American Journal of Scholarly Research and Innovation
Volume 01, Issue 01 (2022)
Page No: 186-219
eISSN: 3067-2163
Doi: 10.63125/6n1yka80

Article

A SYSTEMATIC LITERATURE REVIEW ON ENERGY-EFFICIENT TRANSFORMER DESIGN FOR SMART GRIDS

M A Masud Khan[1]; Roksana Haque[2]; Ammar Bajwa[3]

[1]Manager Grade-1, Production & Marketing, Sena Kalyan Electric Industries (SKEI), Bangladesh
Email: khan.bangladesh007@gmail.com

[2]Apex Footwear limited, Dhaka, Bangladesh
Email: roksanahaque89@gmail.com

[3]Instrumentation and Control Engineer, Al Majal Al Arabi Group, Saudi Arabia
Email: ammar.bajwa1@gmail.com

ABSTRACT

This systematic literature review presents a comprehensive analysis of contemporary developments in energy-efficient transformer design tailored for integration within modern smart grid infrastructures. As the global energy landscape transitions toward decentralized, intelligent, and low-carbon systems, the operational expectations for transformers have expanded considerably. No longer limited to conventional voltage regulation, transformers must now address fluctuating load profiles, reverse power flows from distributed energy resources, harmonic distortion, and integration with digital monitoring and control frameworks. This review systematically evaluates the current state of research by analyzing 87 peer-reviewed articles published between 2013 and 2022, selected through a rigorous process guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 protocol. The review investigates several key dimensions of transformer innovation, including the adoption of amorphous and nanocrystalline core materials for core loss reduction, the deployment of high-temperature superconducting windings for enhanced load efficiency, and the rapid evolution of solid-state transformer architectures enabling bidirectional and high-frequency operation. It also explores the application of IoT and wireless sensor networks in condition monitoring, contributing to improved predictive maintenance and reduced lifecycle costs. Furthermore, the analysis highlights the convergence of technical innovation with environmental priorities, as evidenced by the increasing use of biodegradable ester fluids, modular eco-designs, and life-cycle assessment (LCA) frameworks aimed at reducing carbon footprints and improving recyclability. In addition to synthesizing advancements, the review identifies underexplored areas in the existing literature, such as the scarcity of long-term performance evaluations, limited empirical testing under fault or abnormal conditions, integration complexities in hybrid designs, and region-specific barriers in infrastructure and policy adoption. By consolidating these insights, the review provides an essential reference point for researchers, engineers, utility planners, and policymakers seeking to optimize transformer performance, support regulatory compliance, and enable the evolution of sustainable, resilient, and future-ready power distribution systems.

KEYWORDS

Energy-Efficient Transformers; Smart Grid Integration; Transformer Design Optimization; Solid-State Transformers; Amorphous Core Materials;

Citation:
Khan, M. A. M., Haque, R., & Bajwa, A. (2022). *A systematic literature review on energy-efficient transformer design for smart grids*. *American Journal of Scholarly Research and Innovation*, *1*(1), 186–219. https://doi.org/10.63125/6n1yka80

Received:
September 13, 2022

Revised:
October 10, 2022

Accepted:
November 24, 2022

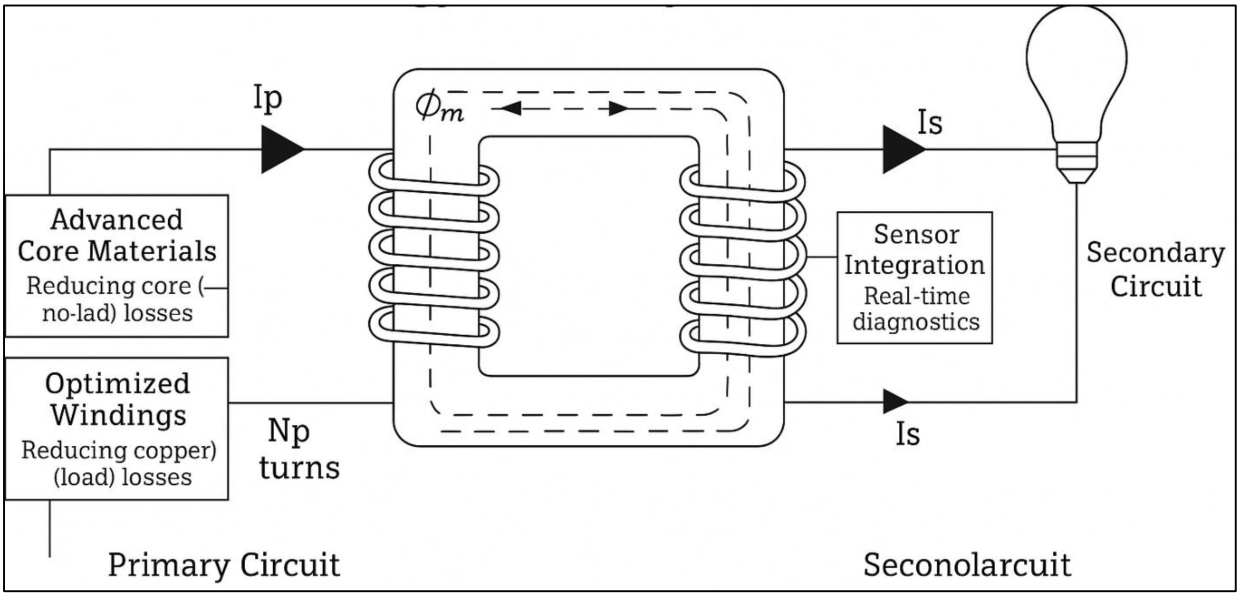
Published:
December 17, 2022

American Journal of Scholarly Research and Innovation
Volume 01, Issue 01 (2022)
Page No: 186-219
eISSN: 3067-2163
Doi: 10.63125/6n1yka80

INTRODUCTION

Transformers are static electrical devices that transfer electrical energy between two or more circuits through electromagnetic induction (Si et al., 2021). They are critical in the transmission and distribution networks for voltage regulation and load balancing (Dias et al., 2017). Energy efficiency in transformers refers to the ability to minimize power losses during operation, primarily no-load (core) losses and load (copper) losses (Zhang et al., 2018). The term "smart grid" refers to an electrical grid enhanced with digital communications, automation, and advanced controls that facilitate real-time monitoring, bidirectional energy flow, and integration of renewable energy sources (Naseer et al., 2021). Within smart grids, transformers are not only passive energy-conversion devices but active agents equipped with sensors, adaptive controls, and diagnostics for real-time load management and predictive maintenance (Hasankhani et al., 2021). Smart grid transformers must operate efficiently under varying load conditions while supporting distributed generation and advanced demand-response functionalities (Zhang et al., 2019). Energy-efficient transformer design focuses on material improvements, topology optimization, and intelligent embedded systems to minimize losses and extend the lifecycle (Naseer et al., 2021). This foundational understanding underpins the critical role of transformer innovation in achieving energy security, minimizing transmission losses, and facilitating decentralized electricity management in modern grid systems.

Figure 1: Smart Grid Transformer Working Principle: Energy-Efficient Design and Functional Integration



Globally, the electricity sector accounts for a substantial proportion of total energy consumption and carbon emissions, with transformers constituting a significant share of distribution-level inefficiencies (Chen et al., 2018). International standards, such as those introduced by the International Electrotechnical Commission (IEC) and U.S. Department of Energy (DOE), have mandated minimum efficiency performance standards (MEPS) for transformer manufacturers to reduce these losses. For instance, the European Union's EcoDesign Directive has pushed manufacturers toward lower-loss materials, intelligent control systems, and recyclable insulation components (Si et al., 2021). In emerging economies, initiatives such as India's Perform, Achieve and Trade (PAT) Scheme and China's Green Energy Efficiency Labeling Program promote transformer retrofitting and adoption of advanced distribution transformers ((Ahmad et al., 2017). These global policy frameworks signify an aligned interest among nations to reduce grid losses and enhance electrical system efficiency through transformative design (Guan et al., 2017). The strategic role of transformers in meeting national sustainability and energy transition goals has elevated their redesign into a priority research area, backed by funding programs, innovation consortia, and transnational collaborations (Di Santo et al., 2018). The international significance lies not only in environmental impacts but also in the economic benefits derived from lifetime energy savings, reduced maintenance, and optimized grid performance ((Xu et al., 2021).

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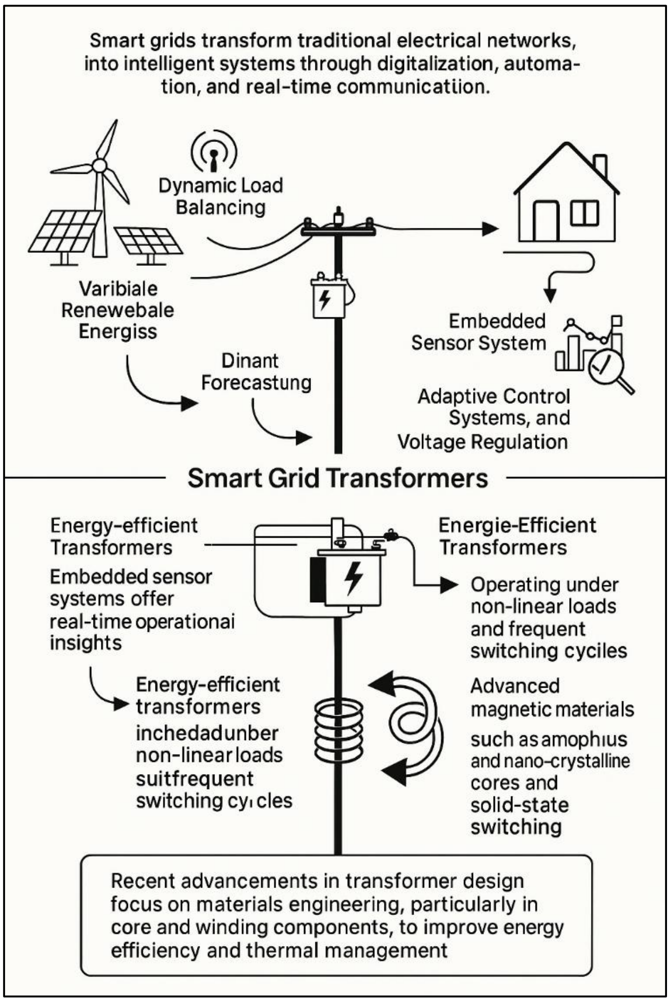
Figure 2: Evolution of Transformer Technology in the Smart Grid: From Conventional Networks to Intelligent Energy Systems



Smart grids transform traditional electrical networks into intelligent systems through digitalization, automation, and real-time communication, demanding a corresponding evolution in transformer technology (Lin & Tsai, 2015). Transformers in smart grids must support dynamic load balancing, integrate variable renewable energy sources, and offer real-time operational insights via embedded sensor systems (Dehghanpour et al., 2018). Their role expands to facilitating load forecasting, grid fault detection, and voltage regulation, which necessitates adaptive control systems and machine-learning-based predictive maintenance modules (Tom et al., 2020). Energy-efficient transformers embedded within the smart grid must be capable of operating under non-linear loads and frequent switching cycles, which introduces thermal and dielectric stresses (Abid & Hasan, 2018). Integration challenges are further complicated by distributed generation, such as rooftop photovoltaics and electric vehicle charging stations, which impose reverse power flows and harmonic distortions (Ahmad et al., 2021). Transformer design must therefore incorporate advanced magnetic materials, such as amorphous and nano-crystalline cores, and solid-state switching technologies that reduce eddy current losses and electromagnetic interference (Li et al., 2019). Their strategic function within the smart grid positions energy-efficient transformers as central to digital grid modernization initiatives, particularly under Industry 4.0 and Grid 2.0 frameworks (Yaacoub & Abu-Dayya, 2014). Recent advancements in transformer design emphasize materials engineering, particularly in core and winding components, to improve energy efficiency and thermal management (Ota et al., 2012). Amorphous metal cores exhibit low hysteresis loss and high electrical resistivity, reducing no-load losses by up to 70% compared to traditional silicon steel cores ((Yu et al., 2016). Additionally, high-temperature superconducting (HTS) windings have gained traction for their near-zero resistance and minimal I^2R losses, although challenges in cryogenic system integration persist (Pang et al., 2012). Innovative coil designs, including spiral and pancake windings, facilitate optimal current density distribution and minimize electromagnetic leakage fields (Kim et al., 2013). Use of advanced insulation systems—such as thermally upgraded cellulose and ester-based fluids—enhances dielectric strength and reduces thermal degradation (Zhang et al., 2018). These improvements contribute to longer service life and reduced energy dissipation, particularly under high-frequency and partial load conditions (Bhattarai et al., 2019). Finite Element Analysis (FEA)-based simulation tools have allowed researchers to optimize core cross-sections, reduce vibration-induced losses, and predict electromagnetic behavior with high precision (Musleh et al., 2019). Thus, material innovation and geometric optimization converge to define the current trajectory of energy-efficient transformer development.

Solid-state transformers (SSTs) represent a paradigm shift in transformer technology by utilizing power electronics to replace conventional magnetic and mechanical components (Erol-Kantarci & Mouftah, 2015). These devices employ insulated-gate bipolar transistors (IGBTs) or silicon carbide (SiC) MOSFETs for high-frequency switching, enabling compact size, reduced losses, and multi-functionality (Marian et al., 2020). SSTs also facilitate voltage regulation, reactive power compensation, and seamless DC–AC interfacing, making them ideal for integration with renewables and electric vehicles (Su et al., 2012). Embedded digital control systems within SSTs monitor temperature, load current, harmonics, and insulation health in real time, enhancing operational safety and preventive diagnostics (Marques et al., 2018). While SSTs currently face constraints in terms of cost, scalability, and fault tolerance, pilot implementations in microgrids and high-performance industrial setups show promising results (Zhou, Zheng & Zhang, 2020). Researchers have proposed hybrid transformers that combine conventional magnetic designs with modular power electronic converters to balance efficiency with resilience (Su et al., 2014).

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These advancements underscore a broader shift toward intelligent, software-defined transformers as essential infrastructure for digitalized electricity ecosystems (Di Somma et al., 2018).
Internet of Things (IoT) technologies have transformed the operation and maintenance of modern transformers by enabling condition-based monitoring and control (Donadee & Ilic, 2014). Sensors embedded within transformer tanks measure variables such as oil temperature, dissolved gas levels, vibration, and humidity, transmitting data to centralized or edge-based analytics platforms (Denholm et al., 2015). These data streams allow predictive fault diagnostics, optimize load tap changer operations, and trigger maintenance alerts, thus preventing catastrophic failures and extending asset life (Yang et al., 2015). Integration of digital twin technology further allows real-time simulation and virtual modeling of transformer behavior under different stress scenarios (Jow et al., 2017). Wireless sensor networks and 5G-based communication systems ensure low-latency feedback loops, especially in large-scale grid deployments (Ghosh & Sampalli, 2019). The combination of intelligent hardware and cloud-based software enables decentralized asset management, particularly in remote or underserved regions where grid operators lack on-site infrastructure (Nafi et al., 2016). Moreover, data collected from IoT-equipped transformers contribute to AI-driven decision-support systems that optimize network topology, detect anomalies, and dynamically balance loads (Shaukat et al., 2018). These applications mark a technological convergence of physical power systems with cyber-physical frameworks that underpin the resilience of smart grids.
The development and deployment of energy-efficient transformers are heavily guided by international standards, efficiency benchmarks, and harmonized testing protocols. Standards such as IEC 60076, IEEE C57, and DOE 2016 define permissible losses, insulation levels, and safety metrics under varying environmental and loading conditions. Transformer Energy Performance Standards (TEPS) have evolved to categorize devices based on energy-saving potential, noise levels, and environmental impact (Deng et al., 2015). These metrics guide procurement decisions by utilities and facilitate lifecycle cost analysis by considering not just upfront costs but long-term operating savings. Further, Life Cycle Assessment (LCA) methodologies have been applied to transformer systems to evaluate carbon footprints, recyclability, and embedded energy across production, use, and disposal stages (González et al., 2021). Testing platforms have moved toward digital validation environments using smart grid simulators and hardware-in-the-loop (HIL) systems for performance verification under real-world conditions (Tuna et al., 2017). Globally harmonized efficiency metrics and performance indices are thus instrumental in aligning research outputs with market adoption and regulatory approval . These frameworks collectively ensure that innovations in transformer design not only meet technical goals but also contribute to broader socio-economic and environmental benchmarks set by global energy policies.The principal objective of this systematic literature review is to comprehensively analyze, categorize, and synthesize existing scholarly contributions on energy-efficient transformer design in the context of smart grid integration. As smart grids become central to modern power infrastructure, there is a growing demand for transformers that can operate efficiently under dynamic, decentralized, and highly variable grid conditions. Traditional transformer architectures, which were designed for unidirectional and stable energy flows, are increasingly inadequate in managing the load variability, reverse power flows, and harmonic disturbances introduced by renewable energy sources and distributed energy systems. Therefore, the objective of this review is to explore how design improvements—particularly in materials, winding configurations, core topology, insulation systems, and embedded digital technologies—contribute to minimizing losses, enhancing thermal performance, and improving operational reliability. Specifically, the review seeks to address how energy-efficient transformers support voltage regulation, load balancing, and real-time diagnostics within intelligent grid environments. Furthermore, this study aims to identify the dominant technological trends, performance benchmarks, and regulatory frameworks that guide research and development in this area. Another core objective is to highlight research gaps in the literature, such as limited longitudinal studies, lack of standardized testing protocols for next-generation transformers, and insufficient empirical data on field performance of solid-state and digitally enhanced transformers. By synthesizing 87 peer-reviewed articles published between 2013 and 2022, this review intends to construct a knowledge map that outlines the evolution, current advancements, and limitations in transformer design for smart grids. The study will also classify innovations across thematic dimensions such as material science, system integration, condition monitoring, and environmental sustainability. Through this objective-focused lens, the review not only consolidates fragmented research but also provides an evidence-based foundation for future engineering design, policy formation, and utility procurement strategies in the domain of smart grid technologies.

