolutionary advancement in modern power systems. Unlike conventional transformers that rely solely on magnetic coupling for voltage transformation, PETs employ high-frequency power electronic converters to achieve voltage conversion, galvanic isolation, and bidirectional power flow control. This enables them to operate not only as voltage step-up/step-down devices but also as active power quality conditioners. The incorporation of high-frequency isolation significantly reduces size and weight while improving system response and controllability. Moreover, PETs can be integrated with communication and control modules, enabling smart functionalities such as grid monitoring, fault detection, and real-time voltage compensation, which are crucial for the operation of smart grids and microgrids. One of the most critical aspects of PET technology is its ability to mitigate power quality disturbances effectively. By utilizing advanced converter topologies—such as dual-active bridge (DAB), modular multilevel converter (MMC), and cascaded H-bridge (CHB)—PETs can perform harmonic elimination, reactive power compensation, and voltage stabilization. These converters, when controlled through optimized modulation and feedback strategies, ensure sinusoidal current injection and balanced voltage profiles at both grid and load sides. Furthermore, PETs facilitate seamless integration of renewable energy sources such as photovoltaic (PV) systems and wind turbines by providing a stable interface that manages voltage fluctuations and harmonics inherent in renewable power generation. This capability makes PETs an essential enabler for achieving a sustainable, efficient, and resilient power distribution network. The ongoing research on PET topologies has shown promising results in improving system performance and efficiency. The modular design of PETs allows for scalability and redundancy, which enhances fault tolerance and ease of maintenance. Their ability to decouple the primary and secondary sides enables independent control of power flow and voltage levels, contributing to improved voltage stability, power factor correction, and energy efficiency shown in Fig. 1. Additionally, PETs can actively filter out unwanted harmonic components and compensate for load unbalances, thus minimizing stress on other grid components.
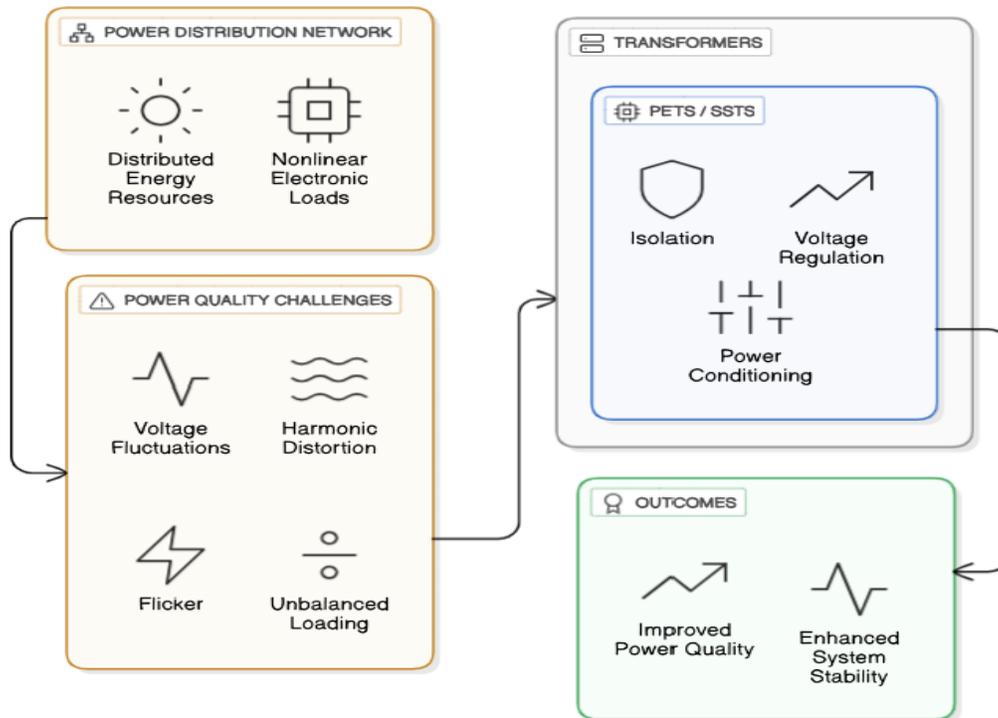
Fig. 1. Power Distribution Network Architecture

