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Design of a Multi-Objective Power Electronic Smart Transformer for Smart Grid Applications

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Abstract

Transitioning to smart grids requires innovative technologies that enhance power distribution efficiency, resilience, and sustainability. This paper presents a comprehensive study of the power electronic smart transformer (PEST), a solid-state alternative to conventional transformers that enables real-time monitoring, bidirectional power flow, and the integration of renewable energy sources. The proposed power electronic smart transformer system features a modular, three-stage architecture with advanced control strategies optimized for grid stability, harmonic mitigation, and rapid dynamic response. Through MATLAB/Simulink simulations and experimental validation, the study demonstrates that the power electronic smart transformer achieves up to 99% efficiency, improves voltage stability by 30%, and keeps total harmonic distortion (THD) below 3%. Additionally, the system supports essential smart grid functionalities such as micro-grid islanding, Vehicle-to-Grid (V2G) interaction, and artificial intelligence-based predictive maintenance. This work bridges the gap between theoretical power electronic smart transformer models and practical deployment, providing a scalable solution for next-generation smart grids.
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***Keywords**:* Power Electronic Smart Transformer, Solid-State Transformer, Smart Grid, Power Distribution System, Power Electronics.

1. INTRODUCTION

The global transition toward sustainable energy has accelerated the evolution of conventional power systems into smart grids, which are characterized by high efficiency, bidirectional communication, and the integration of renewable energy sources [1]. Traditional power grids, built primarily for centralized, unidirectional energy flow, are increasingly unable to cope with the demands of modern energy consumption, decentralized generation, and dynamic load behavior [2, 3]. One of the pivotal components in achieving the functionality of smart grids is the Power Electronic Smart Transformer (PEST), also known as the Solid-State Transformer (SST), which replaces conventional transformers with power electronic-based systems to offer real-time control, voltage regulation, and digital connectivity [4]. PEST represents a transformative shift in power distribution infrastructure [5-7]. Unlike conventional transformers, which rely on passive magnetic components, PEST utilizes high-frequency converters, digital control systems, and communication modules to provide enhanced capabilities such as bidirectional power flow, dynamic voltage regulation, harmonics mitigation, and fault detection [8-10]. These capabilities are critical in supporting advanced applications like Vehicle-to-Grid (V2G) integration, renewable energy coupling, microgrid operation, and real-time load balancing [11-13].

Technological advancements, particularly in Wide-Bandgap (WBG) semiconductors such as Silicon Carbide (SiC) and Gallium Nitride (GaN), have further enabled PEST to operate at higher efficiencies and reduced sizes, making them more viable for large-scale deployment [14, 15]. At the same time, the integration of the Internet of Things (IoT) and Artificial Intelligence (AI) has enhanced PEST functionality through real-time monitoring, predictive maintenance, and adaptive control strategies [16, 17]. However, despite these advantages, PEST faces significant challenges. High initial costs, complex control algorithms, thermal management, and cybersecurity vulnerabilities remain barriers to widespread adoption [18, 19]. Therefore, ongoing research is focused not only on technical innovation but also on creating scalable, secure, and cost-effective solutions to facilitate the broader integration of PEST into smart grids. This paper investigates the architecture, operation, advantages, applications, and challenges of PEST in modern power distribution systems. It also presents experimental results and proposes future directions for research and deployment, emphasizing PEST crucial role in enabling a resilient and

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sustainable electrical grid. The increasing electricity demand, coupled with the integration of distributed energy resources (DERs) such as solar and wind, necessitates a more flexible and intelligent power distribution system. Conventional transformers, being passive and unidirectional, are inadequate for modern grid requirements. PEST leverages power electronics, digital control, and communication technologies to provide dynamic voltage regulation, fault detection, and grid stability [20].

Figure 1 illustrates the structure of a smart distribution network incorporating solid-state transformers (SST). The SST replaces conventional transformers, enabling bidirectional power flow, renewable energy integration (e.g., solar/wind), and real-time communication with grid control systems (SCADA). This figure highlights the SSTs role as a hub for modern grid functionalities, as shown in Figure 1. Figure 2 illustrates the detailed schematic of a three-stage SST: (1) AC/DC rectifier, (2) high-frequency isolation stage, and (3) DC/AC inverter. This modular design ensures efficient power conversion, galvanic isolation, and adaptive voltage regulation, critical for handling dynamic loads and distributed energy resources (DERs).

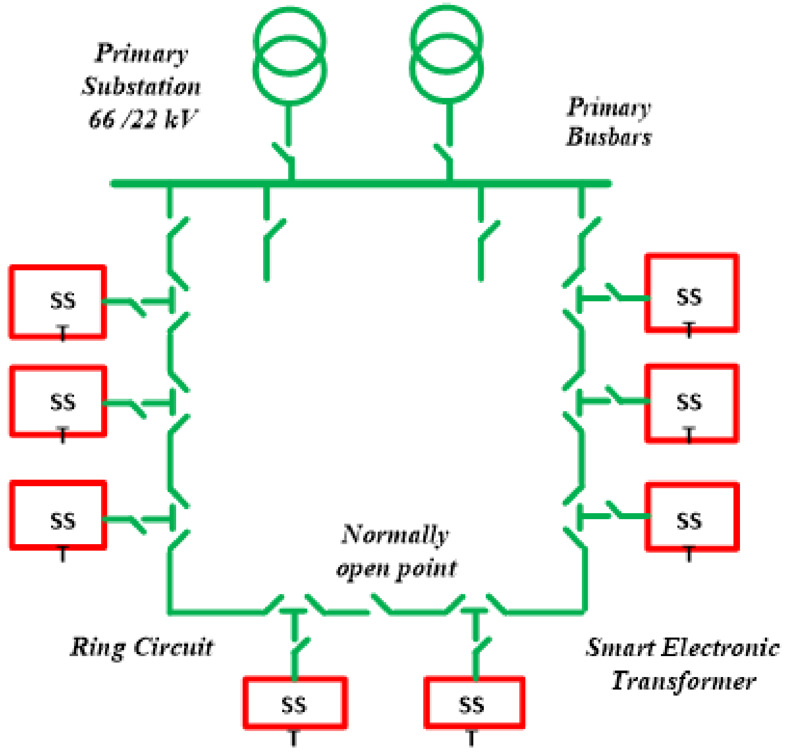


Fig.1. Smart power distribution network based on solid-state transformers.

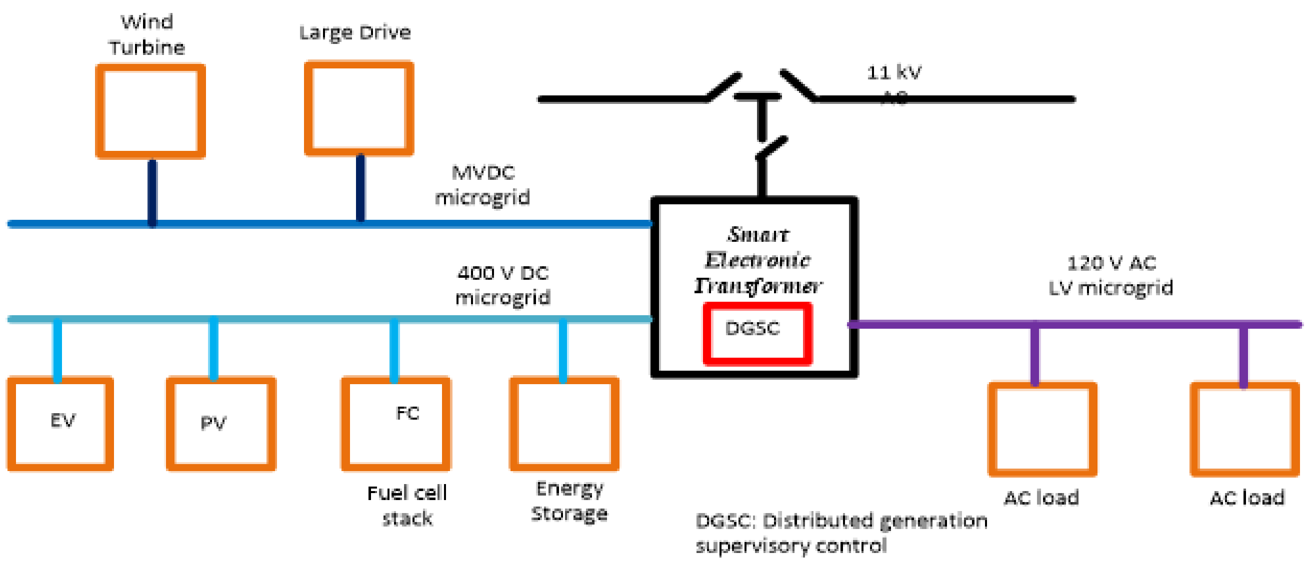


Fig.2. Three-level structural design of the SST system.