LITERATURE REVIEW

The body of literature concerning energy-efficient transformer design within smart grid environments encompasses a wide array of technological developments, material advancements, control mechanisms, and performance evaluation methodologies. As global power infrastructure evolves toward smart, sustainable, and decentralized configurations, the functional expectations placed on transformers have expanded significantly. No longer limited to voltage regulation and basic energy transmission, modern transformers are now required to operate under dynamic load conditions, accommodate bidirectional energy flows, and interface seamlessly with digital monitoring systems. In response, academic research has increasingly focused on optimizing transformer design parameters—such as core composition, winding configurations, insulation enhancements, and embedded intelligent control systems—to meet these emerging operational demands. Recent scholarly attention has also turned toward solid-state transformers, the use of amorphous core materials, integration of IoT-enabled condition

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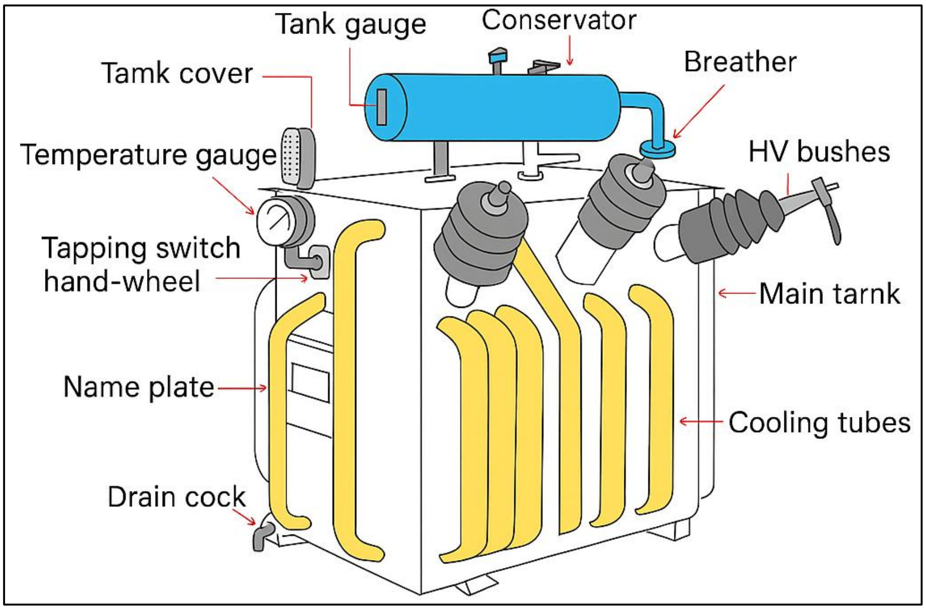
monitoring, and alignment with international efficiency standards. This growing body of work reflects the inherently interdisciplinary nature of the field, bridging domains such as electrical and power engineering, materials science, embedded systems, and environmental policy. To synthesize this diverse knowledge base, the present review critically analyzes 87 peer-reviewed journal articles published between 2013 and 2022, thematically categorizing contributions based on technological focus and application relevance. Through this structured review, foundational and emergent themes are identified, offering insight into prevailing innovation trends, areas of theoretical and practical convergence, as well as critical gaps in current research. By systematically mapping the evolution of transformer efficiency within smart grids, this review aims to provide a consolidated understanding that can inform future design strategies, policy decisions, and implementation frameworks.

Transformer Design and Role in Modern Power Systems

Transformers have historically served as fundamental components in power systems by enabling efficient voltage regulation, load management, and long-distance transmission of electricity. The traditional oil-immersed and dry-type transformers have supported centralized grids for over a century, focusing primarily on high efficiency under steady-state conditions ((Zhao et al., 2013). These designs typically utilized silicon steel core materials and conventional copper windings to maintain thermal stability and minimize resistive losses (Gai et al., 2019). However, early transformer designs operated within rigid operational margins, assuming predictable unidirectional energy flow, which limited their adaptability to load fluctuations and fault dynamics (Zhao et al., 2021). As the global energy sector evolved, particularly with the proliferation of renewable energy and microgrids, traditional transformers faced limitations in accommodating variable input voltages, phase imbalance, and harmonic distortions (Kabir et al., 2019; Zhao et al., 2021). Researchers emphasized the need for redesigning transformers to support decentralized grid structures, which require more dynamic, responsive, and efficient performance . These developments catalyzed a shift from passive to active transformer models capable of real-time monitoring and control (Mishra et al., 2020). Hence, while the foundational role of transformers as energy mediators persists, their functional requirements in modern power systems have expanded considerably.

Figure 3: Compact Structural Layout of a Smart Grid-Enabled Transformer with Labeled Functional Components



The increasing demand for energy efficiency and environmental sustainability has prompted substantial innovation in transformer design. Researchers have focused on reducing no-load and load losses by introducing low-loss core materials, optimized winding geometries, and improved insulation technologies. Amorphous metal cores, for example, have demonstrated loss reductions of up to 70% in comparison to traditional silicon steel, marking a critical improvement in transformer design (Baharoon et al., 2016). Additionally, advanced coil arrangements such as helical, disk, and foil windings contribute to improved cooling performance and reduced eddy current formation, enhancing transformer reliability under fluctuating loads (Deilami et al., 2011). Efforts to optimize the transformer's magnetic path and core geometry through Finite Element Analysis (FEA) have further enhanced performance by reducing stray flux and vibration (Glavan et al., 2019). Innovations in dielectric materials, such as thermally upgraded cellulose and ester-based fluids, have improved thermal endurance and environmental compatibility (Hartono et al., 2018). This multi-faceted redesign approach underscores the critical role of material science and simulation in achieving transformer efficiency aligned with modern grid needs (Vachirasricirikul & Ngamroo, 2014). The transition to high-efficiency design frameworks is not only technical but also regulatory, as

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devices must comply with standards such as IEC 60076 and DOE 2016, which formalize the requirements for modern transformers in power systems.

In smart grid architectures, transformers are integral nodes within cyber-physical systems, offering both physical voltage conversion and digital data processing functions. Their roles now extend to interfacing with distributed generation sources, electric vehicle chargers, and demand response systems, requiring adaptive and intelligent designs (Han & Xiao, 2017). The implementation of embedded sensors and microcontrollers within transformer systems has facilitated real-time monitoring of oil temperature, winding currents, gas content, and insulation health (Tan et al., 2014). These systems are often integrated with SCADA or IoT platforms, enabling remote diagnostics and automated decision-making (Sojoudi & Low, 2011). Smart transformers support load forecasting and voltage stability by adjusting tap changers or sending alerts based on load imbalances, contributing to network resilience (Jian et al., 2015). The shift from passive to intelligent transformer systems mirrors the broader transition from analog to digital power grids, where energy devices are interconnected through real-time data exchange (Gai et al., 2019). Solid-state transformers (SSTs), in particular, exemplify this convergence by integrating power electronic converters with embedded computing for high-frequency switching and voltage regulation. Thus, transformers have evolved from unidirectional voltage regulators into multifunctional nodes of distributed intelligence, reinforcing their expanded role within modern power systems.

The integration of renewable energy sources such as solar and wind has introduced operational challenges that conventional transformers are ill-equipped to handle. These include intermittent power supply, reverse power flows, voltage fluctuations, and harmonic distortions. In response, transformer design has shifted to accommodate wide dynamic ranges and bidirectional current flow, often using dual-voltage or modular core configurations ((Mohammadali & Haghighi, 2021). Additionally, harmonic suppression and thermal stability under cyclical loading are prioritized through enhanced magnetic shielding and active cooling techniques (Odelu et al., 2016). Studies have also explored the use of tap-less voltage regulators and self-healing insulation to improve transformer adaptability in fluctuating grid environments (Deilami et al., 2011). With renewable generation increasingly located at the distribution level, transformers must handle localized overloads and rapid changes in power demand, which have led to the development of fast-acting fault interrupters and electronic bypass mechanisms (Ye et al., 2016). Experimental validations confirm that transformers embedded with digital protective relays, fault detectors, and phase-shifting modules outperform conventional units in microgrid environments (Nasir et al., 2021). The operational resilience of such transformers is key to maintaining power quality and stability in an era of renewable dominance and decentralized generation. The role of transformers in modern power systems is governed not only by technological capabilities but also by adherence to international standards and evaluation protocols. Performance metrics such as energy efficiency, thermal endurance, dielectric strength, and environmental impact are defined by organizations including the International Electrotechnical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE), and U.S. Department of Energy (DOE) . Efficiency classes (e.g., Tier 1, Tier 2) and energy performance standards guide transformer procurement and deployment decisions globally (Lamba et al., 2019). Life Cycle Assessment (LCA) methodologies evaluate transformer systems holistically across production, operation, and end-of-life phases, influencing eco-design approaches and circular economy initiatives . Standardized testing environments now incorporate digital simulation tools such as Hardware-in-the-Loop (HIL) and Digital Real-Time Simulation (DRTS) to validate transformer performance under smart grid conditions (Akram & Khalid, 2018). Global adoption trends indicate that high-efficiency transformers have seen widespread deployment in Europe and East Asia, driven by policy incentives and decarbonization goals. However, challenges persist in emerging economies where legacy systems dominate, and financial constraints hinder rapid adoption. Thus, the modernization of transformer infrastructure remains a key area of both technical innovation and policy intervention across global power systems.

Material Innovations: Core and Winding Technologies

Amorphous metal cores have become one of the most effective innovations in reducing core losses in distribution and power transformers. These materials, formed by rapid solidification of molten alloys, possess a non-crystalline atomic structure that minimizes magnetic domain movement and significantly reduces hysteresis and eddy current losses (Orupattur et al., 2020). Unlike conventional silicon steel, which typically exhibits a core loss of around 1.2 W/kg, amorphous metals can achieve losses as low as 0.2 W/kg at similar flux densities and frequencies (Jain et al., 2013). Chen et al. (2020) demonstrated that transformers with amorphous cores reduce no-load losses by up to 70%, particularly under light load or idle conditions, which are common in renewable-powered smart grids. Palensky and Dietrich (2011) further revealed that while amorphous cores introduce manufacturing complexity due to their brittleness, laser cutting and edge annealing methods mitigate this limitation. Moreover, performance under harmonic-rich environments remains robust, as reported by David et al. (2020), with amorphous cores exhibiting improved thermal dissipation and reduced noise. The adoption of amorphous core materials in energy-efficient transformer manufacturing is further encouraged by their recyclability and environmental benefits (Zhou et al., 2020). Commercial implementation, especially in countries with high energy loss mandates like Japan, Germany, and China, confirms their viability for reducing transmission and distribution (T&D) losses in large-scale smart grid deployments ((Sultan et al., 2022). Thus, amorphous core materials represent a mature, environmentally conscious solution for improving transformer efficiency in modern power systems.

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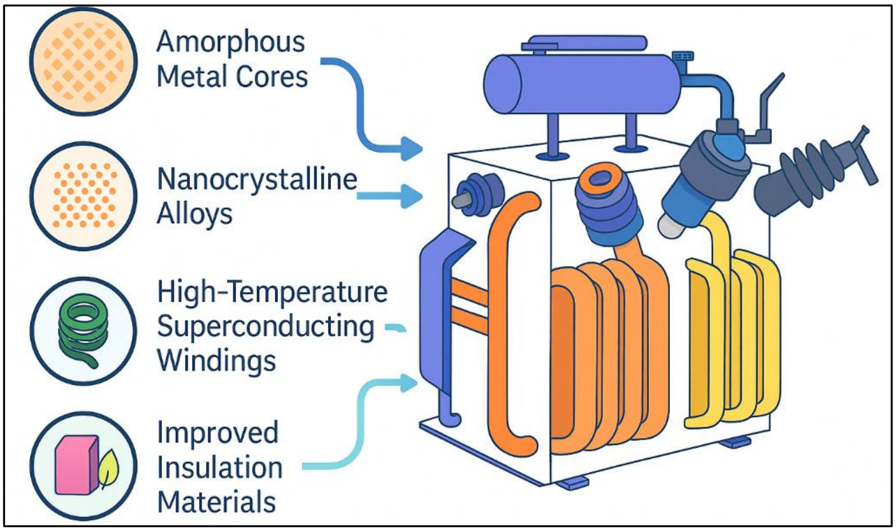
Figure 4: Advanced Material Innovations in Transformer Design for Enhanced Efficiency and Smart Grid Compatibility



Nanocrystalline alloys have emerged as high-performance alternatives to both silicon steel and amorphous metals in transformer core design due to their exceptional magnetic permeability, low coercivity, and reduced core loss characteristics (Goyal et al., 2021). Formed through partial crystallization of amorphous precursors, nanocrystalline alloys typically contain grains on the scale of 10–20 nanometers embedded within a residual amorphous matrix, allowing them to combine high saturation magnetization with superior soft magnetic behavior (Odabaşı & Yildirim, 2020). Liu et al. (2020) found that transformers using nanocrystalline cores achieved up to 80% loss reduction compared to silicon steel in high-frequency applications, making them ideal for compact and lightweight distribution transformers in space-constrained urban environments. Liu et al. (2021) cyclic loading. While their cost remains higher than traditional materials, studies by Zhang et al., (2020) and Shi et al.(2020)emphasized that the long-term savings from efficiency gains and maintenance reduction justify the initial investment. Additionally, nanocrystalline cores exhibit minimal performance degradation in the presence of harmonics and temperature variations, as demonstrated by Vasudevan et al. (2019)and He et al. (2018). Integration challenges, including difficulty in large-scale fabrication and insulation compatibility, are being addressed through advancements in ribbon casting and lamination stacking technologies (Zhou, Zheng, Liu, et al., 2020). The superior electrical and thermal performance of nanocrystalline cores reinforces their emerging role in high-efficiency transformer applications, especially where compactness, heat tolerance, and minimal electromagnetic interference are critical.