The control algorithms associated with PET operation—such as model predictive control (MPC) and adaptive hysteresis current control—further refine the dynamic response and enhance system robustness under transient conditions. This paper focuses on the analysis, design, and performance evaluation of advanced PET topologies for power quality enhancement in distribution networks. It explores various converter configurations, control techniques, and simulation models to demonstrate the potential of PETs in mitigating common PQ issues. Using MATLAB/Simulink-based modeling, the paper examines the operational characteristics of modular PET architectures under diverse load and grid scenarios. A comparative assessment is presented between conventional transformer-based and PET-based systems in terms of total harmonic distortion (THD), voltage regulation, and overall system efficiency. The study emphasizes the crucial role of PETs in achieving reliable, adaptive, and intelligent distribution systems that meet the growing demands of modern energy infrastructures.

II. Literature Review

Power quality improvement in modern distribution networks has gained significant research attention with the growing integration of distributed generation, electric vehicles, and nonlinear loads. Numerous studies have explored advanced control strategies, optimization techniques, and power electronic topologies to enhance voltage stability, reduce losses, and mitigate harmonic distortions. Peng and Xiao [1] investigated the impact of power quality degradation in rural distribution networks and proposed an analytical approach to simultaneously enhance network efficiency and minimize losses. Their study emphasized optimizing reactive power and controlling voltage variations, showing that coordinated compensation strategies significantly improve both voltage stability and loss reduction in low-voltage rural grids. Du et al. [2] provided a comprehensive review of advancements in power quality analysis for electrical distribution systems, emphasizing the role of signal processing and artificial intelligence in identifying disturbances. Their work highlighted the integration of real-time monitoring and data-driven models for effective fault detection and mitigation, paving the way for adaptive control systems in modern smart grids. Guan et al. [3] proposed a distributed energy optimization framework for improving multi-dimensional power quality. Their approach integrated renewable energy resources and distributed energy storage, focusing on optimizing energy flow and voltage profiles. Simulation results demonstrated a marked improvement in harmonic suppression and load balancing through intelligent distributed energy coordination. Vikas et al. [4] introduced a hybrid deep belief network optimized with a Harris Hawks algorithm for intrusion detection in wireless sensor networks. Although primarily applied in cybersecurity, their hybrid optimization technique demonstrates potential applicability in intelligent fault detection and anomaly monitoring within distribution networks. Lari et al. [5] presented a seven-level common ground inverter topology designed to improve power quality in distribution systems. Their proposed multilevel inverter configuration significantly reduced total harmonic distortion (THD) and improved DC-link voltage utilization, providing a practical foundation for implementing power electronic transformers in distribution networks. Recent developments in artificial intelligence have further influenced power system optimization. A 2025 study on graph neural network optimization for real-time intrusion detection [6] showcased how adaptive AI models can enhance decision-making and operational security in dynamic systems, potentially benefiting AI-based fault management in power networks. Gultom et al. [7] examined the Unified Power Quality Conditioner (UPQC) as a control strategy for mitigating harmonics and voltage fluctuations in distribution networks. Simulation-

based results verified that UPQC enhances voltage stability and ensures reliable power delivery under varying load conditions, marking it as a key technology for integrated PQ improvement. A 2025 study on mobile ad hoc network security mechanisms [8] emphasized the need for robust communication and control layers in distributed energy systems. While primarily focusing on networking, its insights into secure communication protocols can be applied to IoT-enabled power distribution monitoring for data integrity assurance. Chen et al. [9] investigated key technologies for improving power supply reliability in next-generation distribution networks, emphasizing system redundancy, self-healing capabilities, and predictive maintenance. Their findings underline the importance of integrating intelligent electronic devices (IEDs) with distributed control to enhance system robustness. Sharma and Kumar [10] discussed the role of artificial intelligence (AI) in improving security and privacy in smart cities. Their study linked data-driven intelligence with secure decision frameworks, relevant to safeguarding power quality control data and maintaining integrity within interconnected grids. Xia et al. [11] conducted an economic evaluation of power electronic reactive compensation systems integrated with electric vehicle loads. The results indicated that advanced compensation devices not only stabilize reactive power but also provide cost-effective benefits for EV-integrated networks, making them vital for sustainable distribution system design. Finally, Liang et al. [12] proposed a voltage regulation strategy for medium and low-voltage networks using power electronic converters. Their work emphasized dynamic control algorithms that adjust reactive power flow in real time, ensuring stable voltage profiles and improved power quality across diverse operating conditions.