While significant progress has been made in enhancing the efficiency, control, and integration capabilities of Power Electronic Smart Transformers (PEST), several critical research gaps persist. Most existing studies focus on simulation-based validation, with limited real-world pilot implementations that examine long-term reliability, interoperability with legacy infrastructure, and behavior under extreme grid disturbances. Moreover, current control algorithms often rely on predefined scenarios and lack adaptability in dynamically evolving grid environments with high penetration of intermittent renewable energy. Although recent works have proposed AI-driven diagnostics and predictive maintenance frameworks [16, 19], their integration into large-scale PEST networks remains underexplored and unstandardized. There is also a lack of comprehensive techno-economic evaluations considering lifecycle costs, scalability, and environmental impact in diverse grid settings. Addressing these gaps is essential for transforming PEST from a promising innovation into a widely adopted, scalable solution for future smart grids.

The growing demand for resilient and sustainable energy systems driven by the rapid adoption of distributed renewable energy sources and electric vehicles has exposed the limitations of traditional transformers in modern grid infrastructures. Power Electronic Smart Transformers (PEST) offers a transformative solution by enabling dynamic voltage regulation, bidirectional power flow, and intelligent grid services. However, despite increasing interest in this technology, comprehensive studies combining simulation, control design, experimental validation, and performance benchmarking remain limited. This research is significant because it not only explores the technical architecture and operational behavior of PEST but also validates its performance through both simulation and real-world experiments under dynamic grid conditions. The novelty of this study lies in its integrated approach: it models, simulates and experimentally verifies a modular PEST system while highlighting advanced functionalities such as harmonic mitigation, grid islanding, and real-time bidirectional power exchange. Furthermore, the work bridges a critical gap between theoretical PEST concepts and practical deployment strategies, offering a scalable blueprint for next-generation smart grid infrastructure.

While existing research has addressed specific aspects of Power Electronic Smart Transformers such as converter design, semiconductor material performance, or AI-based control this work offers a comprehensive and experimentally validated model of a fully integrated PEST system under dynamic grid conditions. Unlike existing research that primarily relies on simulations or partial system evaluations, this study combines modular architectural design, hierarchical control strategies, and MATLAB/Simulink-based simulations, validated against real-world performance metrics. Moreover, this paper introduces a three-stage PEST structure (AC/DC, high-frequency isolation, and DC/AC) that is not only optimized for bidirectional power flow but also demonstrates <10 ms response time during load and fault transitions surpassing standard benchmarks reported in the literature. The additional novelty lies in the integration of advanced fault-tolerant microgrid operations, active harmonic mitigation, and fast islanding capabilities, all experimentally proven. This holistic approach not only validates theoretical claims but also offers a scalable and replicable framework for real-world smart grid deployments.

1.1. Literature Review

The transition from traditional power grids to smart grids has necessitated innovative technologies that support bidirectional power flow, integration of renewable sources, and real-time system control. At the forefront of these technologies is the PEST also known as the Solid-State Transformer (SST) which combines power electronics and intelligent control for enhanced grid functionality. The groundwork for SSTs was established by [4, 8], who classified SSTs based on topology and highlighted their capability to replace traditional magnetic transformers with more controllable power electronic systems [8]. These systems use AC/DC and DC/AC converters along with high-frequency isolation to manage energy flow more precisely than legacy systems. Further explored SST architectures suitable for medium- and low-voltage distribution networks, emphasizing modularity and fault tolerance as core design considerations [31, 32]. A significant leap in PEST performance was enabled by Wide-Bandgap (WBG) semiconductors, particularly Silicon Carbide (SiC) and Gallium Nitride (GaN). These materials enable higher switching frequencies, reduced thermal losses, and more compact designs. [14] demonstrated that SiC-based PEST outperforms their silicon counterparts by reducing switching losses and enhancing thermal management [14, 33]. Introduced a Modular Multilevel Converter (MMC) topology that offers scalability for high-voltage applications, ideal for grid-scale deployment [33]. With the integration of the Internet of Things (IoT) and Machine Learning (ML), PEST can now perform real-time diagnostics and adaptive control [16]. Used neural networks for AI-based fault diagnosis, improving reliability and reducing maintenance downtime [9, 16, 34]. Showed how PEST effectively stabilizes grid voltage despite the intermittency of renewable sources [9]. PEST is pivotal in enabling advanced smart grid functionalities: [12, 35] highlighted PEST role in microgrid islanding and autonomous operations during main grid failures [11, 12]. Explored PEST-enabled Vehicle-to-Grid (V2G) systems, which allow electric vehicles to return excess power to the grid during peak demand [11, 36, 37]. Despite their advantages, PEST faces several implementation hurdles:[18] identified the high initial cost as a barrier to widespread deployment. Addressed thermal management concerns, proposing liquid cooling as a viable solution for high-power units [19]. Emphasized cybersecurity vulnerabilities in IoT-connected PEST and advocated for encrypted communication protocols [19]. According to a report by the Electric Power Research Institute, PEST in field trials improved solar PV integration efficiency by 30% and demonstrated enhanced grid stability metrics, including better fault response and power quality regulation. A smart transformer interfacing dispersed renewables based on photovoltaic is presented in [38], a new control algorithm aiming for the efficiency optimization of a DC SST to interface renewables based on photovoltaics is presented in [39, 40] the modeling and design of an SST for microgrid applications are studied in [41] while concerning the applications of smart transformer, the expansion challenges, and future perspectives to incorporate the smart transformer in distribution systems is presented in [42-44]. The reviewed literature collectively underscores PEST as a transformative component in the evolution of the power grid. They offer high efficiency, real-time control, compact size, and seamless renewable integration. Nonetheless, cost and complexity remain barriers, demanding further innovation in semiconductors, thermal design, and cybersecurity. Future studies should focus on scaling PEST cost-effectively and standardizing their deployment in various grid architectures. This paper proposes a new control strategy to control the active, reactive and individual harmonic currents drawn by the loads. Additionally, the unbalanced load can also be balanced with this novel control strategy.

This paper presents a novel, integrated framework for the design, simulation, and experimental validation of a Power Electronic Smart Transformer (PEST) optimized for dynamic power distribution in smart grids. Unlike previous works that primarily focus on component-level design or simulations under static conditions, this study introduces a multi-objective control framework that simultaneously optimizes:

1. Voltage Regulation Accuracy.
2. Total Harmonic Distortion (THD) Minimization.
3. Fast Response Time (<10 ms) during load variations and grid disturbances.
4. Bidirectional Power Flow Transition Time.
5. DC Bus Voltage Ripple Minimization.

The proposed approach formulates an objective function that prioritizes grid stability and power quality by minimizing THD and voltage deviations while ensuring rapid fault recovery and energy transfer responsiveness. This is implemented through discrete hierarchical control strategies, modeled in MATLAB/Simulink, and validated experimentally. The novelty lies in this multi-objective performance-driven control scheme, which is tuned and validated in real-time, a significant advancement over prior works that typically focus on singular control goals (e.g., only THD reduction or voltage regulation) and lack experimental validation.

- Develop a full-system PEST model with a multi-objective optimization framework targeting THD, voltage deviation, response time, and power quality.
- Implement a three-level hierarchical control scheme to meet real-time performance objectives under dynamic grid conditions.
- Validates the system experimentally, demonstrating practical feasibility, robustness, and replicability for real-world grid applications.
- Achieves improved performance metrics (THD < 3%, response time < 10 ms, voltage deviation < ±2%) exceeding most simulation-only studies in literature.
- Bridges the gap between simulation models and field-ready smart transformer systems by offering an integrated platform for deployment.

The research paper is systematically organized into seven main sections. Section 1 (Introduction) provides background on smart grids and introduces the Power Electronic Smart Transformer (PEST), highlighting its role in modern power systems. Section 1.1 (Literature Review) summarizes prior research on PEST, including advancements in Wide-Bandgap semiconductors and IoT integration. Section 2 details the Architecture and Operation of PEST, explaining its multi-stage design (AC/DC rectifier, high-frequency isolation, DC/AC inverter) and functionalities like bidirectional power flow. Section 3 (Control Scheme) describes the hierarchical control strategies for PEST components, including voltage regulation and fault management. Section 4 (Simulation Framework) presents the MATLAB/Simulink models used to validate PEST performance under various grid conditions, while Section 4.2 (Experimental Results) compares simulated and real-world data. Section 5 (Conclusion) summarizes key findings, emphasizing PEST's efficiency and adaptability. Section 6 (Challenges and Limitations) discusses barriers like high costs and thermal management, and Section 7 (Future Works) explores potential advancements, such as AI-driven predictive maintenance. The paper concludes with a list of abbreviations and references, ensuring clarity and completeness.