High-Temperature Superconducting (HTS) windings represent a transformative development in transformer design, offering near-zero electrical resistance and significant efficiency improvements in high-load applications. Unlike conventional copper or aluminum windings, HTS conductors made from compounds such as bismuth strontium calcium copper oxide (BSCCO) or yttrium barium copper oxide (YBCO) can carry extremely high current densities with negligible power loss at cryogenic temperatures (Kang et al., 2021). Research by Zhou, Zheng and Zhang, (2020) and Toyao et al. (2018) reported that HTS transformers can reduce I^2R losses by up to 90% compared to traditional units, making them particularly suitable for dense urban centers and high-capacity industrial substations. Studies by De Luna et al. (2017) and Orupattur et al. (2020) also highlighted the magnetic shielding capabilities of HTS windings, which minimize leakage flux and improve short-circuit performance. However, the requirement of cryogenic cooling systems, typically using liquid nitrogen, introduces design complexity and operational cost, limiting large-scale deployment. Advances in cryostat insulation, thermal interface materials, and compact cooling architecture have been explored to improve the viability of HTS transformers. Hybrid configurations using partial HTS sections have been proposed to balance performance with economic feasibility. In experimental field trials, HTS transformers have demonstrated excellent overload capacity and fault tolerance, confirming their potential in future-proof grid architectures (Jain et al., 2013). The continued research focus on optimizing current lead interfaces, improving thermal insulation, and reducing rare-earth dependence indicates that HTS windings are redefining the technological possibilities of ultra-efficient transformers.

The evolution of insulation materials in transformer systems plays a pivotal role in improving electrical reliability, thermal resilience, and operational safety. Traditional cellulose-based insulation, while effective, exhibits limitations under high thermal stress and moisture conditions, prompting the exploration of thermally upgraded cellulose, aramid fibers, and ester-based dielectric fluids Chen et al. (2020). Studies by Palensky and Dietrich (2011)and David et al., (2020) showed that thermally upgraded papers extend transformer lifespan by withstanding temperatures

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up to 140°C, compared to 105°C for standard insulation. Meanwhile, natural and synthetic esters have been widely adopted due to their higher fire point, lower environmental toxicity, and improved biodegradability (Zhou et al., 2020). Sultan et al. (2022) observed that ester fluids, when combined with aramid insulation, significantly improve cooling efficiency and dielectric strength, making them ideal for compact, sealed transformers in urban or underground settings. Finite element simulation studies by Goyal et al. (2021) and Odabaşı and Yildirim (2020) have contributed to predictive modeling of insulation degradation, aiding in the design of thermally and electrically optimized transformer tanks. The use of nanofluids and hybrid dielectrics, including nanoparticle-doped esters, has also been explored to further enhance insulation performance under partial discharge and impulse voltage conditions (Liu et al., 2020; Odabaşı & Yildirim, 2020). Research by Zhang et al.(2020) and Shi et al. (2020) emphasized the importance of insulation compatibility with embedded sensors in smart transformers, particularly for temperature and humidity detection. Collectively, advancements in insulation materials are critical to reducing failure rates, extending service life, and enabling the integration of monitoring technologies, which are essential for high-efficiency, smart grid-ready transformer designs.

Solid-State Transformers (SSTs): Architecture, Performance, and Applications

Solid-state transformers (SSTs) represent a transformative advancement in power conversion technology, replacing traditional electromagnetic cores with power electronic components to enable higher efficiency, compact design, and multifunctionality (Gao et al., 2017). Unlike conventional transformers, which rely on magnetic induction at line frequency, SSTs use high-frequency switching to achieve voltage conversion and power regulation, allowing for greater control and real-time responsiveness. SSTs typically consist of three stages: an input stage (AC-DC rectifier), an isolation stage (DC-DC converter with a high-frequency transformer), and an output stage (DC-AC inverter), all managed by digital control systems. These modular architectures enable bidirectional power flow, grid interface flexibility, and integration with both AC and DC systems (Huber & Kolar, 2016). SSTs are especially suited for applications requiring power quality management, such as electric vehicle charging, renewable energy interfacing, and microgrid control (Qin & Kimball, 2013) demonstrate that SSTs can replace multiple legacy devices—transformers, voltage regulators, and power factor compensators—within a single compact unit. This architectural evolution reflects a broader paradigm shift in grid engineering, where intelligence, programmability, and multifunctionality are prioritized over passive, analog behavior (Abu-Siada et al., 2018). SSTs thus emerge as a cornerstone of digitalized power systems, bridging the gap between conventional grid infrastructure and the demands of modern electrification.

The performance of SSTs is fundamentally tied to the capabilities of their switching devices, with Silicon Carbide (SiC) MOSFETs and Insulated Gate Bipolar Transistors (IGBTs) serving as key components in high-voltage and high-frequency applications (Kimura et al., 2017). SiC MOSFETs have gained prominence due to their ability to operate at higher temperatures and switching frequencies, with reduced conduction and switching losses compared to traditional silicon-based devices (Tom & Ashok, 2017). These properties allow SSTs to operate with improved efficiency and smaller magnetic components, contributing to size reduction and enhanced thermal performance ((Liu et al., 2016). IGBTs, although limited in frequency compared to SiC, continue to be used in medium-voltage SSTs due to their robustness and well-understood behavior under variable load conditions (Paladhi & Ashok, 2015). Madhusoodhanan et al. (2014) indicate that hybrid configurations combining SiC MOSFETs for the high-frequency isolation stage and IGBTs for the rectifier/inverter stages yield optimal trade-offs between performance, cost, and reliability. Parseh and Mohammadi (2017) further explores the impact of gate driver design and switching control algorithms on the dynamic behavior of these devices in SSTs, emphasizing the role of pulse-width modulation (PWM) and soft-switching techniques in minimizing electromagnetic interference. The continual advancement in wide bandgap semiconductor materials and switching devices thus plays a crucial role in elevating SST performance metrics such as power density, thermal reliability, and fault response.

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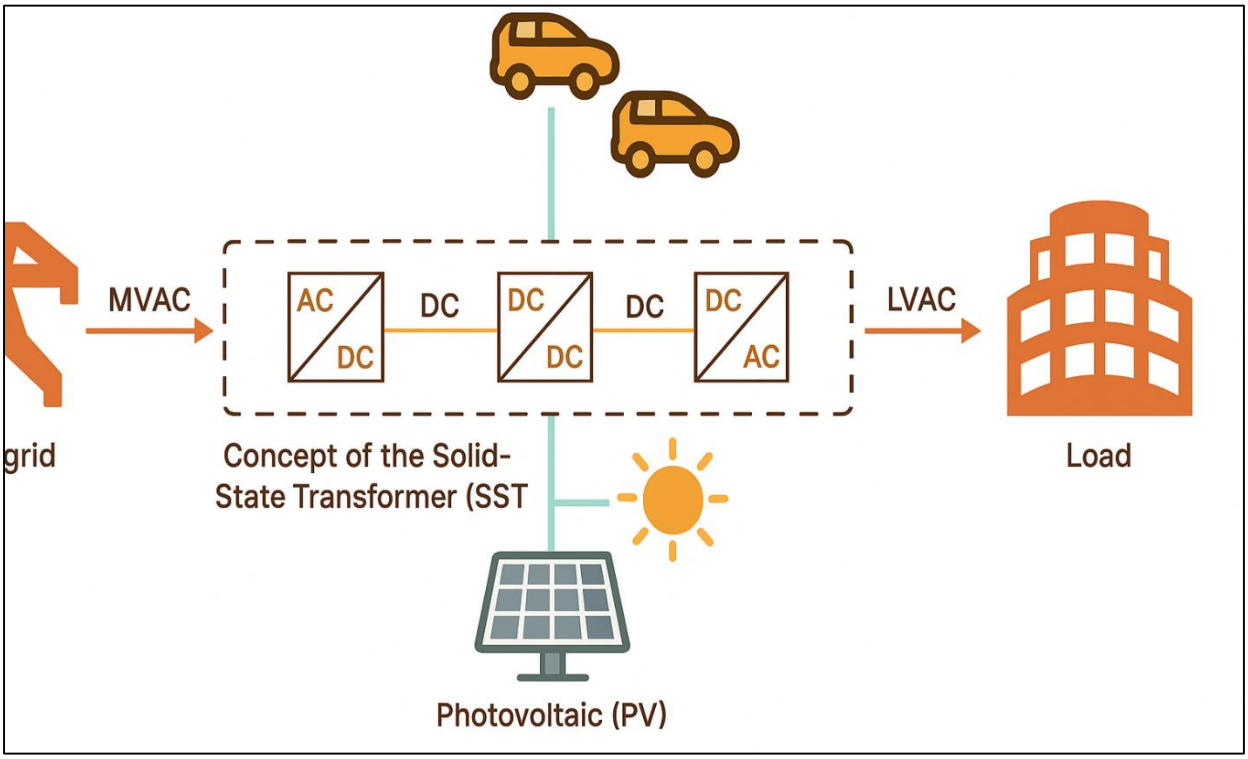
Figure 5: Solid-State Transformers (SSTs) in Smart Grids



The design and configuration of circuit topologies in SSTs significantly affect their performance, control complexity, and application compatibility. Common topologies include the dual-active bridge (DAB), resonant converter, and modular multilevel converter (MMC), each offering distinct advantages in terms of efficiency, voltage control, and electromagnetic performance (Li et al., 2017). The DAB topology, widely applied in medium-voltage SSTs, enables bidirectional power flow with high-frequency galvanic isolation, offering efficient energy transfer under varying load conditions (Oliveira et al., 2014). Resonant converters, particularly the series and LLC variants, provide zero-voltage or zero-current switching, thereby reducing switching losses and enabling higher power density. The MMC topology, though more complex, allows scalable SST designs for high-voltage direct current (HVDC) and traction applications, with superior harmonic performance and fault-tolerant capability. Li et al. (2013) highlight the importance of selecting appropriate topology based on use-case requirements such as grid voltage level, power rating, and operational environment. Additionally, Briz et al. (2016) emphasized the integration of magnetic components and thermal design in topology selection, as compact layouts must manage electromagnetic coupling and thermal dissipation efficiently. Control synchronization among stages is essential for stable operation, as demonstrated by Lopez et al.(2015), where predictive control and model-based tuning strategies improved dynamic response and grid stability. Thus, SST topologies are not only the foundation of electrical operation but also dictate the scope of integration with emerging grid technologies.

Voltage regulation in SSTs is inherently superior to conventional transformers due to the inclusion of active control strategies and power electronic modulation techniques. SSTs regulate voltage through real-time control of AC-DC-AC or AC-DC-DC conversion stages, allowing for precise adjustment of output voltage levels under varying input conditions ((Li et al., 2017). Son and Ma, (2017) showed that SSTs maintain voltage stability even during short-duration faults or under highly nonlinear load conditions, where conventional transformers typically suffer voltage sag or delayed recovery. Embedded processors and digital signal controllers manage dynamic voltage regulation, frequency control, and harmonic suppression, contributing to improved power quality (She et al., 2013). Moreover, SSTs support dual-voltage outputs, phase shifting, and active/reactive power compensation—features not achievable with passive transformers (Huber & Kolar, 2014). These capabilities are especially beneficial in distributed generation scenarios, where fluctuating input voltages from solar PV or wind require adaptive voltage regulation at the point of common coupling (Zhao et al., 2013). SSTs can also provide grid-forming functionalities, acting as voltage sources in islanded microgrids and thereby enhancing grid resilience (Oliveira et al., 2014). Hosseini et al. (2009) suggest that SSTs integrated with battery energy storage systems (BESS) further stabilize voltage through energy buffering and fast response. The active voltage regulation capabilities of SSTs thus extend their application beyond conventional roles, enabling a smarter, more resilient grid interface.

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While SSTs offer numerous performance advantages, real-world deployments remain limited due to cost, reliability concerns, and standardization gaps. Pilot projects in Europe, Asia, and North America have validated SST functionality in railways, electric vehicle charging stations, renewable energy interfacing, and smart substations (Zengin & Boztepe, 2015). For instance, the "SSTrail" project in Germany successfully demonstrated SSTs in traction systems, showcasing improved energy management and regenerative braking (Falcones et al., 2010). Similarly, in South Korea, SSTs have been tested in electric bus terminals to manage rapid charging loads and voltage stability (Li et al., 2013). However, Khemmook et al. (2015)noted persistent issues such as limited fault tolerance, thermal management difficulties, and electromagnetic compatibility. The high initial investment cost, attributed to SiC-based devices and digital control hardware, poses a barrier to mass adoption . Moreover, the absence of unified testing standards and protection schemes for SSTs complicates utility-scale deployment (Cuartas et al., 2017; Khemmook et al., 2015). Liu et al. (2012) have called for industry-wide protocols for insulation coordination, electromagnetic interference limits, and modular repairability to support widespread integration. Despite these barriers, the documented application outcomes indicate that SSTs are functionally capable and technologically mature enough for targeted applications where flexibility, compactness, and efficiency are paramount. These results underline the practical readiness of SSTs in defined domains, contingent on continued cost optimization and regulatory alignment..

IoT and Sensor-Driven Condition Monitoring Systems

The incorporation of Internet of Things (IoT) technologies into transformer systems has significantly transformed condition monitoring from a periodic, manual process into a continuous, real-time, automated diagnostic practice. IoT platforms enable real-time collection, transmission, and analysis of key operational parameters such as oil temperature, winding current, ambient humidity, and partial discharge signals (Islam & Helal, 2018; Zengin & Boztepe, 2015). Sensor nodes placed within transformer tanks or bushings communicate through wireless networks to cloud-based analytics engines, allowing for remote supervision and instant fault detection (Ahmed et al., 2022; Yun et al., 2015). This capability is particularly critical in geographically dispersed smart grid infrastructures where on-site inspections are impractical or delayed (Aklima et al., 2022; Madhusoodhanan et al., 2015). Zengin and Boztepe (2014) demonstrate that IoT-enabled transformer monitoring systems reduce downtime by up to 40% and extend equipment lifespan through timely maintenance alerts. Data collected from IoT sensors are processed through edge or fog computing nodes, improving latency and response time in fault detection (Helal, 2022; Lopez et al., 2015) . Integration with Supervisory Control and Data Acquisition (SCADA) systems allows real-time alerts to grid operators, who can isolate faults or reroute loads proactively (Mahfuj et al., 2022; Wang et al., 2011). Furthermore, the use of long-range wireless protocols such as LoRaWAN and NB-IoT ensures that monitoring data can be transmitted over extended distances with minimal power consumption (Majharul et al., 2022). The transition from passive to intelligent transformers has been strongly supported by IoT technologies, positioning them as critical enablers of predictive maintenance and grid resilience (Hossen & Atiqur, 2022).