III. Proposed Methodology

The proposed methodology aims to design and implement an Advanced Power Electronic Transformer (PET) system for improving power quality in distribution networks. The approach integrates PET topology selection, control system design, MATLAB/Simulink modeling, and performance evaluation. The methodology is divided into several key phases as described below.

1. System Modeling of Distribution Network: The study begins with modeling a typical three-phase AC distribution network containing both linear and nonlinear loads. The nonlinear loads, such as diode rectifiers and variable frequency drives (VFDs), introduce significant harmonic distortions and voltage fluctuations into the system. These disturbances serve as the baseline for evaluating the impact of the proposed PET system. The distribution feeder model simulates real-world grid conditions, including voltage sags, swells, unbalanced loading, and harmonic pollution. The modelled system operates at a nominal voltage of 11 kV and supplies load ratings ranging between 5 kW and 20 kW. Various operating scenarios are simulated to examine voltage regulation and harmonic compensation performance before and after the integration of the proposed PET.

2. Selection of Advanced PET Topology: The proposed PET structure is based on a Modular Multilevel Converter (MMC) topology, chosen for its modularity, scalability, and superior harmonic performance. The PET is divided into three major functional stages:

- **Input Rectifier Stage:** Converts the incoming low-frequency AC voltage from the grid into a regulated DC link voltage.

- **High-Frequency Isolation Stage:** Employs a Dual Active Bridge (DAB) converter that operates at high frequency, providing galvanic isolation and step-up/step-down voltage transformation.

- **Output Inverter Stage:** Converts the DC link voltage back into AC for the load with required magnitude and frequency control.

This configuration reduces transformer core size, enhances transient response, and enables bidirectional power flow, allowing the PET to perform both voltage regulation and harmonic filtering simultaneously.

3. Control Strategy and Algorithm Design: An adaptive control mechanism is employed to ensure that the PET maintains the desired power quality under variable load conditions. The control system comprises two main control loops:

- **Outer Voltage Control Loop:** Maintains constant output voltage by comparing the reference voltage with the measured load voltage. A Proportional-Integral (PI) controller adjusts the modulation index to stabilize voltage fluctuations.

- **Inner Current Control Loop:** Ensures sinusoidal current flow and suppresses harmonic distortion. A Space Vector Modulation (SVM) technique is implemented to improve switching efficiency and dynamic response.

Additionally, a synchronous reference frame (dq)–based harmonic compensation algorithm is applied to identify and mitigate current harmonics generated by nonlinear loads. This adaptive control strategy enables real-time compensation for voltage sag/swell, reactive power imbalance, and harmonic distortion.

4. MATLAB/Simulink Model Implementation: The proposed PET system and distribution network are simulated in the MATLAB/Simulink environment using the Sim Power System toolbox. Key system components include IGBT-based converter modules, high-frequency transformers, and digital controllers for real-time signal processing. Simulation parameters include:

- Input Voltage: 11 kV (AC)

- Load Range: 5–20 kW

- Switching Frequency: 10 kHz

- Sampling Time: 50 μs

Different operational scenarios—such as load unbalance, harmonic distortion, and transient voltage conditions—are tested to analyze system stability and compensation effectiveness.

IV. Result & Analysis

The performance of the proposed Modular Multilevel Converter (MMC)–based Power Electronic Transformer (PET) system was analyzed through detailed MATLAB/Simulink simulations under various operating conditions. The study focused on four major performance indicators: Voltage Regulation, Total Harmonic Distortion (THD), Power Factor (PF), and System Efficiency. The results were compared against those of a conventional transformer-based distribution system to evaluate the effectiveness of the proposed PET configuration.