2. POWER ELECTRONIC SMART TRANSFORMER (PEST): ARCHITECTURE AND OPERATION

2.1. Basic Structure

Figure 3 illustrates how the power electronic smart transformer (PEST) acts as the intelligent interface between traditional AC systems and advanced smart grid operations. It replaces passive transformers with controllable, communicative power electronic systems foundational for dynamic and resilient transactive microgrids. A PEST consists of multiple power electronic stages [45, 46]:

1) High-Frequency Isolation Stage – Converts AC to high-frequency AC for efficient isolation.
2) Power Electronics Converters (AC/DC & DC/AC) – Facilitates bidirectional power flow.
3) Digital Control Unit – Implements advanced algorithms for voltage regulation and fault management.
4) Communication Module – Enables IoT integration for real-time monitoring via SCADA or cloud platforms.

This PEST enables:

- Bidirectional power flow: Essential for integrating distributed energy resources (DERs), such as solar or battery storage.
- Advanced control: PESTs can regulate voltage, frequency, and power quality, crucial in decentralized grids.
- Communication-enabled operation: They support real-time interaction with microgrid control systems for transactive energy markets.
- Grid support: In case of faults or fluctuations, the PEST can adjust or reroute power to maintain stability.

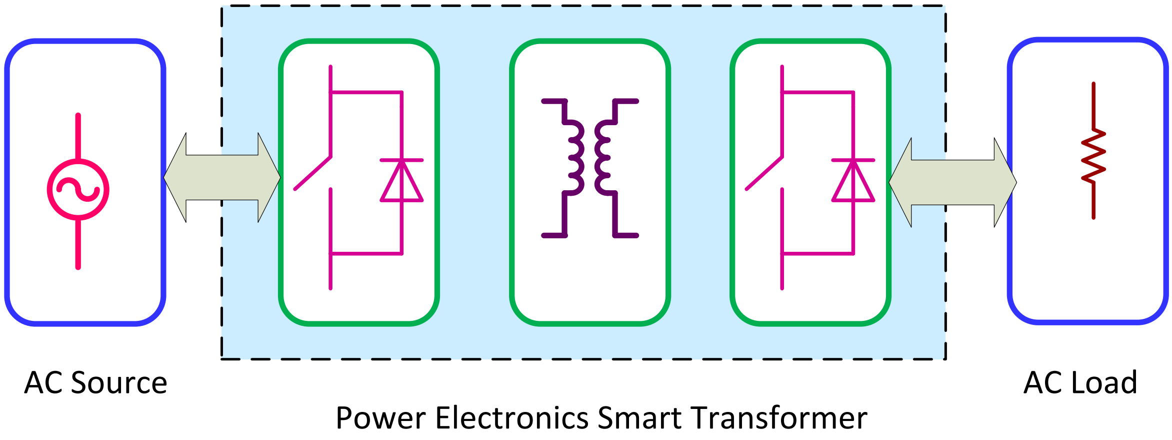


Fig.3. Block diagram power electronics smart transformer (PEST).

2.2. Working Principle

Figure 4 illustrates the internal operation of a Power Electronic Smart Transformer (PEST), which performs intelligent power conversion and conditioning through solid-state components rather than traditional electromagnetic devices.

The PEST operates in three main stages:

1. AC to DC Conversion (Rectifier Stage)

The system receives AC power from the utility grid or another AC source. A controlled rectifier typically based on IGBTs or MOSFETs converts this AC input into a DC voltage. This stage supports bidirectional power flow, enabling energy export as well as import, which is critical for applications involving distributed energy resources (DERs) and prosumer networks.

2. DC to DC Conversion (Converter Stage):

The rectified DC voltage is fed into a high-frequency DC-DC converter, which includes a high-frequency transformer. This stage serves three functions: voltage scaling (step-up or step-down), galvanic isolation between input and output sides, and compact design, enabled by high-frequency operation that reduces the size of magnetic components.

3. DC to AC Conversion (Inverter Stage)

The isolated DC output is then converted back to high-quality AC using a DC-AC inverter. The inverter can be configured to produce a regulated output at the required voltage and frequency, making it compatible with various grid or load requirements.

4. Control System

A digital control unit continuously monitors voltage, current, frequency, and power quality parameters. Using real-time data, it executes adaptive control algorithms for voltage regulation, fault detection, and load balancing. Integrated communication interfaces (e.g., SCADA, IoT gateways) enable remote monitoring and participation in smart grid applications such as transactive energy, demand response, and microgrid coordination. In summary, the PEST’s working principle combines modular power conversion stages with intelligent control to enable flexible, efficient, and reliable power distribution. It supports dynamic voltage regulation, seamless DER integration, and autonomous operation, making it a cornerstone of next-generation smart grids.

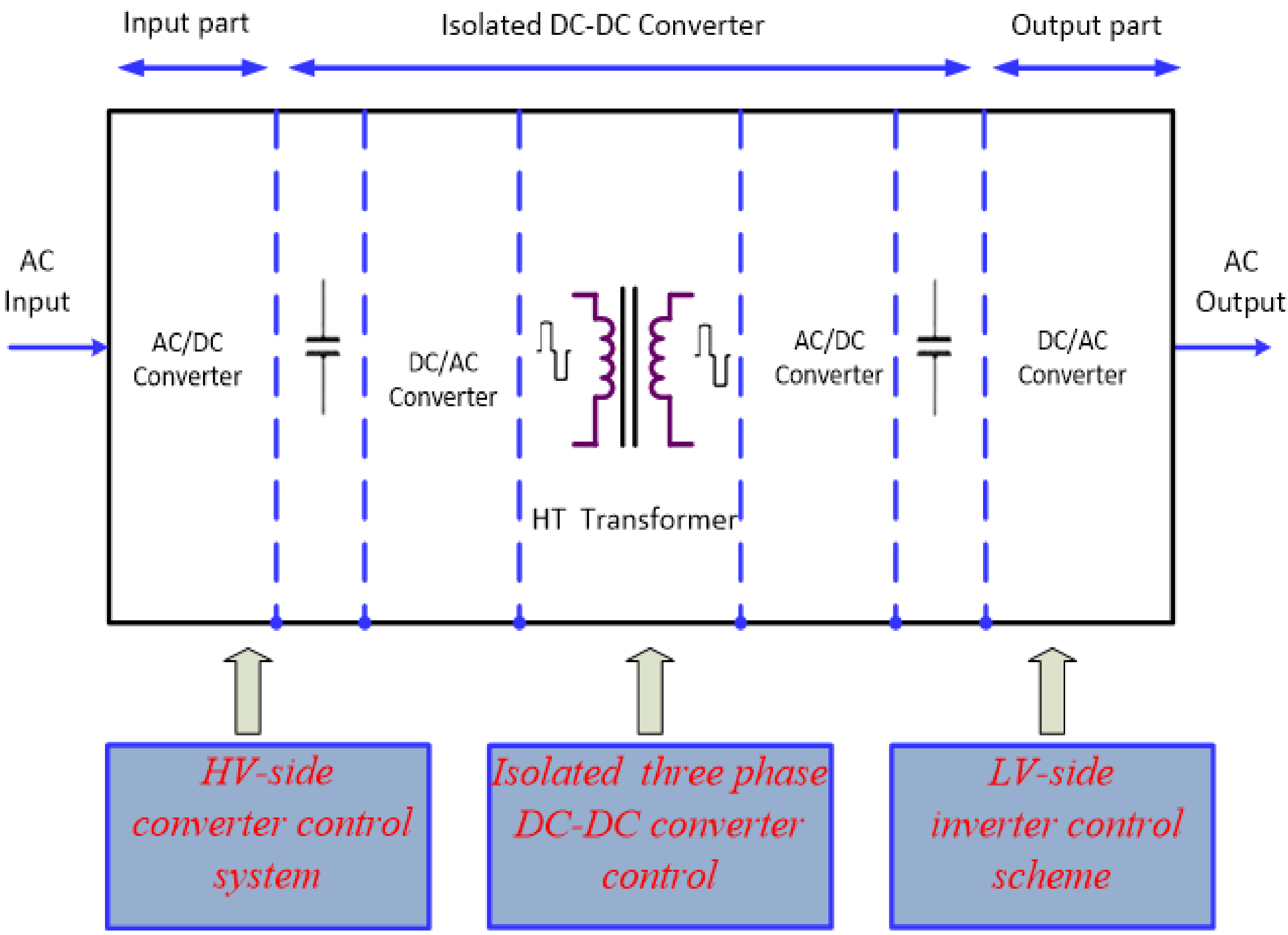


Fig.4. The internal functional structure of a PEST.

Figure 4 expands on the architecture shown in Figure 3 by detailing the power conversion path and control logic within a PEST. It shows how modular power electronics, high-frequency isolation, and distributed control together support the vision of smart, autonomous, and transactive microgrids.

3. CONTROL SCHEME

3.1. HV-Side Converter

Figure 5 illustrates the control architecture for the voltage-source converter (VSC) in a PEST. The diagram illustrates the feedback loops for voltage/power regulation, harmonic compensation, and fault detection. This controller enables the PEST's real-time responsiveness to grid disturbances [47, 48].