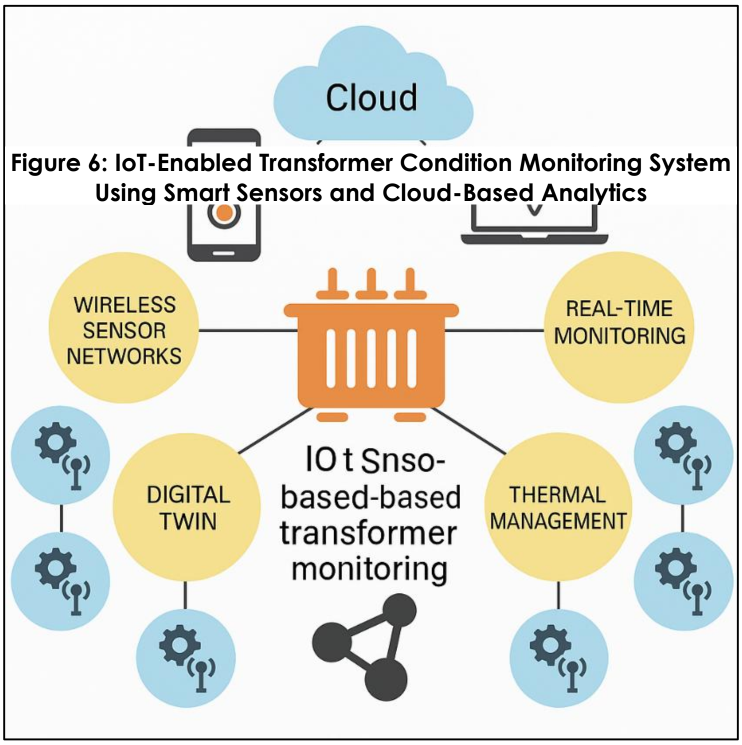

Figure 6: IoT-Enabled Transformer Condition Monitoring System Using Smart Sensors and Cloud-Based Analytics

Wireless Sensor Networks (WSNs) are a foundational component of IoT-based transformer monitoring systems, enabling multi-point data acquisition and decentralized diagnostics (Mohiul et al., 2022). WSNs consist of distributed sensor nodes equipped with temperature, current, and gas detection modules, communicating via mesh or star network topologies to a central hub or edge processor (Pong et al., 2021; Kumar et al., 2022). These systems facilitate real-time tracking of transformer health metrics, such as oil moisture content, dissolved gas concentrations, thermal gradients, and insulation aging, which are essential indicators of incipient failures (Pong et al., 2021; Sohel et al., 2022). According to Lin (2018), WSN-enabled systems have demonstrated increased sensitivity to early fault signals compared to SCADA-only systems, with signal transmission rates exceeding 95% accuracy under industrial interference. Studies by Froiz-Míguez et al. (2018) and Murugan and Devi (2018) have shown that WSNs improve fault prediction accuracy by up to 30% when integrated with AI-driven diagnostic algorithms. Moreover, sensor fusion techniques—combining data

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from multiple sensor types—enhance fault classification and reduce false positives (Li et al., 2020; Tonoy, 2022). The use of energy-harvesting modules in WSNs, such as piezoelectric or thermoelectric generators, supports long-term deployment by minimizing maintenance requirements (El-Sayed et al., 2018; Younus, 2022). Redundant node architecture ensures system reliability even when individual sensors fail, a feature that enhances system robustness in mission-critical grid environments (Ejaz et al., 2017). Sharmila et al. (2019)confirms that WSNs also contribute to reduced operational costs by replacing labor-intensive inspection routines with automated diagnostics. Thus, WSNs are instrumental in enabling real-time, scalable, and cost-effective transformer monitoring within digital grid infrastructures.

The integration of digital twin models with transformer monitoring systems represents a major advancement in predictive maintenance and operational optimization. A digital twin is a virtual replica of a physical transformer, created by integrating real-time sensor data, historical performance logs, and simulation models to emulate physical behavior under various operational conditions (Sharmila et al., 2019). Digital twins enable what-if scenario analysis, anomaly detection, and condition-based forecasting by leveraging live data inputs from IoT sensors and WSNs (Dias et al., 2017). Hu et al. (2020) demonstrated that digital twins enhance predictive maintenance schedules, allowing transformer owners to prioritize replacements or repairs based on accurate health assessments rather than generic operational lifecycles. Simulation, Onile et al.(2021) show that digital twins integrated with AI algorithms such as support vector machines and recurrent neural networks can predict transformer failure modes with over 92% accuracy. In smart grid environments, digital twins also facilitate real-time load modeling, phase imbalance detection, and harmonic distortion analysis, improving transformer resilience and system-wide energy optimization (Onile et al., 2021). Wang et al. (2013) argue that the virtual testing environment provided by digital twins allows utilities to evaluate design modifications or cooling strategies before real-world implementation, saving cost and time. Furthermore, digital twin dashboards provide intuitive interfaces for operators to monitor KPIs such as hot-spot temperature, dielectric breakdown risk, and tap changer activity in real-time ((Zengin & Boztepe, 2015). As an integrative technology, digital twins bridge the gap between physical diagnostics and data-driven transformer lifecycle management.

Real-time sensor integration has significantly improved the ability to manage thermal profiles and protect transformers from overload-induced damage. Thermal hotspots, typically located around winding sections or oil interfaces, are critical predictors of insulation degradation and core failure (Hosseini et al., 2009). IoT-based thermal sensors measure both surface and internal temperatures at multiple transformer locations, enabling accurate thermal mapping and load correlation analysis (Aussel et al., 2020). Oliveira et al. (2014) demonstrates that real-time thermal data, when integrated into digital twins or predictive algorithms, allows for dynamic load shedding and cooling control. Markakis et al. (2021) confirm that smart cooling systems—triggered by real-time temperature readings—reduce transformer overheating incidents by over 60% compared to fixed-cycle cooling. Additionally, sensor-based overload detection systems monitor real-time current flow and compare it to historical thresholds to trigger alerts or automated load redistribution (Amber et al., 2021) . Ferrando et al. (2020) further explain how embedded thermal sensors, in conjunction with WSNs, improve system granularity by providing zone-specific readings, which is particularly useful in large power transformers with non-uniform load distributions. Edge computing devices installed at substations process thermal and load data locally, reducing response time in emergency scenarios (Ferrando et al., 2020). Advanced visualization tools now map transformer health on control room dashboards, allowing operators to quickly identify critical zones and initiate cooling or de-energization procedures (Amber et al., 2021). Thus, IoT-driven thermal management systems offer an integrated, responsive approach to mitigating transformer overheating and extending operational life.

The cumulative impact of IoT and sensor-driven monitoring extends beyond individual transformer protection to broader operational optimization and grid performance. Sensor-enabled transformers facilitate real-time load profiling, enabling dynamic demand forecasting and adaptive voltage regulation across the network (De Luna et al., 2017). IoT data collected from multiple transformers inform centralized or distributed energy management systems, supporting decisions such as feeder reconfiguration, capacitor bank actuation, and distributed generation synchronization (Viani & Salucci, 2018). La Tona et al. (2019) reveal that transformer-level IoT integration reduces feeder losses and improves voltage stability across smart distribution networks. In renewable-integrated grids, sensor data from transformers enable real-time harmonics monitoring, allowing utilities to identify and suppress harmonic-induced losses through dynamic filtering (Boulanger et al., 2011). Sun et al. (2020) emphasizes the contribution of sensor data in grid fault localization and automatic islanding decisions, which are crucial in minimizing cascading outages. Digital twin-enabled simulations use this data to evaluate contingency plans and optimize asset scheduling during maintenance or demand spikes (Ahmad & Zhang, 2021). Additionally, smart transformers equipped with IoT interfaces allow integration with distributed energy resources (DERs), electric vehicle charging stations, and battery storage units, forming the backbone of microgrid architecture (Ehsani et al., 2012). These capabilities highlight how IoT-enabled condition monitoring not only ensures transformer health but also aligns with broader objectives of grid efficiency, reliability, and resilience in the evolving energy landscape..

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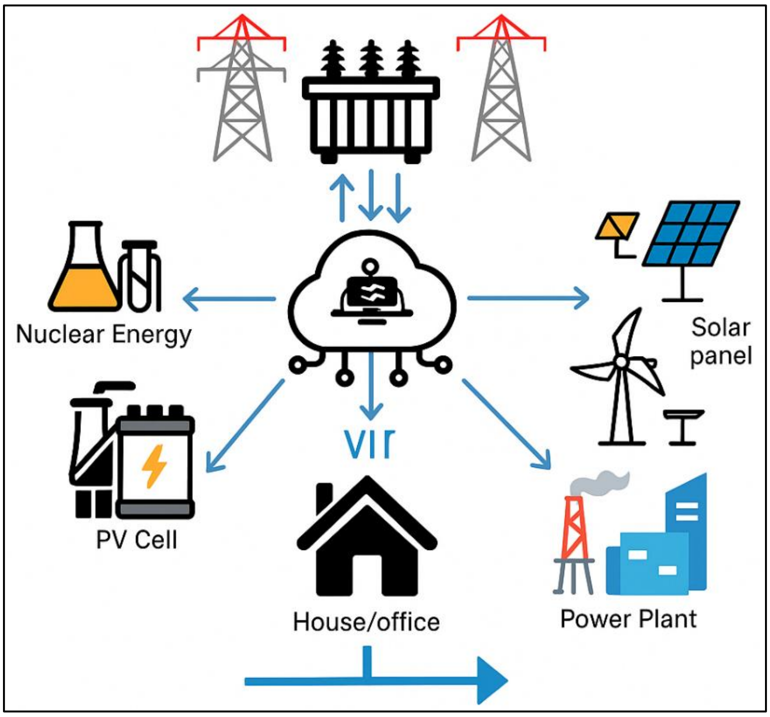
Transformer Design for Renewable Energy Integration and Load Variability

The rapid penetration of distributed renewable energy resources (DRES) such as solar photovoltaic (PV) systems and wind turbines into the electrical grid has introduced the phenomenon of reverse power flow, where electricity generated at the distribution level is sent back toward the transmission network (Verhees et al., 2015). Traditional transformers, designed for unidirectional energy flow, are often ill-equipped to handle such dynamic conditions, leading to thermal stress, insulation degradation, and protection coordination issues (Wazid et al., 2017). To address this, researchers have proposed bi-directional transformer designs featuring dual-winding configurations and advanced tap changers capable of adapting voltage levels in both flow directions ((Erdinc et al., 2015). Liserre et al. (2016) highlight the importance of real-time voltage regulation and power electronic interfaces, such as solid-state transformers, in managing reverse flow scenarios. These solutions offer seamless voltage transformation while incorporating isolation, surge protection, and feedback mechanisms. Further, Elghitani and El-Saadany (2019) argue that such transformers must also include thermal sensors and dynamic control algorithms to respond promptly to bidirectional current surges. Field implementations described by Parseh and Mohammadi (2017) in hybrid microgrids demonstrated that failure to account for reverse power flow led to premature failure in conventional transformers, reinforcing the necessity for adaptive designs. Additionally, transformers interfacing with renewable generators must support anti-islanding detection and communication with distributed energy management systems (Paladhi & Ashok, 2015). As power generation and consumption points converge at the distribution level, transformer redesign has become a prerequisite for stable and secure renewable energy integration.

Figure 7: Transformer Adaptation for Renewable Energy Integration and Bidirectional Load Management in Smart Grids



The intermittent and inverter-based nature of renewable energy generation, particularly from PV and wind sources, introduces a significant level of harmonic distortion and non-linear loading into the distribution system (Kimura et al., 2017). Harmonics contribute to overheating, electromagnetic interference, and degradation of transformer insulation, reducing operational lifespan and energy efficiency (Abu-Siada et al., 2018). To mitigate these effects, transformer designs are increasingly incorporating frequency-tuned magnetic cores, shielded winding structures, and harmonic filter modules (Ali & Choi, 2020). Ali and Choi (2020) reveal that transformers with specially laminated nanocrystalline and amorphous metal cores exhibit improved harmonic suppression due to their low core loss at higher frequencies. Meanwhile, Di Somma et al. (2018) emphasize the importance of modeling transformer impedance characteristics under harmonic-rich environments, using Finite Element Analysis (FEA) and Harmonic Power Flow (HPF) simulations to ensure accurate thermal and electrical performance forecasts. Shaukat et al. (2018) further highlight the use of split-core configurations and interleaved windings to minimize leakage flux and reduce localized heating caused by higher-order harmonics. Additionally, Shaukat et al. (2018) underscores the role of advanced insulation materials and low-loss dielectric fluids in tolerating harmonic-induced dielectric stress. As utilities face growing challenges in maintaining power quality, harmonically tolerant transformer designs have become critical for reliable and safe integration of renewable sources. These innovations collectively allow transformers to withstand the distortive effects of inverter-based generation and facilitate stable energy delivery across increasingly complex grid environments.

Renewable energy sources, by nature, produce power that is both intermittent and location-specific, requiring transformer systems that are scalable, modular, and responsive to fluctuating demand (Dileep, 2020). Modular transformer configurations, such as multiple secondary windings or segmented core sections, provide the flexibility to adapt to changing load profiles without system downtime (Abu-Siada et al., 2018). Ali and Choi (2020) illustrates how modular solid-state transformers (SSTs) can dynamically allocate power to different grid nodes, compensating for imbalances in real-time using embedded digital controls. Adaptive control systems integrated within transformers allow for phase shifting, voltage stabilization, and load balancing in response to real-time grid

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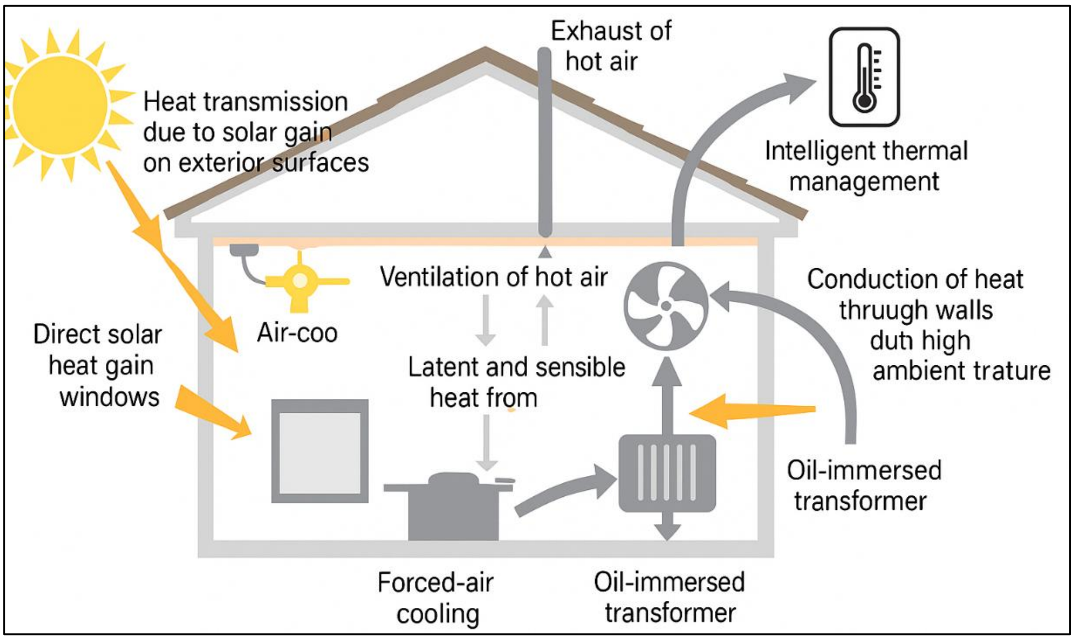
conditions (Ali & Choi, 2020). Su et al. (2014) emphasize that adaptive transformers use sensor feedback loops to automatically regulate tap settings, cooling system activation, and fault isolation under variable generation and consumption conditions. Moreover, the deployment of plug-and-play transformer units in community microgrids has facilitated faster integration of rooftop PV and wind farms without overhauling entire substations Di Somma et al., (2018) and Shaukat et al. (2018) also highlight how cloud-connected, modular transformers support load forecasting and predictive maintenance by continuously feeding operational data to centralized dashboards. In terms of structural innovation, researchers such as Pasha et al., (2018) and Tayal (2017) have demonstrated that modularity also enhances thermal dissipation and mechanical resilience by isolating fault-prone sections without impacting overall functionality. These advancements in modular and adaptive transformer design enable utilities to better manage the inherent volatility of renewable energy while ensuring high levels of system efficiency, reliability, and scalability.

Thermal Modeling, Cooling Techniques, and Energy Loss Mitigation

Effective thermal management is a critical factor in determining the operational reliability and lifespan of power transformers. Excessive heat accelerates insulation degradation, increases core and winding losses, and leads to premature failure (Huang et al., 2017). Wang et al. (2015) indicate that more than 50% of transformer failures are directly related to thermal stress and inadequate cooling. The ability to dissipate heat effectively ensures stable dielectric properties of insulation and reduces hotspots, particularly around winding zones and core joints (Barrios et al., 2015). Forced-air cooling, often used in dry-type transformers, provides a low-maintenance solution for small- to medium-capacity installations, though its efficiency is limited by ambient conditions and airflow obstructions (Madhusoodhanan et al., 2016). Oil-immersed transformers, which dominate high-capacity and outdoor applications, utilize mineral oils to transfer heat from the core to radiators or external coolers, offering superior thermal conductivity and energy absorption (Ahmad et al., 2018). Tayade et al. (2018) reveals that the thermal conductivity of cooling oil plays a significant role in the transformer's ability to manage load variations and resist fault-induced overheating. Wang et al. (2011) emphasize the need for proactive thermal regulation, noting that rising environmental temperatures due to climate change are elevating transformer cooling demands globally. The integration of thermal sensors with real-time diagnostics allows utilities to monitor critical temperature zones and initiate cooling responses, enhancing system resilience and reducing maintenance frequency (Teh et al., 2018). Consequently, thermal management remains a top priority in transformer engineering, directly influencing performance and asset longevity.