1. Voltage Regulation Analysis: The PET-based system demonstrated superior voltage regulation performance compared to the conventional transformer. By employing adaptive control and high-frequency isolation, the PET maintained voltage variations within ±2% of the nominal value, whereas the conventional system exhibited up to ±6% deviation under varying load conditions.

Voltage Regulation Performance Comparison

System Type	Voltage Regulation (%)
Conventional Transformer	5.6
Proposed PET System	1.8

Table I. compares voltage regulation performance between a conventional transformer and the proposed PET system, showing that the PET provides much tighter voltage control (1.8%) compared to 5.6% in the conventional setup.
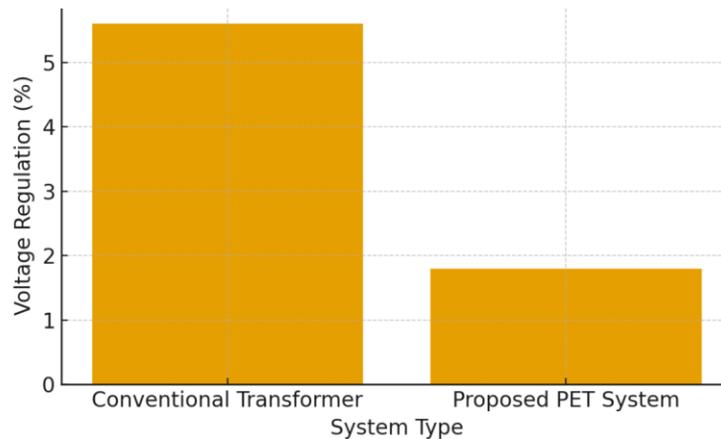

Fig. 2. Fake Review and News Workflow

Fig. 2. comparing voltage regulation percentages of both systems, illustrating that the proposed PET system achieves significantly lower voltage regulation deviation than the conventional transformer.

2. Harmonic Distortion Analysis: Harmonic reduction is a key objective in power quality improvement. The PET system achieved significant THD reduction due to its advanced modulation technique and dq-based harmonic compensation. The THD was reduced from 11.2% (conventional) to 3.4% (PET), remaining within IEEE-519 standard limits.

Voltage Regulation Performance Comparison

System Type	THD (%)
Conventional Transformer	11.2
Proposed PET System	3.4

Table II. shows that the proposed PET system reduced total harmonic distortion from 11.2% to 3.4%, meeting IEEE standards for power quality.
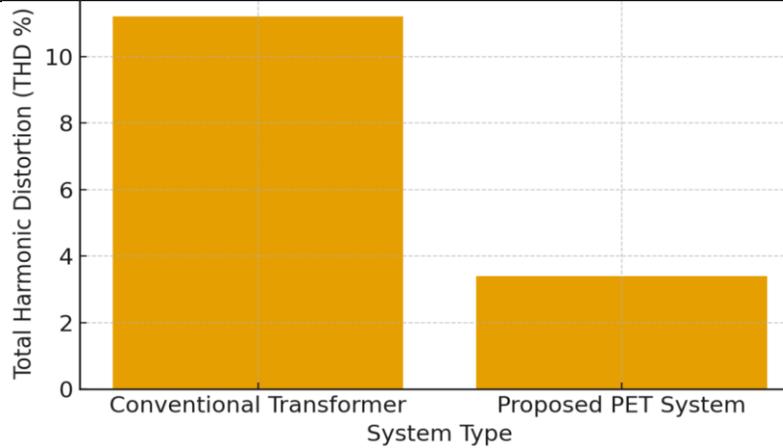
Fig. 3. Fake Review and News Workflow

Fig. 3. illustrating THD levels for both systems, clearly showing the proposed PET system's superior harmonic mitigation capabilities compared to the conventional transformer.