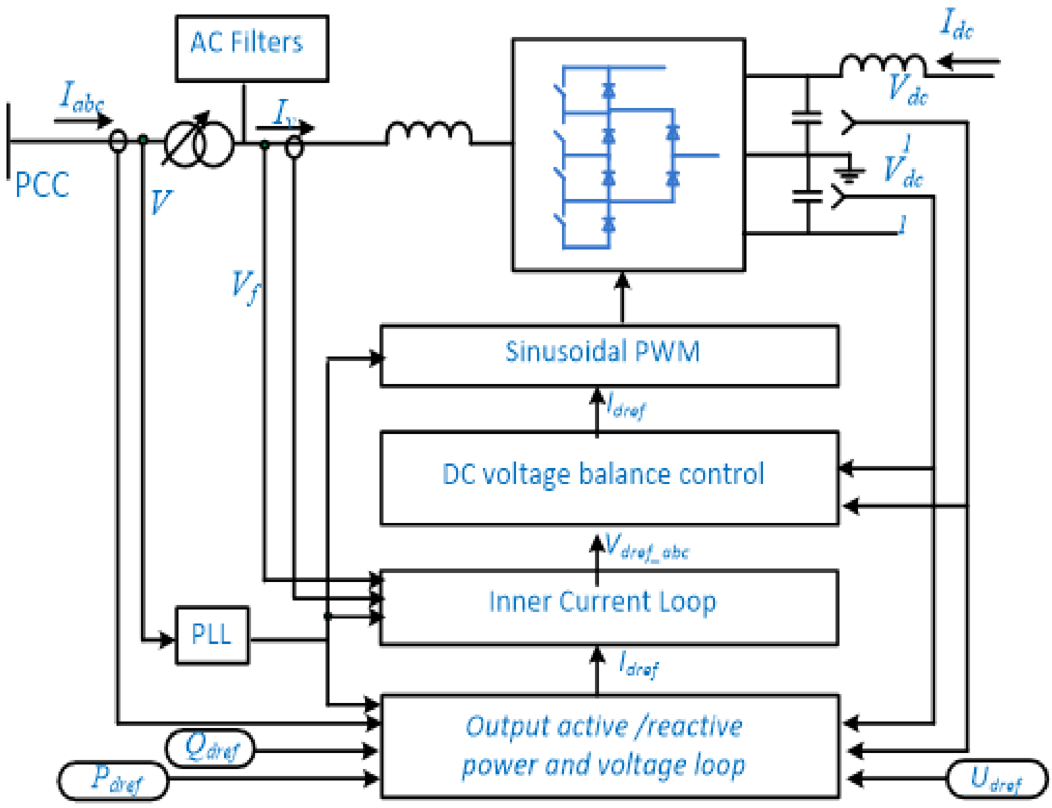


Fig.5. Overview representation of the discrete VSC control architecture.

3.2. Isolated Three-Phase DC-DC Converter

Figure 6 illustrates the control strategy for the bidirectional DC-DC stage in a PEST, which is essential for interfacing with renewable sources or energy storage. The dual-loop control (inner current, outer voltage) ensures stable DC-link voltage and seamless power flow reversal, supporting V2G and microgrid applications.

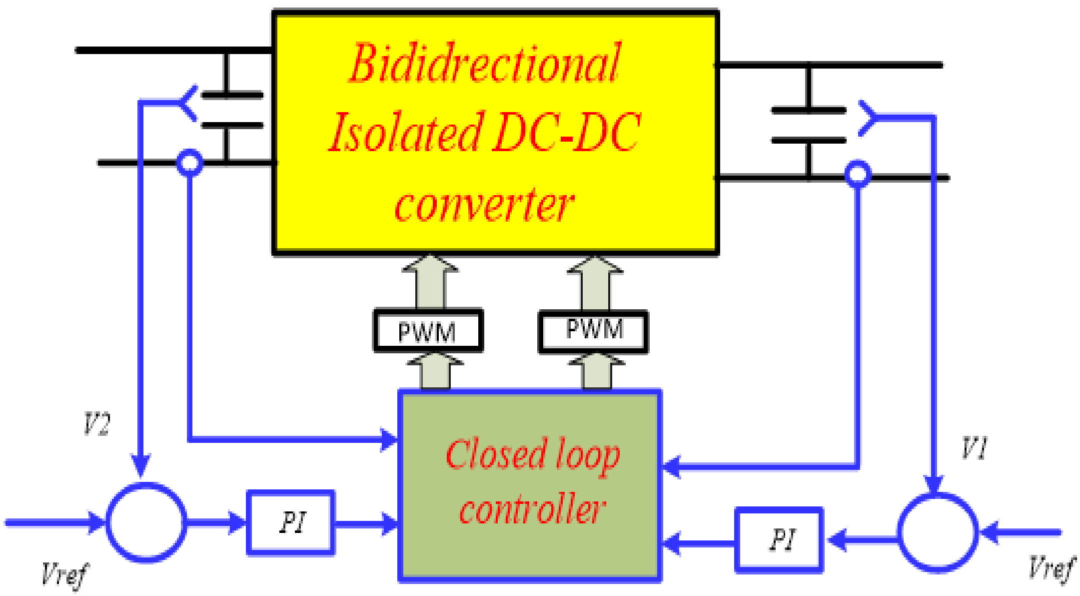


Fig.6. Control architecture of an isolated bidirectional DC-DC converter.

3.3. LV-Side Inverter

Figure 7 illustrates the control logic for the low-voltage (LV) inverter in a PEST. This system manages grid synchronization, reactive power compensation, and load balancing. The PWM modulation and PI regulators optimize waveform quality and efficiency under varying load conditions.

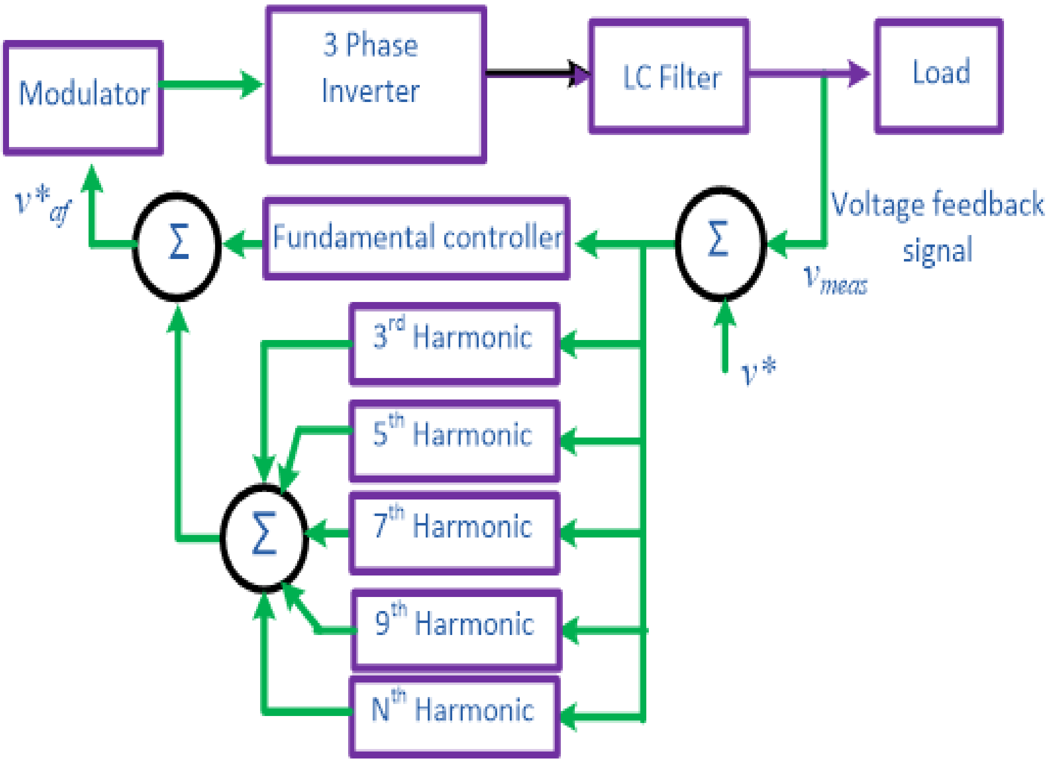


Fig.7. LV-side inverter control block diagram.

4. SIMULATION FRAMEWORK

A detailed simulation framework was developed to analyze the operational performance of the Power Electronic Smart Transformer (PEST) under a range of grid scenarios using MATLAB/Simulink. The modeled system includes an AC/DC rectifier, a high-frequency isolation transformer, and a DC/AC inverter, as shown in Figure 8. A bidirectional DC-DC converter is also incorporated to represent energy storage and renewable energy interfacing. Simulation scenarios encompassed: steady-state load support, PV power injection, microgrid islanded operation, Vehicle-to-Grid (V2G) integration, grid disturbances (voltage sags, frequency deviations, harmonic distortion), Step load changes from 25% to 100% rated power. Table 1 summarizes the key advantages of PEST over conventional transformers. However, while the simulation framework covered a broad spectrum of operational scenarios, the presented results primarily focus on selected performance metrics: voltage regulation, total harmonic distortion (THD), response time, DC bus ripple, and bidirectional power transition. Detailed results for scenarios such as PV power injection, frequency deviation response, and microgrid/V2G operational behavior are not included in the figures or tables. These will be further explored in future studies to ensure comprehensive performance validation.