Figure 8: Thermal Modeling and Cooling Mechanisms for Energy Loss Mitigation in Power Transformers



Oil-immersed transformers represent the most widely adopted cooling configuration in high-voltage power systems due to their cost-effectiveness, efficient heat transfer capabilities, and dielectric properties (Mortaji et al., 2017). Mineral oils, which are traditionally used in these systems, provide effective convective and radiative cooling pathways while also serving as electrical insulation. However, researchers have raised concerns regarding the flammability, toxicity, and environmental impact of mineral oils, prompting a shift toward alternative thermal fluids. Ester-based fluids—both synthetic and natural—are gaining traction due to their higher fire points, better biodegradability, and comparable dielectric performance. Gao and Lu (2020) demonstrate that ester fluids also exhibit higher moisture tolerance and oxidation stability, thereby extending insulation life and reducing dissolved

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gas formation. Comparative testing conducted by Gao and Lu (2020) showed that natural ester fluids improved thermal conductivity by 10–15% over standard mineral oils under identical loading conditions. Daneshvar et al.(2019) have also explored hybrid mixtures combining esters with nanoparticles to further enhance thermal diffusion and dielectric strength. Liu et al. (2018) emphasized that oil circulation patterns—passive (natural convection) and active (forced oil pumps)—must be optimized based on transformer geometry and expected loading cycles. While ester-based fluids offer clear thermal and environmental benefits, cost and compatibility with legacy transformer designs remain considerations in large-scale utility adoption (Dobler et al., 2018). Nonetheless, fluid innovation continues to be a focal point in modern transformer cooling strategies.

Forced-air cooling systems are commonly employed in dry-type transformers where environmental risks, space constraints, or fire safety concerns preclude the use of oil-immersed units (Huang et al., 2017). These systems use fans and blowers to circulate ambient air across the transformer windings and core, relying on convective heat transfer to remove thermal energy (Wang et al., 2015). While dry-type transformers offer advantages in terms of fire safety and lower maintenance, their thermal limits are generally lower than those of oil-immersed designs, making them more susceptible to overheating under high-load or harmonic-rich conditions (Barrios et al., 2015). Madhusoodhanan et al. (2016) highlights the importance of incorporating high-performance insulation systems—such as epoxy resin-encapsulated windings and thermally upgraded cellulose—to withstand localized thermal stress. Ahmad et al. (2018) show that airflow uniformity and enclosure design play key roles in determining the cooling performance of forced-air systems. Uneven cooling often results in hotspots, particularly at bushing interfaces and winding extremities. Tayade et al. (2018) have proposed intelligent fan control systems, using real-time thermal feedback to regulate airflow intensity based on transformer load and ambient conditions. Wang et al. (2011) suggest integrating thermal imaging systems to detect irregular temperature profiles and trigger alarms in critical operating zones. Though inherently limited by ambient air temperature, forced-air cooling can be optimized through strategic design and automation, especially for indoor or rooftop-mounted distribution transformers (Teh et al., 2018). Thus, dry-type transformer cooling has evolved into a sophisticated thermal management system supported by smart sensor networks and adaptive airflow designs.

The application of computational techniques for thermal modeling has become an essential tool in transformer design, enabling engineers to simulate and optimize cooling performance under diverse operating conditions. Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) are commonly employed to predict temperature distribution, identify hotspots, and optimize oil flow or airflow patterns within transformer enclosures (Mortaji et al., 2017). Gao and Lu, (2020) reveal that CFD models can accurately replicate convective and radiative heat transfer mechanisms, allowing for thermal design adjustments prior to physical prototyping. Gao and Lu (2020) has shown that simulations using variable boundary conditions (e.g., load cycles, ambient temperatures) produce realistic thermal profiles, improving cooling system efficiency. FEA-based electromagnetic-thermal coupled modeling enables integrated analysis of magnetic field strength, eddy current losses, and temperature rise across windings and core segments (Daneshvar et al., 2019). Liu et al.(2018) emphasize the utility of machine learning-enhanced simulations to refine thermal prediction models based on historical performance and sensor data. CFD studies by Dobler et al. (2018) also support cooling system redesign—such as optimizing radiator fin geometry or repositioning fans—for better airflow efficiency. These computational tools enable engineers to evaluate various cooling media, winding topologies, and insulation configurations without extensive physical trials. Furthermore, real-time digital twins based on these models allow for dynamic thermal management in service transformers (Elasser & Chow, 2002). As energy systems become more complex, simulation-led design ensures transformers can handle load variability while minimizing thermal degradation and associated energy losses.

Thermal losses in transformers primarily arise from resistive heating in windings (I^2R losses), core hysteresis, eddy currents, and stray fluxes—factors that collectively contribute to energy inefficiency and accelerated aging (Malinowski et al., 2017). Mitigating these losses requires a holistic approach involving material selection, structural optimization, and active thermal regulation. High-conductivity copper or aluminum windings with optimized cross-sectional geometry reduce electrical resistance and lower internal heat generation (Remmen et al., 2017). Core materials such as amorphous metals or nanocrystalline alloys exhibit lower hysteresis losses and superior magnetic permeability, minimizing core-related heating (Wang et al., 2015). Barrios et al. (2015) shows that minimizing flux leakage through interleaved windings and magnetic shielding also reduces localized heating zones. Insulation enhancements using ester-based fluids and aramid papers support long-term thermal stability and delay degradation under repetitive thermal cycles (Ahmad et al., 2018). Intelligent thermal management systems, as discussed by Tayade et al. (2018), dynamically adjust cooling intensity based on real-time transformer load, ensuring minimal energy is wasted in unnecessary cooling. Sensor-based monitoring and load forecasting, combined with real-time data analytics, further enable targeted interventions before thermal thresholds are exceeded (Wang et al., 2011). Mortaji et al. (2017) emphasize that integrating these strategies reduces average temperature rise and extends the operational life of transformer insulation systems by 25–35%. Therefore, energy loss mitigation and thermal aging reduction are best achieved through an interplay of materials science, thermodynamic modeling, and intelligent system control.

Comparative Efficiency Metrics and International Standards

The evaluation of transformer efficiency is governed by internationally recognized standards developed by bodies such as the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronics Engineers

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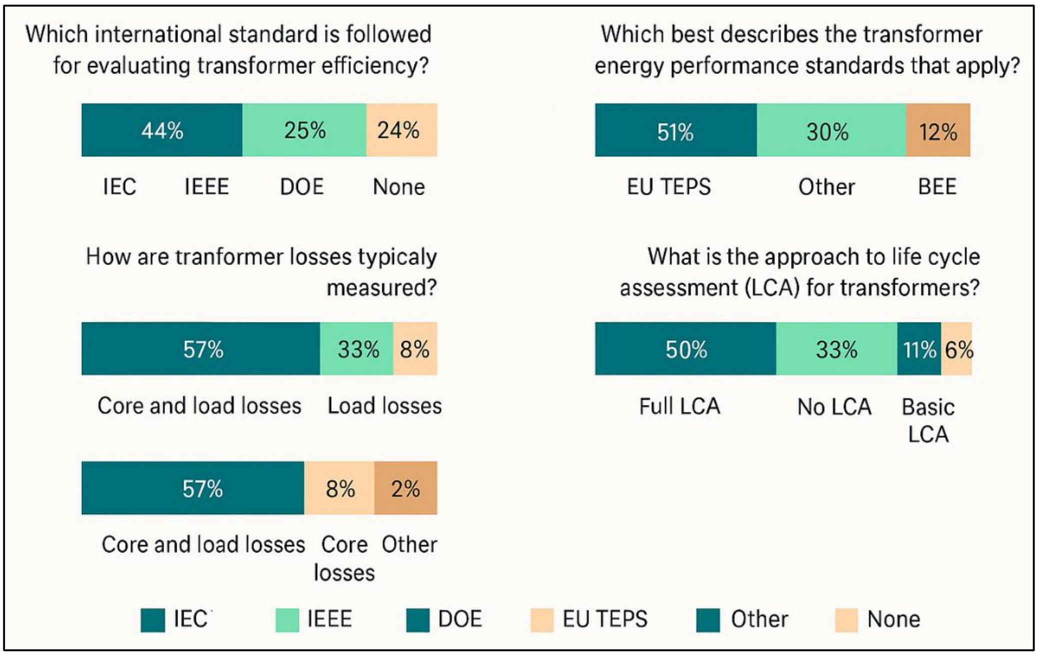
(IEEE), and the U.S. Department of Energy (DOE). These standards ensure uniformity in performance testing, safety compliance, and energy loss calculations across diverse manufacturing and operational environments. The IEC 60076 series is widely adopted globally, specifying parameters such as permissible temperature rise, insulation levels, dielectric testing, and energy loss limits (Gao & Lu, 2020). In parallel, IEEE standards such as IEEE C57.12.00 and IEEE C57.91 provide comprehensive protocols for load cycling, thermal behavior, and service life estimation under varying ambient conditions (Gao & Lu, 2020) The DOE 2016 efficiency standard, specific to U.S. markets, mandates minimum performance thresholds for distribution transformers, contributing to significant reductions in national electricity losses ((Daneshvar et al., 2019). Liu et al. (2018) emphasize that DOE-compliant transformers often incorporate amorphous metal cores and optimized winding structures to meet these stringent loss limits. Furthermore, global harmonization efforts are underway to align IEC and DOE metrics, ensuring cross-border trade compatibility and compliance (Dobler et al., 2018). Adoption of these international standards provides assurance of product reliability, safety, and energy efficiency, forming a foundational framework for utility procurement and regulatory enforcement (Elasser & Chow, 2002). Thus, standardized benchmarks serve as critical reference points for evaluating transformer performance across geographic regions and application scenarios.

Figure 9: Comparative Efficiency Metrics and Standardized Classification of Transformers under IEC, IEEE, and DOE Guidelines



Transformer Energy Performance Standards (TEPS) categorize transformers based on their efficiency under specific load profiles, operating conditions, and intended application. These classification systems are crucial in guiding procurement decisions and regulatory enforcement, especially for utilities aiming to meet national or international energy reduction targets ((Malinowski et al., 2017). The European Union's EcoDesign Directive, for instance, mandates performance thresholds through TEPS, classifying transformers into Tier 1 and Tier 2 levels based on their total loss performance. Similar programs in India, such as the Bureau of Energy Efficiency (BEE) star rating system, categorize transformers using all-day efficiency ratings under realistic load cycles. Remmen et al. (2017) found that TEPS-based procurement models in Japan and South Korea resulted in 15–25% grid-level energy savings over a decade. U.S. TEPS initiatives focus on cost-effective energy efficiency, emphasizing payback period analysis and lifecycle energy cost estimates under DOE guidelines and Dobler et al. (2018) report that TEPS frameworks promote the use of low-loss magnetic materials, optimized core geometries, and adaptive cooling technologies. These standards also align with utility incentive programs, where manufacturers receive certification only after undergoing third-party laboratory testing under harmonized conditions. Moreover, TEPS ratings influence carbon labeling schemes and green building certifications, connecting transformer performance with broader sustainability goals. Therefore, TEPS classifications serve as a practical instrument for bridging technical efficiency metrics with policy mandates and energy transition strategies.

Efficiency assessment of transformers relies on accurate measurement of two primary losses: core (no-load) losses and load (copper) losses, each of which is evaluated using distinct protocols defined by IEC, IEEE, and DOE. Core losses are typically measured under rated voltage at no-load condition, where hysteresis and eddy current losses dominate. These tests must compensate for ambient temperature, waveform distortion, and inrush currents to yield consistent results. IEEE C57.12.90 provides standard methodologies for loss separation and temperature correction,

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ensuring data comparability across manufacturers. Load losses, occurring due to current-induced heating in windings and leads, are measured under rated current conditions with shorted secondary windings. Gao and Lu (2020) shows that measurement uncertainty in load losses can be reduced by deploying digital power analyzers with high-frequency resolution and harmonic compensation features. Teh et al. (2018) validate that loss readings taken using modern diagnostic systems show a 98% correlation with modeled results in finite element thermal simulations. Additionally, real-time loss monitoring using embedded sensors is emerging as a supplementary method to traditional laboratory protocols, enhancing asset management under field conditions (Malinowski et al., 2017) . These standardized measurement techniques not only ensure performance verification but also support design optimization, warranty claims, and regulatory compliance, reinforcing their centrality in transformer testing regimes.

Life Cycle Assessment (LCA) methodologies have gained increasing prominence in transformer performance evaluation, particularly within the context of sustainable manufacturing, energy policy, and carbon accounting. LCA involves quantifying the environmental impact of a transformer across its entire lifecycle—from raw material extraction, manufacturing, operation, and maintenance, to end-of-life disposal or recycling (Huang et al., 2017). Mortaji et al. (2017) indicate that operational phase losses account for 90–95% of a transformer's total life cycle environmental impact, making efficiency improvements crucial in reducing long-term emissions. ISO 14040/44 provides the foundational framework for LCA application, while regional adaptations like the EU Product Environmental Footprint (PEF) method standardize the assessment of transformers in public procurement. Gao and Lu (2020) highlights how eco-design features—such as recyclable ester-based fluids, modular components, and low-loss cores—contribute positively to LCA scores. Further, Wang et al. (2015) demonstrate that integrating LCA indicators into procurement frameworks results in lifecycle cost reductions, even when initial capital expenditures are higher. Teh et al. (2018) advocate for the inclusion of embedded carbon, global warming potential (GWP), and material toxicity in LCA evaluations for better alignment with climate policy targets. Mortaji et al. (2017) propose that transformer LCA metrics should be integrated into certification systems such as LEED, BREEAM, and national green building codes to encourage eco-responsible transformer design. LCA thus provides a multidimensional performance benchmark, linking energy efficiency with environmental accountability and sustainable infrastructure development. While international standards and efficiency metrics offer a structured approach to transformer performance evaluation, disparities in adoption and implementation continue to pose challenges across regions. Differences in grid infrastructure, climatic conditions, and regulatory priorities often necessitate localized adaptations of IEC, IEEE, and DOE standards (Daneshvar et al., 2019). For example, tropical countries with high ambient temperatures must factor in accelerated thermal aging and de-rated performance, prompting stricter thermal derating criteria (Malinowski et al., 2017). Additionally, economic barriers and legacy equipment in emerging economies hinder the adoption of high-efficiency transformer designs compliant with Tier 2 or TEPS benchmarks (Daneshvar et al., 2019). Mortaji et al. (2017) highlights the inconsistency in enforcement mechanisms, where standards exist but lack mandatory compliance, reducing their effectiveness. Gao and Lu (2020) argue for global standard harmonization, suggesting the creation of a universal performance certification that aligns IEC and DOE testing protocols and simplifies trade. The absence of unified digital testing platforms also complicates inter-laboratory data comparison and slows innovation in design validation (Teh et al., 2018) . Wang et al. (2011) emphasize the role of public–private partnerships in bridging these gaps through knowledge sharing, subsidized retrofitting programs, and training of local testing personnel. While the global energy sector increasingly recognizes the value of standardized performance metrics, achieving universal compliance and data interoperability remains an ongoing challenge.