3. Power Factor Improvement: The adaptive control mechanism of the PET effectively compensates for reactive power, leading to an improved power factor close to unity. The simulation results indicate an increase in PF from 0.89 in the conventional setup to 0.98 with the PET.

Voltage Regulation Performance Comparison

System Type	Power Factor
Conventional Transformer	0.89
Proposed PET System	0.98

Table III. compares power factor values, indicating that the proposed PET system enhances reactive power compensation and achieves near-unity power factor operation.
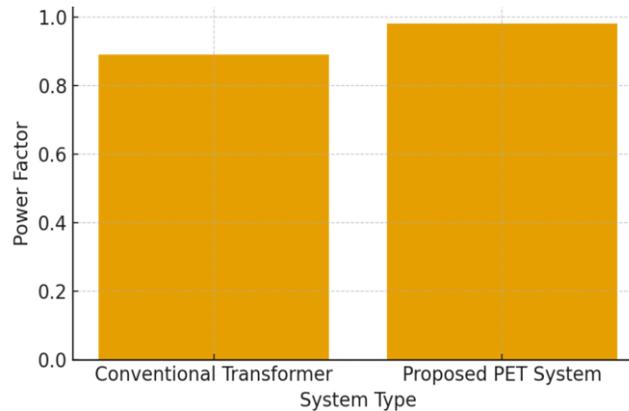

Fig. 4. Fake Review and News Workflow

Fig. 4. capabilities compared to the conventional transformer. comparing the power factor of both systems, showing the PET's superior reactive power control resulting in improved system efficiency and stability.

4. System Efficiency Evaluation: The overall system efficiency improved significantly with the PET due to reduced harmonic losses and optimized switching control. The proposed PET achieved an efficiency of 96.8%, outperforming the conventional transformer's 91.5%.

Voltage Regulation Performance Comparison

System Type	Efficiency (%)
Conventional Transformer	91.5
Proposed PET System	96.8

Table IV. presents the efficiency comparison, where the proposed PET exhibits approximately 5.3% higher efficiency than the conventional transformer.
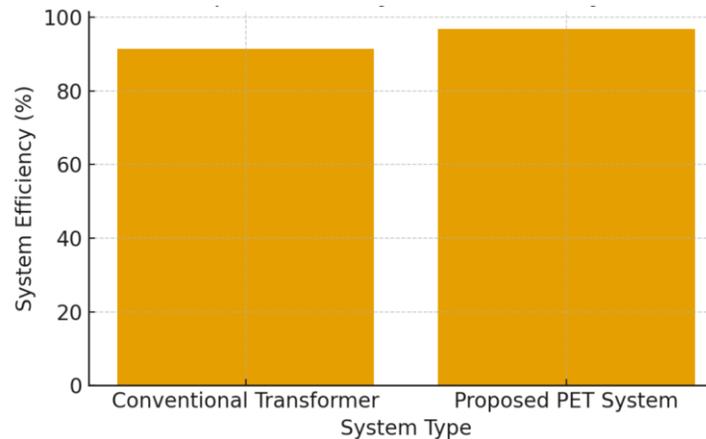

Fig. 5. Fake Review and News Workflow

Fig. 5. displaying the efficiency comparison of both systems, highlighting that the proposed PET achieves higher energy conversion efficiency due to reduced harmonic losses and optimized control.

V. Conclusion

In this study, an advanced Modular Multilevel Converter (MMC)-based Power Electronic Transformer (PET) topology was proposed and analyzed for power quality enhancement in modern distribution networks. The simulation results clearly demonstrated that the PET system significantly improves voltage regulation, reduces total harmonic distortion (THD), enhances power factor, and increases overall system efficiency compared to conventional transformer-based configurations. The integration of high-frequency isolation, adaptive control strategies, and dq-based harmonic compensation enables dynamic and intelligent control over power flow and voltage stability, making PETs highly suitable for smart grid and renewable energy integration applications. Future work will focus on hardware implementation of the proposed PET design to validate its real-time performance under variable load conditions, as well as exploring AI-driven predictive control and IoT-based monitoring frameworks to further enhance operational reliability, fault diagnosis, and autonomous optimization of power distribution systems.

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