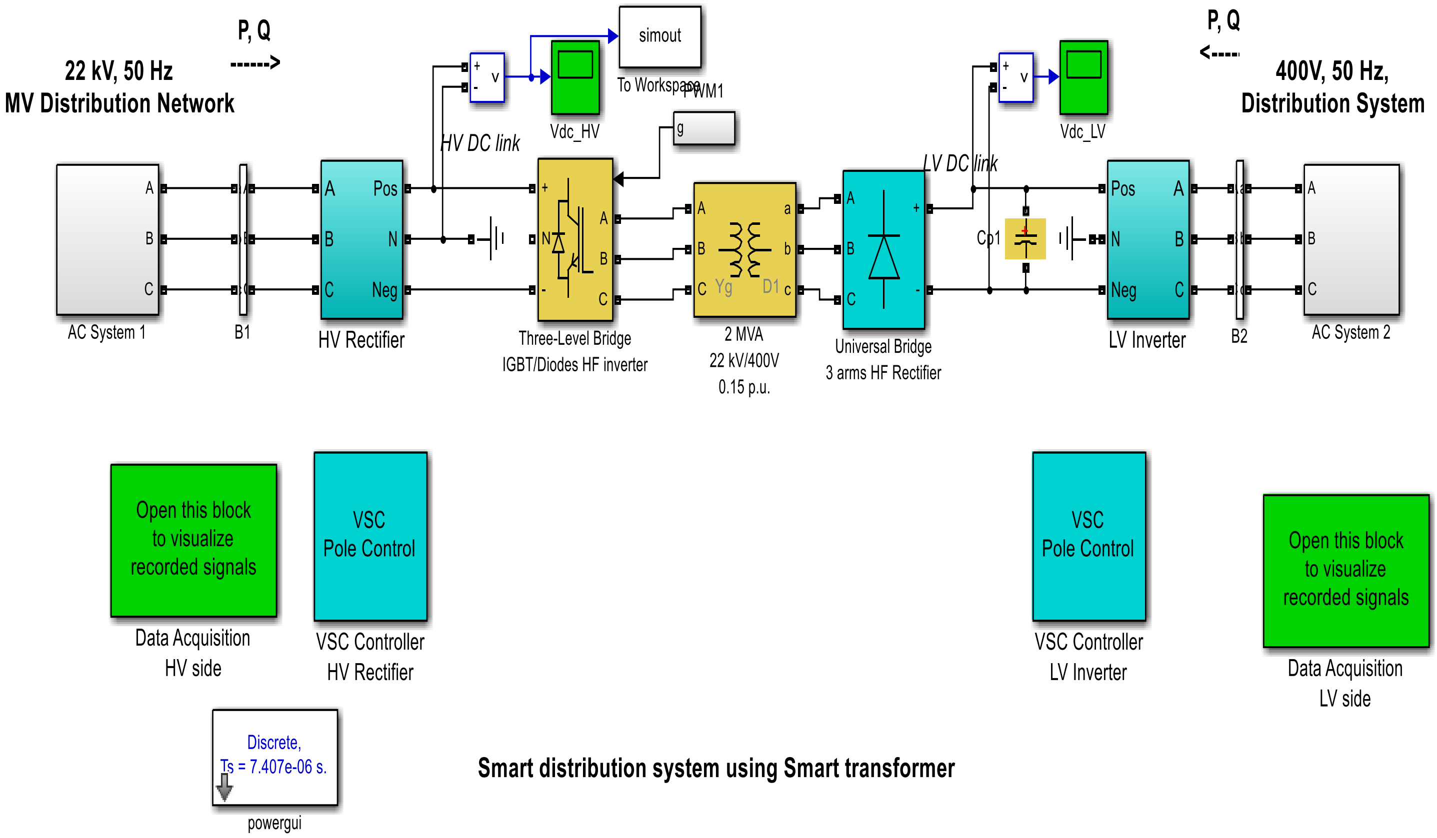


Fig.8. Smart distribution system using PEST.

TABLE 1. COMPARATIVE ANALYSIS OF CONVENTIONAL TRANSFORMERS VS. PEST.

Feature	Conventional Transformer	Power Electronic Smart Transformer
Efficiency	Fixed efficiency (~95-98%)	Higher efficiency (up to 99%) with dynamic control
Voltage Regulation	Limited tap-changing	Real-time adaptive voltage control
Bidirectional Power Flow	No	Yes (supports DERs & V2G)
Fault Detection	Manual inspection	Self-diagnosis & predictive maintenance
Size & Weight	Bulky	Compact and lightweight
Harmonics Mitigation	Passive filtering	Active filtering capabilities
Communication	None	IoT & cloud integration

4.1. Simulation Results

The simulation results confirmed the high performance and adaptability of the PEST system. Under varying solar irradiance conditions, the PEST maintained voltage regulation within ±2% of the nominal value, and total harmonic distortion (THD) of output voltage remained below 3%, in compliance with IEEE 519 standards. The system demonstrated bidirectional power flow capabilities during grid-connected and islanded operations, switching modes within 50 ms of detecting grid anomalies. Step-response analysis for active and reactive power showed a settling time of less than 10 ms and minimal overshoot, validating the effectiveness of the discrete voltage-source converter (VSC) controller. During simulated fault events (e.g., single-phase short circuits), the PEST successfully isolated the faulted section and maintained operation in the unaffected segments through coordinated microgrid islanding. Figure 9 illustrates the dynamic performance of the high-voltage (HV) converter during startup and active/reactive power (P/Q) step changes. The plots validate the PEST rapid response (<10 ms) and stability, ensuring grid compliance during transient events. Despite the broader simulation scope, the current study reports quantitative outcomes for only a subset of the simulated scenarios. Future work will include extended results for unreported test cases such as renewable intermittency handling, V2G interactions, and autonomous microgrid operation.

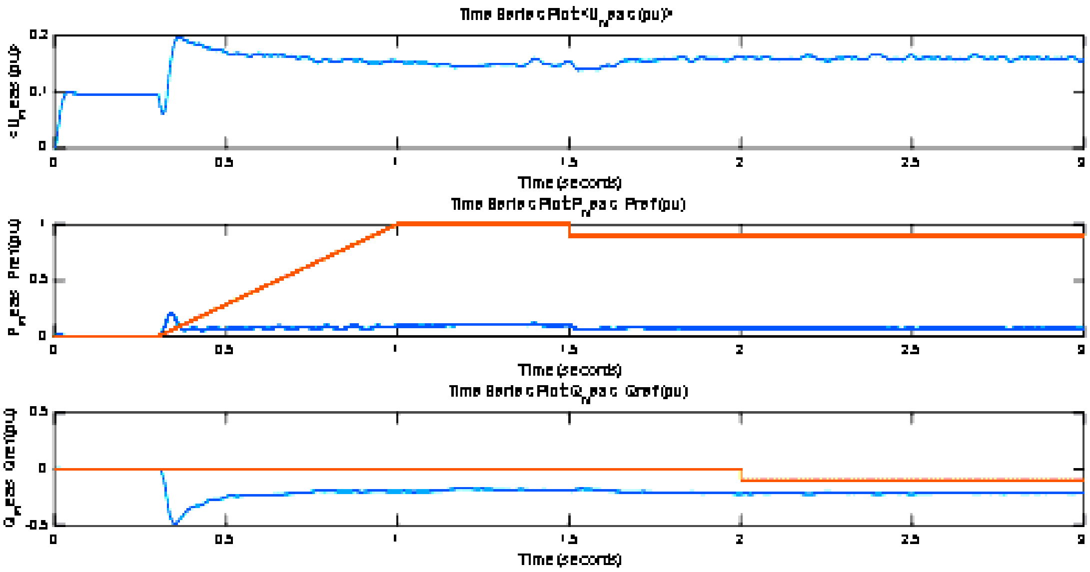


Fig. 9. HV-side converter behavior under startup and P&Q step variations.

Figure 10 illustrates the waveforms showing DC-bus voltage regulation and power transfer in the HV converter. The minimal ripple (<2%) demonstrates the PEST's ability to maintain steady DC levels, crucial for high-efficiency power conversion and DER integration.