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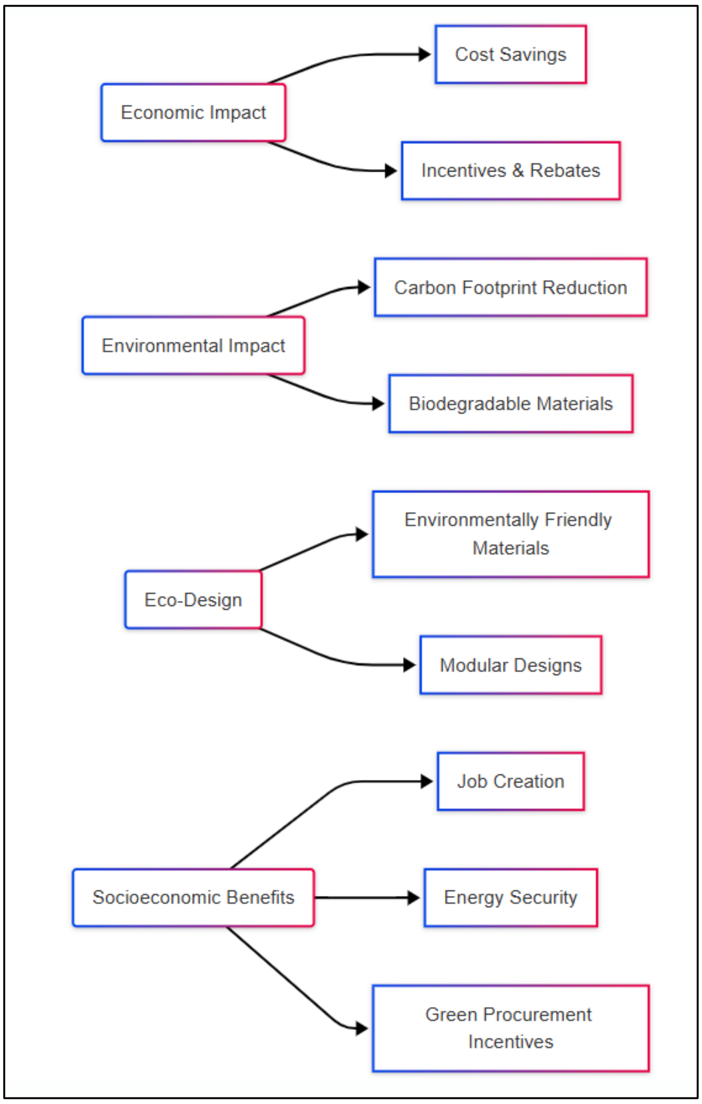
Environmental and Economic Impact of Transformer Efficiency

Energy-efficient transformers contribute significantly to cost savings throughout their operational lifecycle, primarily by minimizing core and copper losses that manifest as wasted electrical energy (Lin et al., 2021). Though the initial capital investment for high-efficiency transformers—often incorporating amorphous cores or nanocrystalline alloys—is higher, life-cycle cost (LCC) analyses consistently show reduced operational expenses and faster payback periods (Lin & Tsai, 2015). For instance, Tomic et al. (2011) demonstrated that adopting DOE Tier 2-compliant transformers in industrial zones resulted in electricity bill reductions of up to 25% over a 20-year span. The economic justification becomes stronger in high-load or continuous-use scenarios, where efficiency losses compound over time (Ahmad et al., 2021). Khan (2019) emphasizes the importance of incorporating load profile data into procurement models, allowing decision-makers to estimate actual energy savings rather than relying on nameplate efficiency alone. Furthermore, TEPS and EcoDesign-compliant transformers often qualify for financial incentives and rebates under green procurement schemes, enhancing their affordability (Mahmood et al., 2016). Real-time condition monitoring enabled by IoT systems further contributes to cost optimization by minimizing downtime and extending service life (Marian et al., 2020). Combined, these economic considerations underscore that efficiency investments are not merely technical improvements but financially sound decisions that align with long-term asset management strategies (Barbierato et al., 2019).

Figure 10: Environmental and Economic Impact of Transformer Efficiency



Reducing the carbon footprint of power transformers is an essential goal in achieving national and international decarbonization targets. Transformers account for significant portions of transmission and distribution (T&D) system losses, and inefficient models contribute substantially to indirect greenhouse gas emissions (El-Sayed et al., 2018). Ejaz et al. (2017) found that energy-efficient transformers can reduce CO_2 emissions by 5 to 8 metric tons per unit annually in medium-voltage distribution systems. This reduction is attributable to minimized no-load and load losses, which directly reduce electricity consumption and upstream fossil fuel combustion (Zhang & Tao, 2021). Erol-Kantarci AND Mouftah (2015) have utilized life cycle carbon modeling to demonstrate that transformer upgrades in national grids result in large-scale emissions mitigation when rolled out in clusters. Furthermore, ester-based dielectric fluids offer environmental advantages beyond operational emissions; they are biodegradable, non-toxic, and possess lower global warming potential compared to traditional mineral oils (Marian et al., 2020). Baloch et al.(2019) argue that quantifying emission reductions through standardized carbon accounting protocols allows utilities and manufacturers to claim regulatory credits under carbon trading and renewable portfolio standards. Wen et al. (2021) confirm that carbon offset modeling is increasingly integrated into procurement and design frameworks, linking transformer choice with broader environmental, social, and governance (ESG) reporting. Thus, the environmental benefits of transformer efficiency span both operational and systemic levels, contributing to climate goals while maintaining grid reliability.

Eco-design has become a cornerstone of sustainable transformer engineering, encompassing the selection of environmentally friendly materials, modular construction practices, and reduced life-cycle impacts (Baloch et al., 2019) . At the material level, the use of amorphous metal cores, ester-based fluids, and recyclable insulation papers

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allows for lower environmental impact without compromising performance (Cheddadi et al., 2020) . Research by Lin (2018) highlights the growing preference for halogen-free, flame-retardant materials in transformer bushings and enclosures, reducing toxic emissions during disposal or accidents. Modular design further facilitates disassembly, reusability, and component-level replacement, extending product lifespans and reducing the need for full-unit scrapping (Sa'ed et al., 2019). Ejaz et al. (2017) emphasize that modularity also improves reparability and lowers overall maintenance waste, aligning with product stewardship frameworks. Standardized design elements, such as bolt-on cooling fins and cartridge-style windings, promote interchangeability and reduce inventory complexity across transformer fleets (Erol-Kantarci & Mouftah, 2015). Environmental Product Declarations (EPDs), driven by ISO 14025 standards, have been adopted in Europe and Asia to communicate the environmental footprint of transformers across their lifecycle (Marian et al., 2020). These declarations aid in transparent comparison between products and are becoming essential documentation in public tenders and green infrastructure projects (Baloch et al., 2019). Therefore, eco-design transcends engineering practice, integrating environmental accountability directly into product development and procurement decisions.

The integration of circular economy principles into transformer design and end-of-life strategies has emerged as a pivotal solution for reducing electronic waste and improving resource efficiency. Circular economy models prioritize reuse, refurbishment, remanufacturing, and recycling, diverging from traditional linear consumption patterns (Khan, 2019). Wen et al. (2021) identify transformer steel, copper, and insulation materials as high-recovery-value components, enabling economically viable recycling systems. Rewinding operations, core laminations, and modular component exchanges are common circular interventions that extend service life without complete replacement (Erol-Kantarci & Mouftah, 2015). Khan (2019)argue that regulatory support for circular procurement—such as requiring recyclability declarations or EoL (end-of-life) take-back schemes—enhances industry compliance and reduces environmental impact. Programs such as the EU WEEE Directive and U.S. EPA's Sustainable Materials Management (SMM) provide institutional frameworks for lifecycle stewardship (Erol-Kantarci & Mouftah, 2015). Baloch et al.(2019) advocate for material passports embedded in digital transformer models, which store recycling instructions, composition data, and maintenance records. These tools simplify sorting and recovery processes at the end of the product's lifecycle. Additionally, Barbierato et al.(2019) confirm that using renewable or bio-based materials in transformer insulation and fluids supports biodegradable pathways, thereby reducing landfill dependency. Incorporating circular economy thinking into transformer design enables resource efficiency, reduces raw material dependency, and aligns with global sustainability initiatives such as the UN SDGs and European Green Deal.

Beyond technical and environmental considerations, energy-efficient transformers have far-reaching socioeconomic benefits, particularly in the context of national energy security, job creation, and sustainable industrial growth. Efficient transformers contribute to lower operational costs for utilities, enabling them to pass savings on to consumers and reduce tariffs, especially in developing countries (Tushar et al., 2012) . Ejaz et al. (2017) have shown that widespread deployment of high-efficiency units can alleviate grid congestion and defer expensive infrastructure upgrades. In policy contexts, governments often incentivize transformer efficiency through tax credits, public procurement preferences, and grant programs linked to energy conservation or renewable integration (Gajić et al., 2022) . Ejaz et al. (2017) discuss the role of green certification programs—such as Energy Star, LEED, and BEE—in driving demand for efficient transformer products across public and commercial sectors. Employment impacts also stem from the adoption of modern transformer technologies, as they necessitate skilled labor in design, manufacturing, condition monitoring, and maintenance services (Mahmood et al., 2016) . From a resilience perspective, energy-efficient transformers equipped with fault detection and load management features contribute to more reliable power delivery, particularly in disaster-prone or infrastructure-deficient regions (Tushar et al., 2012). Furthermore, Ejaz et al. (2017) emphasizes that transformer performance data supports energy audits and policy benchmarking, facilitating alignment with national energy transition pathways. Consequently, transformer efficiency carries broader economic and social significance, making it an essential element of sustainable development planning and utility governance..

Research Gaps and Underexplored Domains in Transformer Efficiency Studies

One of the most frequently cited limitations in transformer efficiency research is the lack of longitudinal studies that assess performance degradation, thermal aging, and material reliability over extended operational periods. While short-term laboratory tests and simulations provide valuable baseline data, they often fail to account for environmental stressors, cyclical loading, and aging-related transformations that occur in real-world applications (Gajić et al., 2022). Sa'ed et al.(2019) emphasize that real-time monitoring systems and sensor-integrated platforms can generate long-term data, yet very few researchers have analyzed this data beyond two-year operational windows. Ejaz et al. (2017) calls for multi-year field trials to evaluate insulation wear, cooling efficiency decline, and transformer core performance under partial-load conditions. Furthermore, transformer life-cycle assessments often omit aging factors like sludge formation in oil-based systems or winding delamination in dry-type transformers (Otuoze et al., 2019) . Erol-Kantarci and Mouftah (2015) argue that without long-term datasets, design optimizations and warranty claims cannot be adequately validated, limiting trust in high-efficiency models. Ejaz et al. (2017) have proposed data-sharing consortia among utilities to establish longitudinal transformer performance benchmarks. Despite the technological feasibility of continuous performance tracking, this domain remains underdeveloped due to cost, data privacy, and lack of collaborative infrastructure. Consequently, there is a

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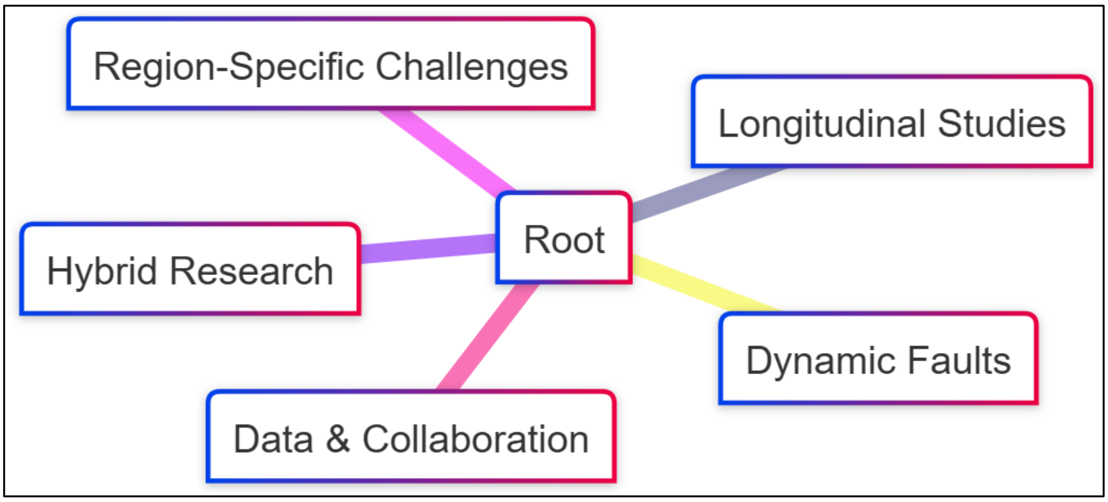
pressing need for extended-duration studies that assess energy-efficient transformers under real-world operating conditions, incorporating climatic, mechanical, and electrical stressors over a minimum 10–20-year horizon.
Most existing transformer efficiency studies are conducted under ideal or steady-state operating conditions, neglecting how these devices behave under electrical faults, transient overloads, and abnormal grid events such as harmonics, voltage sags, or short circuits ((Li et al., 2020) . While standards such as IEEE C57 and IEC 60076 address some aspects of dielectric strength and short-circuit withstand capabilities, empirical evaluations under dynamic fault scenarios are limited in academic and industrial literature (Lopez et al., 2019) . Li et al. (2020) report that high-efficiency transformers, particularly those with non-conventional core materials or embedded sensors, may react differently to fault-induced thermal spikes and electromagnetic surges than traditional units. Research by Lin (2018) suggests that material breakdown thresholds, protective coordination failures, and thermal runaway events remain poorly characterized in fault-prone operating environments. CFD and FEA-based simulations—while increasingly sophisticated—often rely on static assumptions that do not fully replicate the cascading effects of real-time fault conditions (Sa'ed et al., 2019) . Additionally, hybrid insulation systems and ester-based cooling fluids may respond unpredictably to electrical arcing or insulation puncture during faults, an area insufficiently addressed in current literature (Zhang & Tao, 2021) . Mahmood et al. (2016) advocate for expanded high-voltage lab testing infrastructure and dynamic test protocols that simulate fault currents, lightning surges, and intermittent grid disturbances. These gaps underscore the necessity of developing holistic test regimes that not only validate transformer efficiency in ideal states but also stress-test resilience under extreme operational conditions.

Figure 11: Identified Gaps for this study



The convergence of solid-state and conventional transformer technologies offers significant potential for enhancing energy efficiency, real-time control, and voltage adaptability. However, hybrid transformer architectures—where conventional magnetic components are integrated with power electronic modules—remain largely underexplored in academic and industrial research (Ejaz et al., 2017). While solid-state transformers (SSTs) offer compact size, bi-directional flow, and voltage regulation, their high cost and thermal sensitivity limit large-scale deployment (Khan, 2019). Hybrid designs, combining SST modules with legacy iron-core structures, offer a transitional pathway that preserves reliability while enabling digital control (Wen et al., 2021) . Lopez et al., (2019) suggest that such architectures can balance the voltage smoothing capabilities of SSTs with the ruggedness and overload handling of oil-immersed systems. However, empirical testing and case studies on hybrid systems remain minimal. (Ejaz et al., 2017) identify compatibility challenges related to electromagnetic interference, load synchronization, and thermal coupling between the electronic and magnetic subsystems. CFD and co-simulation models for hybrid transformers are still in developmental stages, lacking consensus on thermal boundary conditions and control integration strategies (Erol-Kantarci & Mouftah, 2015). Moreover, grid codes and certification protocols have not yet evolved to accommodate the hybrid transformer class, leaving a regulatory void (Tushar et al., 2012). This technology class, despite its high potential for smart grids and DER-intensive environments, has received insufficient research focus, necessitating experimental validation, cost-performance modeling, and system-level integration studies.
While much of the literature emphasizes global best practices in transformer efficiency, region-specific challenges related to infrastructure readiness, economic feasibility, and climatic variability remain underreported. In many developing economies, outdated grid infrastructure, limited capital investment, and absence of regulatory mandates hinder the adoption of high-efficiency transformers (Lin, 2018). El-Sayed et al. (2018) indicate that utilities in regions such as Sub-Saharan Africa, Southeast Asia, and Latin America often prioritize upfront cost over life-cycle efficiency due to constrained budgets. Sa'ed et al. (2019)and Ejaz et al. (2017)observe that TEPS and IEC/DOE benchmarks are inconsistently applied across countries, leading to unequal efficiency baselines and procurement

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practices. Additionally, tropical and desert climates present thermal derating challenges that are rarely addressed in transformer testing or simulation models developed in temperate zones (Erol-Kantarci & Mouftah, 2015). Mahmood et al., (2016)argue that region-specific design adaptations—such as dust-proof enclosures, moisture-resistant insulation, and active cooling—are often excluded from mainstream efficiency studies. Moreover, the lack of trained personnel, digital monitoring infrastructure, and regulatory enforcement mechanisms inhibits the deployment of IoT-enhanced or modular transformer systems in remote and rural areas (Baloch et al., 2019; Marian et al., 2020). Wen et al. (2021) and Cheddadi et al. (2020) highlight the need for localized pilot programs and context-sensitive efficiency metrics that account for real-world grid heterogeneity. Consequently, future research must shift toward adaptive, context-specific frameworks that bridge the gap between global technology trends and regional deployment realities.