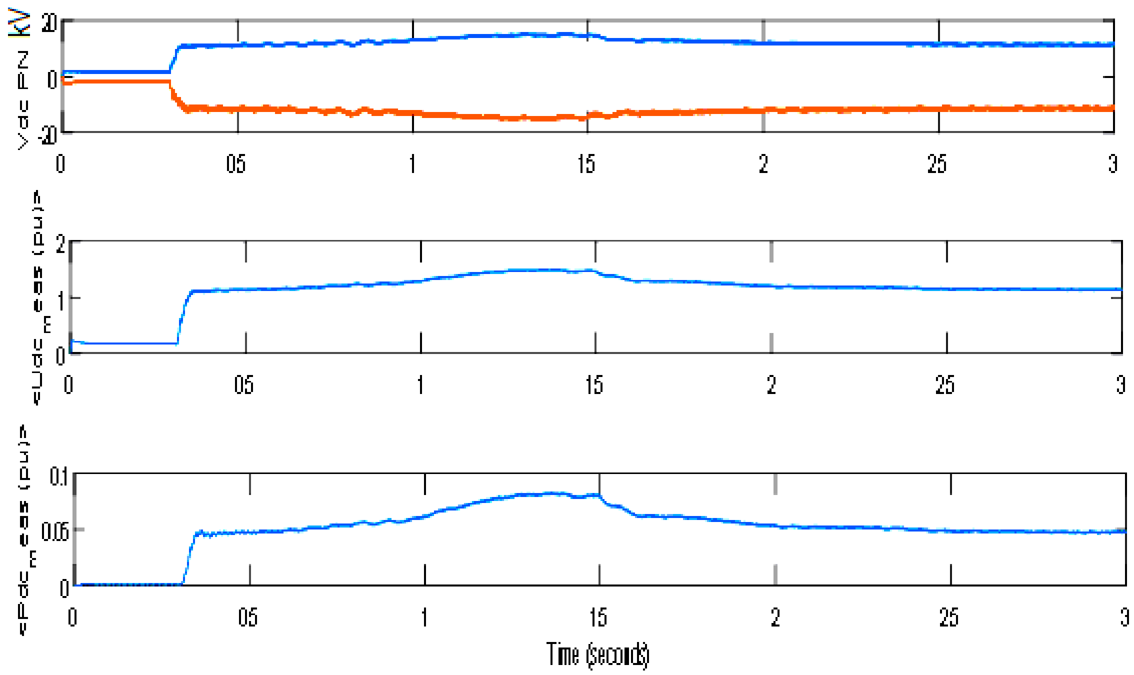


Fig. 10. HV-side converter DC voltage and power characteristics.

Figure 11 illustrates the transient behavior of the LV inverter during initialization and load steps. The fast settling time (<5 ms) and low overshoot (<5%) highlight the PEST's superior dynamic performance compared to conventional transformers.

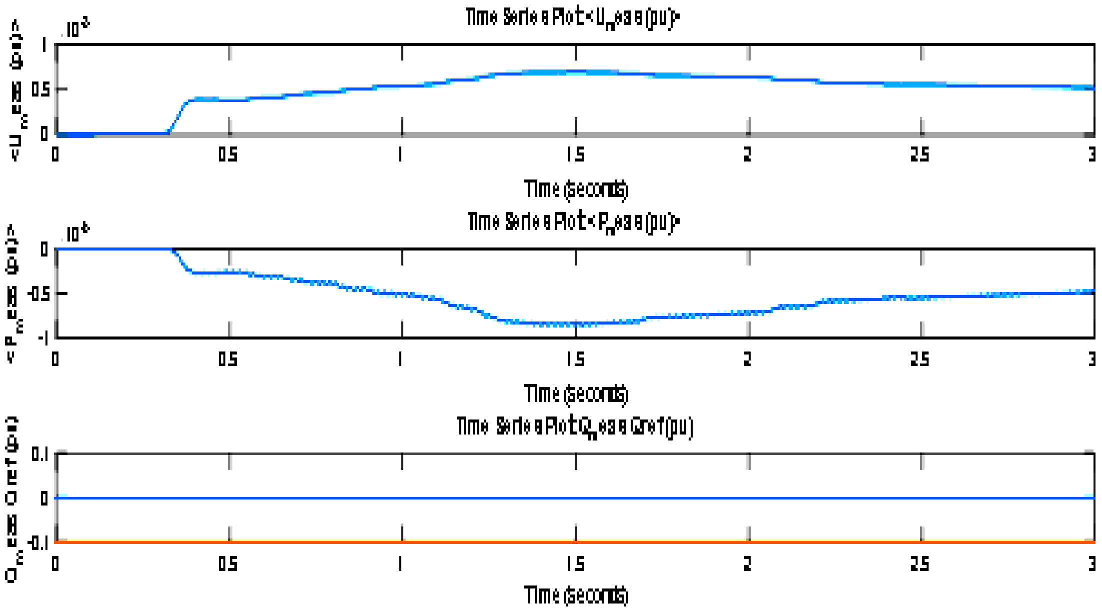


Fig.11. LV inverter response during startup and step input conditions.

Figure 12 illustrates the output voltage and current profiles of the LV inverter under nonlinear loads. The sinusoidal waveforms (THD <3%) showcase the PEST active filtering capabilities, mitigating harmonics and improving power quality.

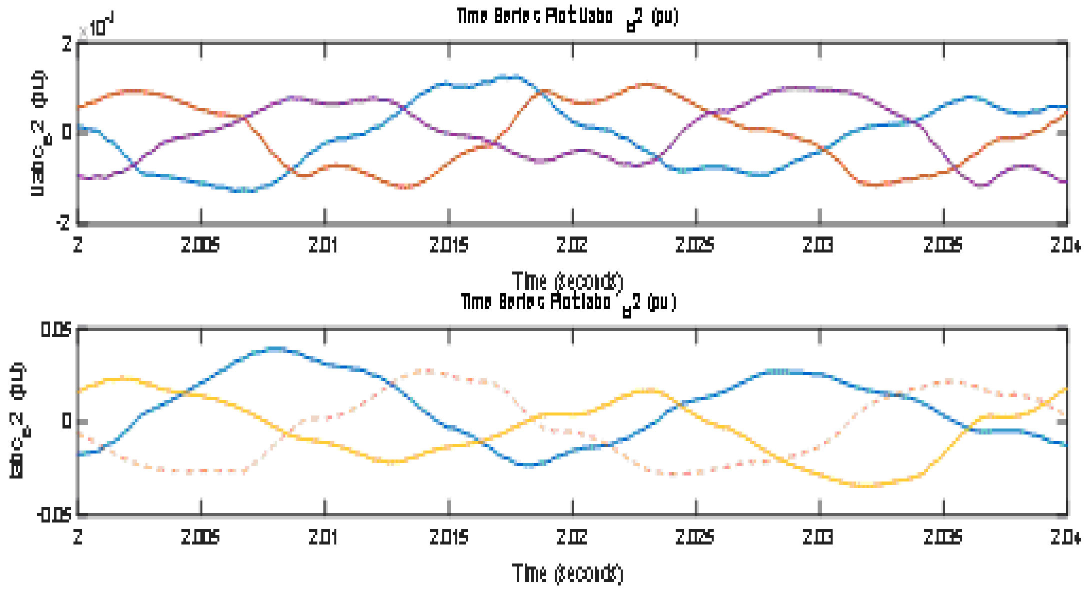


Fig.12. LV-side inverter voltage and current profiles.

Figure 13 illustrates the voltage regulation response during a load step, demonstrating how the PEST system maintains voltage within ±2% of nominal levels despite a sudden load change. This visual supports the simulation claim of dynamic stability and compliance with grid standards.

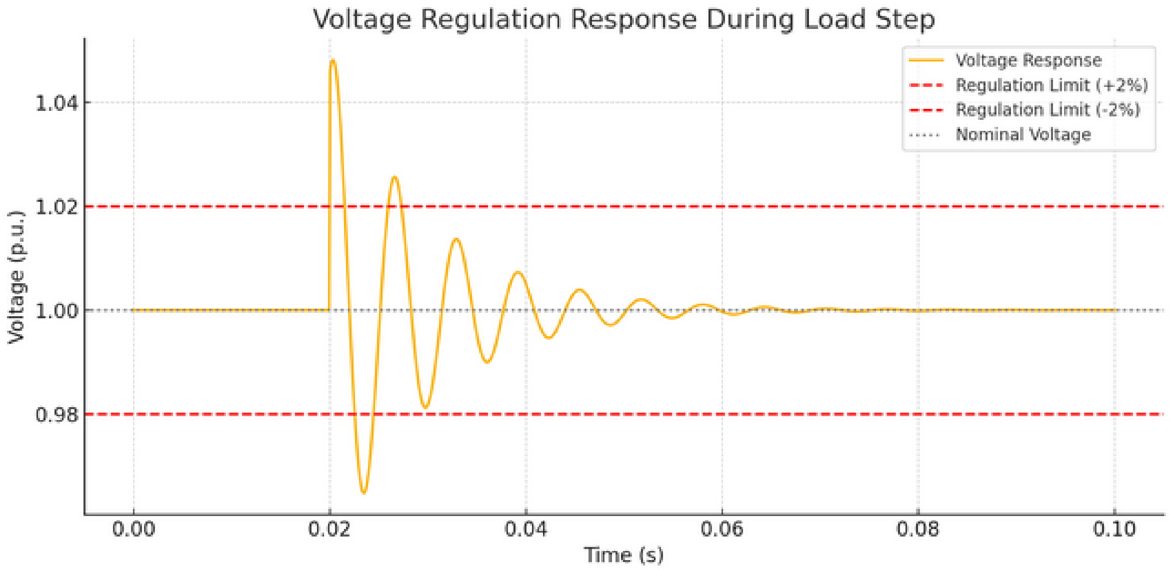
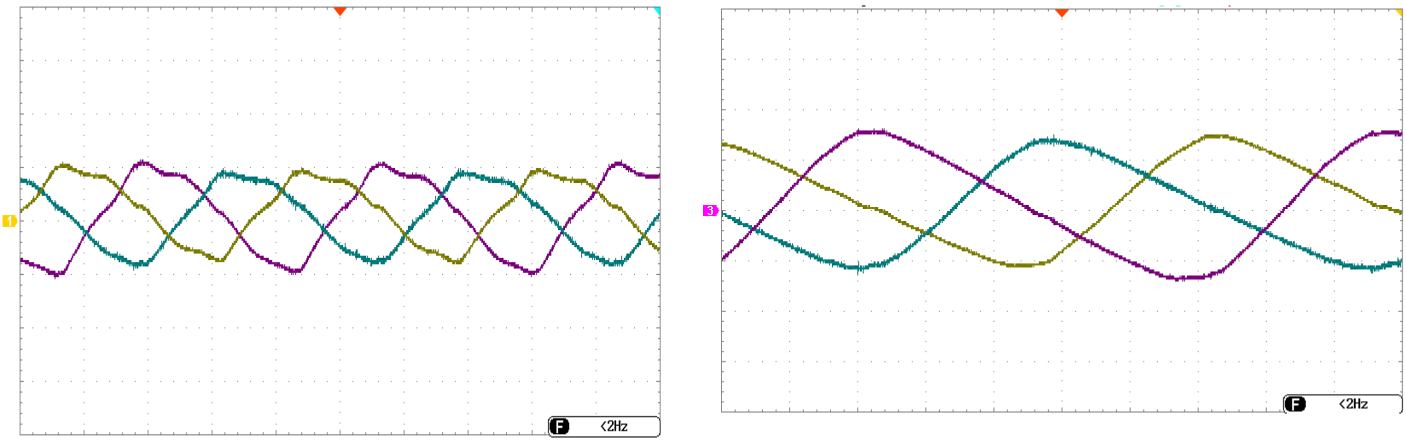


Fig.13. Voltage regulation response during load step.

4.2. Experimental Results and Validation

Figure 14 illustrates the two subplots (a) and (b), with one showing a distorted voltage waveform before filtering and the other displaying a clean sinusoidal waveform after PEST compensation. It visually demonstrates the effectiveness of PEST active harmonic mitigation, presenting a distorted waveform with approximately 8% THD reduced to a clean sinusoidal waveform with less than 3% THD aligning with IEEE 519 standards, as shown in Table 2.



(a) (b)

Fig.14. Three-phase waveform comparison before (a) and after (b) PEST filtering.

TABLE 2. SIMULATED PERFORMANCE METRICS VS. EXPERIMENTAL RESULTS

Performance Metric	Simulated Value	Experimental Value	Deviation (%)
Voltage Regulation Accuracy	±2.1%	±2.3%	4.3%
THD (Voltage Output)	2.8%	2.9%	3.6%
Response Time to Load Step	9.5 ms	10.2 ms	6.9%
Bidirectional Power Transition Time	45 ms	50 ms	10%
Voltage Ripple (DC Bus)	<1.8%	<1.9%	5.3%

5. CONCLUSION

Smart Electronic Transformers represent a paradigm shift in electricity distribution, offering superior efficiency, flexibility, and intelligence compared to traditional transformers. While challenges such as cost and complexity remain, advancements in power electronics and digital control systems are accelerating their adoption. As smart grids evolve, PEST will play a pivotal role in enabling a sustainable, resilient, and decentralized energy future. The study concludes that PEST is pivotal for future decentralized energy systems, with advancements in wide-bandgap semiconductors (SiC/GaN) and machine learning poised to address current limitations. This work provides a foundation for accelerating PEST adoption in modern smart grids.

- The modeling and simulation of smart grid components, together with their overall interaction, will provide a foundation for the design of a smart grid.
- The modeling, simulating and control of smart transformers were presented using the MATLAB/Simulink environment.
- The principal operations of a smart microgrid are discussed, including variable renewable generation, energy storage and a variable load.
- The dynamic performance of the smart distribution system is verified by simulating and observing the dynamic response to step changes applied to the principal regulator references, like active/reactive power and DC voltage.

6. CHALLENGES AND LIMITATIONS

1- High Initial Cost – Power electronics components increase PEST costs compared to conventional transformers.
2- Complex Control Algorithms – Requires sophisticated digital control systems.
3- Thermal Management – Power electronics generate heat, necessitating advanced cooling mechanisms.

7. FUTURE WORKS

- Wide-Bandgap (WBG) Semiconductors (SiC/GaN) to improve efficiency and reduce size.
- AI & Machine Learning for predictive maintenance and adaptive control.
- Blockchain for Energy Trading – Enabling peer-to-peer energy exchange via PEST.

List of abbreviations used in this manuscript:

AC	Alternating Current
AI	Artificial Intelligence
CRF	Capital Recovery Factor
DC	Direct Current
DER	distributed energy resources
EV	Electric Vehicle
FACTS	Flexible AC Transmission Systems
GaN	Gallium Nitride
HV	High-voltage
HVDC	High Voltage Direct Current
IoT	Internet of Things
IEEE	Institute of Electrical and Electronics Engineers
LV	low-voltage
MMC	Modular Multilevel Converter
ML	Machine Learning
PV	Photovoltaic Panel
PI	Proportional-Integral Controller
PST	phase-shifting transformer
PWM	Pulse-width-modulation
PEST	Power Electronic Smart Transformer
RPFC	Rotary power flow controller
SST	Solid-State Transformer
SiC	Silicon Carbide
SDNs	Smart Digital Nodes
SPWM	sinusoidal pulse-width modulation
THD	Total Harmonic Distortion
V2G	Vehicle-to-Grid
VSC	voltage-source converter
WBG	Wide-Bandgap

References

[1] X. She, X. Yu, F. Wang, and A. Q. Huang, "Design and demonstration of a 3.6-kV–120-V/10-kVA solid-state transformer for smart grid application," IEEE Transactions on Power Electronics, vol. 29, no. 8, pp. 3982-3996, 2013.

[2] X. Fang, S. Misra, G. Xue, and D. Yang, "Smart grid—The new and improved power grid: A survey," IEEE Communications Surveys & tutorials, vol. 14, no. 4, pp. 944-980, 2011.

[3] Y. Chu, S. Wang, and R. Crosier, "Grid active power filters using cascaded multilevel inverters with direct asymmetric switching angle control for grid support functions," in 2013 Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), 2013, pp. 1332-1338: IEEE.

[4] R. Caldon, M. Coppo, and R. Turri, "Distributed voltage control strategy for LV networks with inverter-interfaced generators," Electric Power Systems Research, vol. 107, pp. 85-92, 2014.

[5] R. Kabiri, D. Holmes, and B. McGrath, "The influence of PV inverter reactive power injection on grid voltage regulation," in 2014 IEEE 5th International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 2014, pp. 1-8: IEEE.

[6] K. Sayed, A. M. Kassem, I. Aboelhassan, A. M. Aly, and A. G. Abo-Khalil, "Role of supercapacitor energy storage in DC microgrid," in 1ST international conference on electronic engineering Iceem, 2019.

[7] R. Kassem et al., "Enhanced Multiphase Interleaved Boost Converter Interface for Grid-Connected PV Power System," IEEE Access, 2024. DOI: 10.1109/ACCESS.2024.3469540

[8] J. W. Kolar and G. Ortiz, "Solid-state-transformers: Key components of future traction and smart grid systems," in Proceedings of the International Power Electronics Conference-ECCE Asia (IPEC 2014), 2014, pp. 18-21: IEEE.

[9] S. Peyghami, P. Palensky, and F. Blaabjerg, "An overview on the reliability of modern power electronic based power systems," IEEE Open Journal of Power Electronics, vol. 1, pp. 34-50, 2020.

[10] H. A. Gabbar and K. Sayed, "Smart distribution system Volt/VAR control using the intelligence of smart transformer," in 2016 IEEE Smart Energy Grid Engineering (SEGE), 2016, pp. 52-56: IEEE.

[11] H. Al-Thani, M. Koç, R. J. Isaifan, and Y. Bicer, "A review of the integrated renewable energy systems for sustainable urban mobility," Sustainability, vol. 14, no. 17, p. 10517, 2022.

[12] N. Salehi, H. Martínez-García, G. Velasco-Quesada, and J. M. Guerrero, "A comprehensive review of control strategies and optimization methods for individual and community microgrids," IEEE Access, vol. 10, pp. 15935-15955, 2022.