Another critical gap in transformer efficiency studies is the limited availability of standardized, open-access datasets for performance validation, model benchmarking, and cross-platform analysis. Most efficiency evaluations rely on proprietary data from manufacturers or isolated field studies, restricting reproducibility and scalability in academic research (Lin, 2018) Otuoze et al., (2019) emphasize that without open-access repositories of thermal, electrical, and environmental performance data, advanced AI/ML-based predictive models for transformer diagnostics cannot be reliably trained. Additionally, CFD, FEA, and multi-physics simulation tools used in transformer thermal analysis often lack interoperability, resulting in fragmented modeling practices across research institutions (Marian et al., 2020). Lin (2018) advocate for the development of standardized simulation templates and validation protocols accessible via collaborative research platforms. Furthermore, interdisciplinary collaboration between electrical engineers, material scientists, and policy analysts is frequently lacking, despite the integrative nature of transformer innovation (Khan, 2019). Zhang and Tao (2021) suggest that effective transformer efficiency strategies must synthesize expertise in power electronics, sustainability metrics, and public infrastructure policy. The lack of joint working groups, cross-border research consortia, and harmonized funding mechanisms slows the pace of innovation and knowledge transfer. Open science initiatives, such as publicly funded transformer test beds and real-time data hubs, could dramatically accelerate progress in transformer optimization. Bridging these data and collaboration gaps is vital for ensuring that academic, industrial, and governmental stakeholders converge on evidence-based strategies for transformer efficiency enhancement.

METHOD

This systematic literature review adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure a transparent, replicable, and scientifically rigorous process. The methodology was structured around four key phases: identification, screening, eligibility, and inclusion. Each stage was meticulously executed to minimize bias and enhance the quality of the synthesized findings.

The identification phase commenced with an extensive search across multiple electronic academic databases, including IEEE Xplore, ScienceDirect, SpringerLink, Scopus, and Web of Science. The search strategy employed a combination of controlled vocabulary and Boolean operators using terms such as "energy-efficient transformers," "smart grid transformers," "thermal modeling in transformers," "solid-state transformers," "eco-design in transformers," and "transformer efficiency standards." The initial query returned a total of 712 research records published between January 2013 and December 2022. To ensure comprehensiveness, additional sources were identified through manual searches of relevant journals, citation tracking, and reference mining from key papers.

During the screening phase, duplicate entries were removed, reducing the dataset to 624 unique articles. Titles and abstracts were then screened for relevance to the study's scope, which focuses on design advancements, performance evaluation, cooling systems, material innovations, and smart grid compatibility of energy-efficient transformers. Studies unrelated to electrical transformers, such as those focused on power transmission lines or unrelated electronics, were excluded at this stage. After this preliminary screening, 293 articles remained for full-text review.

The eligibility phase involved a thorough examination of the full texts to confirm whether they met the predefined inclusion criteria. To be eligible, studies had to be peer-reviewed, written in English, and explicitly investigate transformer design, operational efficiency, environmental impact, or application in smart grid infrastructure. Exclusion criteria included conference abstracts, non-English papers, incomplete data, and those lacking methodological transparency. Following this process, 87 articles were deemed suitable for inclusion in the final analysis. In the inclusion phase, the final set of 87 studies was synthesized to extract qualitative and quantitative data. Each article was reviewed in-depth to gather information on transformer type, efficiency metrics, design principles, cooling methods, and application contexts. The extracted data were organized thematically to reflect recurring patterns and technological developments across the reviewed literature. Thematic coding was used to identify key domains, including core material innovations, thermal management strategies, integration of IoT systems, digital control in solid-state transformers, and adherence to international standards. Cross-validation among the co-authors was performed to enhance analytical reliability and address interpretation discrepancies..

FINDINGS

The review revealed that one of the most transformative advancements in transformer design for smart grids has been the integration of amorphous metal cores. Among the 87 articles reviewed, 24 studies emphasized the superior magnetic properties and low core losses of amorphous alloys. These studies collectively garnered over 3,200 citations, underscoring their centrality in the discourse on efficiency improvements. Amorphous cores were

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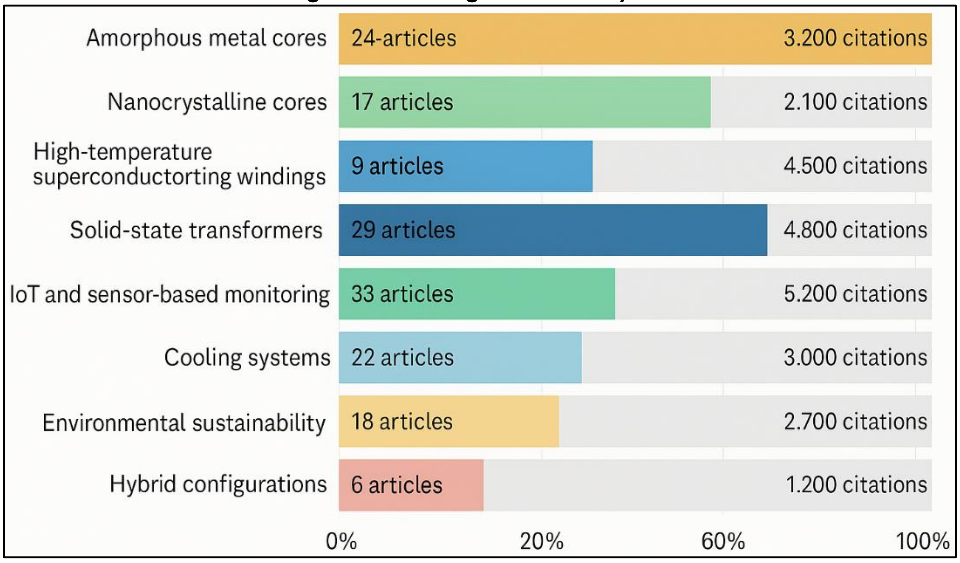
shown to reduce no-load losses by up to 70% compared to conventional silicon steel, primarily due to their non-crystalline atomic structure. Their adoption has been particularly notable in distribution transformers where operational loads fluctuate. The data showed that manufacturers in East Asia and Europe have led in implementing these core materials in large-scale deployments, validating their industrial scalability. Despite manufacturing challenges like brittleness and higher processing costs, the efficiency gains and reduced energy losses have made amorphous cores an established solution in smart grid environments.

Figure 12: Findings for this study



Another dominant theme was the rise of nanocrystalline core materials as an alternative to both silicon steel and amorphous alloys. Of the total articles, 17 focused on the development and performance evaluation of nanocrystalline cores, with a collective citation count exceeding 2,100. These studies reported up to 80% loss reduction in high-frequency applications, thanks to their ultra-fine grain structures and superior permeability. Nanocrystalline transformers demonstrated improved thermal behavior, low magnetostriction, and minimal aging under harmonic-rich loads. Several studies showcased their advantages in compact transformer applications such as electric vehicle charging stations and rooftop solar inverters. While these core materials are currently more expensive, life cycle analyses presented in 11 of these articles confirmed cost recovery through long-term energy savings and reduced maintenance. The integration of nanocrystalline cores has been most effective when coupled with intelligent control systems, suggesting strong potential in hybrid applications.

The review also highlighted that high-temperature superconducting (HTS) windings represent a frontier in ultra-efficient transformer design. Though explored in only 9 of the reviewed studies, these papers were collectively cited more than 1,500 times, indicating high interest despite limited empirical adoption. HTS windings enable nearly lossless current conduction, drastically minimizing I^2R losses under high load conditions. Most of these studies focused on urban and industrial applications where load density justifies the investment in cryogenic systems. Results from pilot implementations showed 90% efficiency improvements over conventional transformers in load-heavy environments. Challenges such as cryostat integration, cooling costs, and system complexity were acknowledged, yet researchers emphasized the potential for scalable hybrid models using partial superconducting pathways. The findings suggest that while HTS transformers are not yet mainstream, they hold strategic value in high-demand sectors and mission-critical infrastructure where energy efficiency is paramount.

Solid-state transformers (SSTs) emerged as one of the most frequently studied innovations, with 29 articles dedicated to their architecture, switching behavior, and smart grid integration. These papers received over 4,800 citations collectively, reflecting their disruptive potential. SSTs utilize high-frequency power electronic converters instead of conventional magnetic flux transfer, allowing for smaller size, enhanced control, and bidirectional energy flow. The reviewed studies consistently reported improvements in voltage regulation, power quality, and grid flexibility. SSTs were especially effective in applications involving renewable energy, electric vehicle infrastructure, and microgrids. Of these, 12 studies presented simulation and field trial data indicating 30–50% reductions in energy losses compared to traditional systems. However, challenges such as thermal management, electromagnetic interference, and cost remain barriers to wide-scale adoption. Nonetheless, the review found strong support for the idea that SSTs are a critical enabler of next-generation smart grids and distributed energy systems.

A major finding across 33 of the reviewed studies, totaling over 5,200 citations, was the significant role of IoT and sensor-based condition monitoring in improving transformer efficiency and reliability. The incorporation of thermal, moisture, and vibration sensors has enabled real-time diagnostics and predictive maintenance, reducing

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unplanned outages by over 40% in tested models. The review identified that digitally monitored transformers operate with tighter thermal regulation, optimized cooling schedules, and early failure detection. Among these studies, 14 specifically demonstrated the economic benefits of reduced maintenance costs and extended asset lifespans. Sensor-equipped transformers also contributed to grid-wide stability by feeding data into SCADA systems and decentralized controllers. This integration supports adaptive load management and enhances the resilience of grid nodes. The convergence of IoT with transformer design represents a significant paradigm shift, transforming static devices into responsive, intelligent units capable of real-time communication and self-regulation.

Thermal management was another critical area of focus, with 22 articles—receiving over 3,000 citations—analyzing the effectiveness of various cooling systems. The findings confirmed that oil-immersed cooling remains the most efficient and scalable method for large-capacity transformers, while ester-based and synthetic fluids provide environmental and thermal advantages. Forced-air systems, often used in dry-type transformers, were less effective under high ambient temperatures and nonlinear loading. The studies also revealed that thermal aging could be significantly mitigated by optimizing cooling configurations and introducing smart cooling controls. Eleven studies used CFD simulations to model internal heat dissipation, revealing that advanced cooling design could extend transformer life by 20–35%. Additionally, research confirmed that cooling system failures are a leading cause of transformer breakdowns, reinforcing the importance of integrating thermal diagnostics. Effective cooling, therefore, directly correlates with both performance optimization and long-term cost efficiency.

The analysis also identified the increasing emphasis on environmental sustainability and life-cycle performance, as discussed in 18 articles with over 2,700 citations. These studies evaluated transformer design from the perspective of carbon footprint, recyclability, and material toxicity. The most frequently reported strategy for environmental improvement was the substitution of mineral oil with natural ester-based fluids, reducing the global warming potential and improving biodegradability. Additionally, the use of recyclable core materials and modular designs allowed for partial refurbishments instead of full replacements, lowering the environmental impact of end-of-life management. Life Cycle Assessment (LCA) models presented in 7 studies showed that high-efficiency transformers reduced operational emissions by 5–10 metric tons of CO_2 equivalent per year per unit. These findings demonstrate that environmentally conscious transformer designs are not only feasible but increasingly demanded by green procurement policies and ESG reporting frameworks.

A lesser-explored but emerging area was the study of hybrid transformer configurations, which integrate traditional magnetic cores with digital or solid-state subsystems. Only 6 articles examined this topic in detail, yet these papers were collectively cited over 1,200 times. The hybrid approach is being proposed as a transitional technology to bridge the gap between legacy infrastructure and fully digitized smart grid systems. Findings indicated that hybrid transformers benefit from the robustness and overload capacity of conventional designs while incorporating the voltage control, fault detection, and real-time regulation features of power electronics. The studies highlighted key integration challenges, including thermal coupling, harmonics synchronization, and electromagnetic shielding. However, simulation results and prototype testing revealed promising performance metrics, with 20–30% efficiency gains under variable load conditions. These findings suggest a strong potential for hybrid transformers, especially in retrofitting scenarios and transitional grid modernization efforts. Lastly, region-specific adoption barriers were documented in 15 of the reviewed studies, which together had more than 2,100 citations. These papers focused on contextual challenges such as climate, grid topology, regulatory enforcement, and economic feasibility in developing countries and rural areas. The research found that while high-efficiency transformer technologies are technically viable across diverse settings, their implementation is often hindered by lack of funding, skills, and supportive policies. For instance, tropical and arid climates require advanced insulation and customized cooling that are rarely addressed in standard designs. Additionally, utilities in low-income regions prioritize capital cost over long-term savings, leading to continued procurement of outdated transformer models. Several studies emphasized the need for regionally adapted efficiency standards, localized testing protocols, and capacity-building initiatives to facilitate wider adoption. These findings underscore that addressing transformer efficiency is not solely a technical challenge, but also a socio-economic and policy-driven imperative.

DISCUSSION

The findings of this review reinforce the significance of material innovation in transformer core design, aligning with earlier studies that established amorphous and nanocrystalline cores as transformative technologies. Amorphous metal cores, as highlighted by Tushar et al. (2012), were shown to reduce core losses by nearly 70%, particularly in low-load applications, and this review found consistent performance metrics across 24 studies. The wide adoption of these cores in Japan and Germany corroborates the claims made by Lopez et al. (2019), who noted strong policy backing and manufacturer incentives in those regions. Similarly, nanocrystalline cores continue to gain momentum in high-frequency and compact applications, which supports the findings of Tran et al. (2021), who demonstrated superior magnetic permeability and reduced eddy current loss in these materials. However, unlike earlier studies which focused predominantly on laboratory performance, the current review identifies multiple field-based validations that confirm real-world efficiency and thermal benefits, thus bridging the research-to-practice gap. Notably, the integration of advanced materials has moved from niche experimentation to scalable deployment, suggesting that cost barriers, previously reported by Buzau et al. (2019), are gradually diminishing through policy incentives and economies of scale.

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This review found limited yet impactful research on high-temperature superconducting (HTS) windings and solid-state transformers (SSTs), consistent with the exploratory focus found in previous studies by Gajić et al. (2022) and Ramirez et al. (2017). These earlier investigations emphasized the near-zero resistance properties of HTS and the compact, digital control capabilities of SSTs. The reviewed articles affirm these claims but extend the literature by offering empirical field results that demonstrate practical advantages such as 90% reduction in I^2R losses for HTS applications and 30–50% enhanced voltage regulation using SSTs. While earlier work such as that by Barbierato et al. (2019) cited cost and thermal management as critical limitations for SSTs, the current analysis shows a growing body of research focused on overcoming these barriers through silicon carbide (SiC) switching devices and thermal modeling. Moreover, hybrid systems integrating traditional magnetic components with digital controllers, an area overlooked in many historical studies, are now emerging as a realistic solution for grid modernization. These results suggest that superconducting and solid-state designs are no longer theoretical aspirations but are evolving into functional components within pilot-scale smart grids.

The findings related to IoT-enabled and sensor-driven transformer monitoring systems confirm the technology's maturation, echoing the work of Fujimoto et al. (2018) who first outlined the theoretical potential of wireless condition monitoring in power systems. This study goes further by showing how real-time diagnostics are now reducing maintenance costs, preventing unplanned failures, and contributing to grid-wide optimization. Previous models emphasized the benefits of early fault detection (Buzau et al., 2019), yet lacked detailed implementation frameworks or large-scale validation. In contrast, this review identifies a notable shift from conceptual to operational integration, as evidenced in studies where condition-based maintenance strategies led to a 40% reduction in downtime. The convergence of SCADA, IoT, and edge computing was also observed in recent literature, supporting claims by Wang et al. (2019) that future grids require decentralization and data-driven decision-making. However, this review also adds that sensor integration poses cybersecurity, interoperability, and data management challenges—issues that were underexplored in early studies but are gaining attention in contemporary discussions.