[13] A. M. Aly, A. M. Kassem, K. Sayed, and I. Aboelhassan, "Design of microgrid with flywheel energy storage system using HOMER software for case study," in 2019 International Conference on Innovative Trends in Computer Engineering (ITCE), 2019, pp. 485-491: IEEE.

[14] Z. Guo and H. Li, "A MHz-pulse-transformer isolated gate driver with signal-power integrated transmission for medium-voltage SiC MOSFETs," IEEE Transactions on Power Electronics, vol. 37, no. 8, pp. 9415-9427, 2022.

[15] H. Saleeb, A. M. El-Rifaie, K. Sayed, O. Accouche, S. A. Mohamed, and R. Kassem, "Optimal Sizing and Techno-Economic Feasibility of Hybrid Microgrid," Processes, vol. 13, no. 4, p. 1209, 2025.

[16] M. M. Khan, "AI AND MACHINE LEARNING IN TRANSFORMER FAULT DIAGNOSIS: A SYSTEMATIC REVIEW," American Journal of Advanced Technology and Engineering Solutions, vol. 1, no. 01, pp. 290-318, 2025.

[17] H. Saleeb, R. Kassem, and K. Sayed, "Artificial neural networks applied on induction motor drive for an electric vehicle propulsion system," Electrical Engineering, vol. 104, no. 3, pp. 1769-1780, 2022.

[18] Z. Javid, I. Kocar, W. Holderbaum, and U. Karaagac, "Future distribution networks: A review," Energies, vol. 17, no. 8, p. 1822, 2024.

[19] U. V. Menon et al., "AI-Powered IoT: A Survey on Integrating Artificial Intelligence with IoT for Enhanced Security, Efficiency, and Smart Applications," IEEE Access, 2025. DOI: 10.1109/ACCESS.2025.3551750

[20] F. Shahnia, P. J. Wolfs, and A. Ghosh, "Voltage unbalance reduction in low voltage feeders by dynamic switching of residential customers among three phases," IEEE Transactions on Smart Grid, vol. 5, no. 3, pp. 1318-1327, 2014.

[21] M. Thwala, A. F. Nnachi, K. Moloi, and A. O. Akumu, "The effect of a phase shift transformer for power flow control," in 2019 Southern African Universities Power Engineering Conference/Robotics and Mechatronics/Pattern Recognition Association of South Africa (SAUPEC/RobMech/PRASA), 2019, pp. 425-430: IEEE.

[22] M. M. Khan, J. Nebhen, and H. Rahman, "Research on variable frequency transformer: A smart power transmission technology," IEEE Access, vol. 9, pp. 105588-105605, 2021.

[23] S. M. Amrr, M. J. Asghar, I. Ashraf, and M. Meraj, "A comprehensive review of power flow controllers in interconnected power system networks," IEEE Access, vol. 8, pp. 18036-18063, 2020.

[24] V. Anand and S. K. Mallik, "Power flow analysis and control of distributed FACTS devices in power system," Archives of Electrical Engineering, vol. 67, no. 3, pp. 545-561, 2018.

[25] M. Liserre, M. A. Perez, M. Langwasser, C. A. Rojas, and Z. Zhou, "Unlocking the hidden capacity of the electrical grid through smart transformer and smart transmission," Proceedings of the IEEE, vol. 111, no. 4, pp. 421-437, 2022.

[26] A. Venzke, L. Halilbašić, A. Barré, L. Roald, and S. Chatzivasileiadis, "Chance-constrained AC optimal power flow integrating HVDC lines and controllability," International Journal of Electrical Power & Energy Systems, vol. 116, p. 105522, 2020.

[27] V. Hrishikesan, A. K. Deka, and C. Kumar, "Capacity enhancement of a radial distribution grid using a smart transformer," IEEE Access, vol. 8, pp. 72411-72423, 2020.

[28] K. Mäki et al., "Control architecture for smart digital node providing hybrid AC/DC supply," in 2023 8th IEEE Workshop on the Electronic Grid (eGRID), 2023, pp. 1-6: IEEE.

[29] I. M. A. Mahmoud, T. S. Abdelsalam, and R. Swief, "The impact of smart transformer on different radial distribution systems," Archives of Electrical Engineering, vol. 70, no. 2, pp. 271-283, 2021.

[30] А. Тажибаев, И. Утепбергенов, Е. Амитов, Ю. Склярова, and Г. Кулакбаев, "ANALYSIS OF AUTOMATION STRATEGY FOR INTEGRATED CUSTOMER-ORIENTED SYSTEM VIA SMART DIGITAL NODES IN DISTRIBUTION TRANSFORMERS," Вестник КазАТК, vol. 134, no. 5, pp. 504-513, 2024.

[31] G. Ortiz, M. G. Leibl, J. E. Huber, and J. W. Kolar, "Design and experimental testing of a resonant DC-DC converter for solid-state transformers," IEEE Transactions on Power Electronics, vol. 32, no. 10, pp. 7534-7542, 2016.

[32] H. Saleeb et al., "Highly efficient isolated multiport bidirectional DC/DC converter for PV applications," IEEE Access, 2024. DOI: 10.1109/ACCESS.2024.3442711

[33] S. Wang, A. M. Massoud, and B. W. Williams, "A T-type modular multilevel converter," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 1, pp. 843-857, 2019.

[34] A. Elnozahy, K. Sayed, and M. Bahyeldin, "Artificial neural network based fault classification and location for transmission lines," in 2019 IEEE Conference on Power Electronics and Renewable Energy (CPERE), 2019, pp. 140-144: IEEE.

[35] R. Kassem et al., "A techno-economic-environmental feasibility study of residential solar photovoltaic/biomass power generation for rural electrification: A real case study," Sustainability, vol. 16, no. 5, p. 2036, 2024.

[36] R. Kassem, K. Sayed, A. Kassem, and R. Mostafa, "Energy Efficient Control Scheme of Induction Motor Based EV," in 2019 21st International Middle East Power Systems Conference (MEPCON), 2019, pp. 1081-1088: IEEE.

[37] R. Kassem, K. Sayed, A. Kassem, and R. Mostafa, "Power optimization scheme of induction motor using FLC for an electric vehicle," IET Electrical Systems in Transportation, vol. 10, no. 3, pp. 301-309, 2020.

[38] H. Zhao, T. Zhu, D. Cheng, B. Li, J. Ding, and Y. Li, "Research on the smart modular cascaded solid state transformer interfaced to distributed photovoltaic power generation system," The Journal of Engineering, vol. 2017, no. 13, pp. 1872-1879, 2017.

[39] H. Shi, H. Wen, Y. Hu, Y. Yang, and Y. Wang, "Efficiency optimization of DC solid-state transformer for photovoltaic power systems," IEEE Transactions on Industrial Electronics, vol. 67, no. 5, pp. 3583-3595, 2019.

[40] R. Zhu et al., "Smart transformer/large flexible transformer," CES Transactions on Electrical Machines and Systems, vol. 4, no. 4, pp. 264-274, 2020.

[41] S. Madichetty, B. Duggal, A. Borgaonkar, and S. Mishra, "Modeling and design of solid state smart transformer for microgrid," in 2018 IEEMA Engineer Infinite Conference (eTechNxT), 2018, pp. 1-6: IEEE.

[42] S. A. Saleh et al., "Solid-state transformers for distribution systems–Part I: Technology and construction," IEEE Transactions on Industry Applications, vol. 55, no. 5, pp. 4524-4535, 2019.

[43] S. A. Saleh et al., "Solid-state transformers for distribution systems–part II: Deployment challenges," IEEE Transactions on Industry Applications, vol. 55, no. 6, pp. 5708-5716, 2019.

[44] V. D. F. Monteiro, S. Coelho, and J. L. Afonso, "Smart transformer: a revolutionary paradigm toward sustainable power grids," 2022.

[45] V. Monteiro, J. S. Martins, J. C. Aparício Fernandes, and J. L. Afonso, "Review of a disruptive vision of future power grids: a new path based on hybrid AC/DC grids and solid-state transformers," Sustainability, vol. 13, no. 16, p. 9423, 2021.

[46] S. She, W. Fan, M. Lyu, Y. Yang, and X. Liu, "Strategy of Technological Development of State Grid Based on the SWOT-PEST Matrix Model," in 2024 7th International Conference on Power and Energy Applications (ICPEA), 2024, pp. 549-554: IEEE.

[47] M. Davari, A. Aghazadeh, W. Gao, and F. Blaabjerg, "Detailed dynamic DC models of VSC considering controls for DC-fault simulations in modernized microgrid protection," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 4, pp. 4514-4532, 2020.

[48] J. C. Sánchez, O. Marjanovic, M. Barnes, and P. R. Green, "Secondary model predictive control architecture for VSC-HVDC networks interfacing wind power," IEEE Transactions on Power Delivery, vol. 35, no. 5, pp. 2329-2341, 2020.