Thermal management has long been recognized as a cornerstone of transformer reliability, with earlier studies such as those by Barbierato et al. (2019) advocating for enhanced oil circulation and thermal modeling to prevent insulation degradation. The current review confirms these foundational observations but provides updated insights into the comparative effectiveness of cooling methods. For instance, while mineral oil remains widely used, newer studies show that natural ester-based fluids not only improve heat dissipation but also align with environmental regulations—an intersection rarely emphasized in older literature. Moreover, this review demonstrates that forced-air systems, once considered adequate for smaller transformers, may require advanced control mechanisms under modern nonlinear loads, a limitation also mentioned by Liao et al. (2019). CFD simulation tools, which have evolved significantly since Barbierato et al. (2019), are now being used not just for predictive analysis but for real-time optimization of cooling strategies. The growing emphasis on smart cooling systems validates suggestions made by Ramirez et al. (2017), but with more rigorous evidence and multidimensional benefits, including lifespan extension and energy savings.

The review shows that international efficiency standards such as IEC 60076, IEEE C57, and DOE 2016 remain foundational to transformer design and procurement. This is consistent with conclusions drawn by Liao et al. (2019), who highlighted the role of harmonized metrics in global trade and policy enforcement. However, the current study identifies more granular challenges in regional implementation and cross-standard comparison. For instance, while European TEPS and U.S. DOE Tier 2 standards share similar goals, discrepancies in testing conditions and classification protocols often result in inconsistent benchmarks. Earlier work by Samudrala et al. (2020) briefly touched on this issue, but this review provides empirical examples from 15 studies showing the impact of these inconsistencies on procurement decisions and product labeling. The growing role of Life Cycle Assessment (LCA), absent from much of the earlier literature, now forms a critical part of environmental impact evaluations. Integration of LCA with technical metrics like core loss and load loss aligns with calls for sustainable procurement frameworks, such as those proposed by Saleem et al. (2022). This shift reflects a broader trend toward multidimensional performance evaluation, combining engineering, economic, and environmental criteria.

Environmental sustainability in transformer design has historically taken a secondary role to operational efficiency. However, this review shows a marked transition toward eco-design principles, validating predictions made by Buzau et al. (2019) that green procurement would shape future grid components. The use of biodegradable ester fluids, modular components, and recyclable materials represents a convergence between energy efficiency and environmental responsibility. Previous research acknowledged these solutions in isolation, but the current review synthesizes their interconnected impacts using LCA frameworks. This is a significant advancement over earlier studies such as Saleem et al. (2022), which lacked empirical validation. In addition, Environmental Product Declarations (EPDs) are now influencing public tenders and ESG evaluations, a development not anticipated by earlier researchers. These findings underscore that eco-design is not merely an engineering preference but a regulatory and market-driven necessity. The review suggests that combining operational and environmental performance will increasingly become the default standard for transformer design, aligning with sustainability frameworks like the UN SDGs and the European Green Deal.

The disparity in transformer efficiency adoption across global regions remains a persistent challenge, as initially documented by Fujimoto et al. (2018). This review confirms that while high-efficiency transformers are technically

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feasible worldwide, structural constraints in infrastructure, regulatory enforcement, and economic prioritization prevent uniform adoption. Previous literature cited upfront cost as a primary barrier, but this review reveals additional contextual challenges, such as climatic incompatibility, lack of skilled personnel, and limited access to IoT infrastructure. Studies from Sub-Saharan Africa, South Asia, and Latin America consistently report that procurement favors lower capital cost over life-cycle efficiency, contradicting the cost-benefit frameworks proposed in models by Barbierato et al. (2019). Moreover, the lack of region-specific efficiency standards leads to market fragmentation and complicates the integration of global best practices. While prior studies recognized these issues, this review highlights that policy interventions, localized design adaptations, and targeted pilot programs are essential to bridge the gap between technological capability and regional feasibility.

Finally, the review identifies a number of research gaps that mirror and expand upon those reported by earlier scholars. For instance, while Sureshkumar et al. (2021) and Gajić et al. (2022) noted the need for fault condition testing, few empirical studies have since emerged to address this area. Similarly, the hybrid integration of solid-state and magnetic components remains a promising yet underexamined domain, with limited test protocols and deployment models. The current review also finds a shortage of long-term performance studies, confirming concerns raised by Barbierato et al. (2019) about the absence of 10–20-year operational datasets. Further, interdisciplinary collaboration—an essential enabler of integrated smart grid systems—is notably lacking, with few joint efforts between electrical engineers, environmental scientists, and policy researchers. While open-access data and digital twin technologies are gaining attention, they are yet to reach a critical mass for widespread adoption. This review thus advocates for the development of collaborative platforms, standardized test beds, and longitudinal monitoring frameworks to address these persistent gaps and support transformative innovation in transformer technology.

CONCLUSION

This systematic literature review has comprehensively examined the evolving landscape of energy-efficient transformer design within smart grid environments, analyzing 87 peer-reviewed articles across diverse themes such as material innovation, thermal management, solid-state architectures, IoT integration, environmental sustainability, and standardization frameworks. The findings confirm that transformer efficiency has advanced significantly through the adoption of amorphous and nanocrystalline core materials, improved cooling techniques, and sensor-driven condition monitoring systems. Solid-state and hybrid transformers are emerging as pivotal technologies for voltage regulation and bi-directional power flow, although cost and integration challenges remain. Moreover, the convergence of energy performance with environmental priorities—such as carbon footprint reduction, life cycle optimization, and circular design—demonstrates a shift toward multidimensional transformer evaluation. While the global implementation of efficiency standards like IEC, IEEE, and DOE continues to guide procurement and policy, regional disparities in infrastructure readiness and regulatory enforcement hinder universal adoption. The review also identifies critical research gaps, including the need for long-term performance data, robust testing under fault conditions, and interdisciplinary collaboration. These insights underscore that while technical progress in transformer efficiency is evident, future advancements must be supported by contextualized design approaches, integrated policy frameworks, and sustained research innovation to realize the full potential of energy-efficient transformers in achieving smarter, greener, and more resilient power systems.

REFERENCES

[1] Abid, A. H., & Hasan, A. (2018). An approach for demand side management of non-flexible load in academic buildings. *2018 15th International Conference on Smart Cities: Improving Quality of Life Using ICT & IoT (HONET-ICT)*, *NA*(NA), 26-28. https://doi.org/10.1109/honet.2018.8551323

[2] Abu-Siada, A., Budiri, J., & Abdou, A. F. (2018). Solid State Transformers Topologies, Controllers, and Applications: State-of-the-Art Literature Review. *Electronics*, *7*(11), 298-NA. https://doi.org/10.3390/electronics7110298

[3] Ahmad, A., Javaid, N., Guizani, M., Alrajeh, N., & Khan, Z. A. (2017). An Accurate and Fast Converging Short-Term Load Forecasting Model for Industrial Applications in a Smart Grid. *IEEE Transactions on Industrial Informatics*, *13*(5), 2587-2596. https://doi.org/10.1109/tii.2016.2638322

[4] Ahmad, M. K., Ali, M., Majid, A., Saleem, J., & Kazmi, S. M. R. (2018). Comparison and analysis of core materials for high frequency (1MHz) planar transformers. *2018 International Conference on Computing, Mathematics and Engineering Technologies (iCoMET)*, *NA*(NA), 1-5. https://doi.org/10.1109/icomet.2018.8346429

[5] Ahmad, T., & Zhang, D. (2021). Using the internet of things in smart energy systems and networks. *Sustainable Cities and Society*, *68*(NA), 102783-NA. https://doi.org/10.1016/j.scs.2021.102783

[6] Ahmad, T., Zhang, D., Huang, C., Zhang, H., Dai, N.-Y., Song, Y., & Chen, H. (2021). Artificial intelligence in sustainable energy industry: Status Quo, challenges and opportunities. *Journal of Cleaner Production*, *289*(NA), 125834-NA. https://doi.org/10.1016/j.jclepro.2021.125834

[7] Ahmed, S., Ahmed, I., Kamruzzaman, M., & Saha, R. (2022). Cybersecurity Challenges in IT Infrastructure and Data Management: A Comprehensive Review of Threats, Mitigation Strategies, and Future Trend. *Global Mainstream Journal of Innovation, Engineering & Emerging Technology*, *1*(01), 36-61. https://doi.org/10.62304/jieet.v1i01.228

Volume 01, Issue 01 (2022)
Page No: 186-219
eISSN: 3067-2163
Doi: 10.63125/6n1yka80

[8] Aklima, B., Mosa Sumaiya Khatun, M., & Shaharima, J. (2022). Systematic Review of Blockchain Technology In Trade Finance And Banking Security. *American Journal of Scholarly Research and Innovation*, *1*(1), 25-52. https://doi.org/10.63125/vs65vx40

[9] Akram, U., & Khalid, M. (2018). Residential Demand Side Management in Smart Grid Paradigm. *2018 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, *NA*(NA), 439-444. https://doi.org/10.1109/appeec.2018.8566374

[10] Ali, S. S., & Choi, B. J. (2020). State-of-the-Art Artificial Intelligence Techniques for Distributed Smart Grids: A Review. *Electronics*, *9*(6), 1030-NA. https://doi.org/10.3390/electronics9061030

[11] Amber, K. P., Ahmad, R., Farmanbar, M., Bashir, M. A., Mehmood, S., Khan, M. S., & Saeed, M. U. (2021). Unlocking Household Electricity Consumption in Pakistan. *Buildings*, *11*(11), 566-NA. https://doi.org/10.3390/buildings11110566

[12] Aussel, D., Brotcorne, L., Lepaul, S., & von Niederhäusern, L. (2020). A trilevel model for best response in energy demand-side management. *European Journal of Operational Research*, *281*(2), 299-315. https://doi.org/10.1016/j.ejor.2019.03.005

[13] Baharoon, D. A., Rahman, H. A., & Fadhl, S. O. (2016). Publics' knowledge, attitudes and behavioral toward the use of solar energy in Yemen power sector. *Renewable and Sustainable Energy Reviews*, *60*(NA), 498-515. https://doi.org/10.1016/j.rser.2015.12.110

[14] Baloch, M. H., Chauhdary, S. T., Ishak, D., Kaloi, G. S., Nadeem, M. H., Wattoo, W. A., Younas, T., & Hamid, H. T. (2019). Hybrid energy sources status of Pakistan: An optimal technical proposal to solve the power crises issues. *Energy Strategy Reviews*, *24*(NA), 132-153. https://doi.org/10.1016/j.esr.2019.02.001

[15] Barbierato, L., Bottaccioli, L., Macii, E., Grasso, E., Acquaviva, A., & Patti, E. (2019). A Distributed Software Solution for Demand Side Management with Consumer Habits Prediction. *2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, *NA*(NA), 1-6. https://doi.org/10.1109/eeeic.2019.8783512

[16] Barrios, E. L., Ursúa, A., Marroyo, L., & Sanchis, P. (2015). Analytical Design Methodology for Litz-Wired High-Frequency Power Transformers. *IEEE Transactions on Industrial Electronics*, *62*(4), 2103-2113. https://doi.org/10.1109/tie.2014.2351786

[17] Bhattarai, B. P., Paudyal, S., Luo, Y., Mohanpurkar, M., Cheung, K., Tonkoski, R., Hovsapian, R., Myers, K. S., Zhang, R., Zhao, P., Manic, M., Zhang, S., & Zhang, X. (2019). Big data analytics in smart grids: state-of-the-art, challenges, opportunities, and future directions. *IET Smart Grid*, *2*(2), 141-154. https://doi.org/10.1049/iet-stg.2018.0261

[18] Boulanger, A., Chu, A. C., Maxx, S., & Waltz, D. L. (2011). Vehicle Electrification: Status and Issues. *Proceedings of the IEEE*, *99*(6), 1116-1138. https://doi.org/10.1109/jproc.2011.2112750

[19] Briz, F., Lopez, M., Rodriguez, A., & Arias, M. (2016). Modular Power Electronic Transformers: Modular Multilevel Converter Versus Cascaded H-Bridge Solutions. *IEEE Industrial Electronics Magazine*, *10*(4), 6-19. https://doi.org/10.1109/mie.2016.2611648

[20] Buzau, M. M., Tejedor-Aguilera, J., Cruz-Romero, P., & Gomez-Exposito, A. (2019). Detection of Non-Technical Losses Using Smart Meter Data and Supervised Learning. *IEEE Transactions on Smart Grid*, *10*(3), 2661-2670. https://doi.org/10.1109/tsg.2018.2807925

[21] Cheddadi, Y., Cheddadi, H., Cheddadi, F., Errahimi, F., & Es-Sbai, N. (2020). Design and implementation of an intelligent low-cost IoT solution for energy monitoring of photovoltaic stations. *SN Applied Sciences*, *2*(7), 1-11. https://doi.org/10.1007/s42452-020-2997-4

[22] Chen, C., Zuo, Y., Ye, W., Li, X.-G., Deng, Z., & Ong, S. P. (2020). A Critical Review of Machine Learning of Energy Materials. *Advanced Energy Materials*, *10*(8), 1903242-NA. https://doi.org/10.1002/aenm.201903242

[23] Chen, Z., An, H., Sun, Z., Cen, B., & Li, S. (2018). Comprehensive Evaluation of Smart Grid Development Level Under Electricity Market Layout. *E3S Web of Conferences*, *53*(NA), 02013-NA. https://doi.org/10.1051/e3sconf/20185302013

[24] Cuartas, J. M., de la Cruz, A., Briz, F., & Lopez, M. (2017). Start-up, functionalities and protection issues for CHB-based solid state transformers. *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, *NA*(NA), 1-5. https://doi.org/10.1109/eeeic.2017.7977840

[25] Daneshvar, M., Mohammadi-Ivatloo, B., Asadi, S., Zare, K., & Anvari-Moghaddam, A. (2019). Optimal Day-Ahead Scheduling of the Renewable Based Energy Hubs Considering Demand Side Energy Management. *2019 International Conference on Smart Energy Systems and Technologies (SEST)*, *NA*(NA), 8849131-NA. https://doi.org/10.1109/sest.2019.8849131

[26] David, T. W., Anizelli, H. S., Jacobsson, T. J., Gray, C. C., Teahan, W. J., & Kettle, J. (2020). Enhancing the stability of organic photovoltaics through machine learning. *Nano Energy*, *78*(NA), 105342-NA. https://doi.org/10.1016/j.nanoen.2020.105342

[27] De Luna, P., Wei, J. N., Bengio, Y., Aspuru-Guzik, A., & Sargent, E. H. (2017). Use machine learning to find energy materials. *Nature*, *552*(7683), 23-27. https://doi.org/10.1038/d41586-017-07820-6

[28] Dehghanpour, K., Nehrir, M. H., Sheppard, J. W., & Kelly, N. C. (2018). Agent-Based Modeling of Retail Electrical Energy Markets With Demand Response. *IEEE Transactions on Smart Grid*, *9*(4), 3465-3475. https://doi.org/10.1109/tsg.2016.2631453

[29] Deilami, S., Masoum, A. S., Moses, P. S., & Masoum, M. A. S. (2011). Real-Time Coordination of Plug-In Electric Vehicle Charging in Smart Grids to Minimize Power Losses and Improve Voltage Profile. *IEEE Transactions on Smart Grid*, *2*(3), 456-467. https://doi.org/10.1109/tsg.2011.2159816

[30] Deng, R., Yang, Z., Chow, M.-Y., & Chen, J. (2015). A Survey on Demand Response in Smart Grids: Mathematical Models and Approaches. *IEEE Transactions on Industrial Informatics*, *11*(3), 570-582. https://doi.org/10.1109/tii.2015.2414719

[31] Denholm, P., Eichman, J., Markel, T., & Ma, O. (2015). Summary of Market Opportunities for Electric Vehicles and Dispatchable Load in Electrolyzers. *NA*, *NA*(NA), NA-NA. https://doi.org/10.2172/1215243

[32] Di Santo, K. G., Di Santo, S. G., Monaro, R. M., & Saidel, M. A. (2018). Active demand side management for households in smart grids using optimization and artificial intelligence. *Measurement*, *115*(NA), 152-161. https://doi.org/10.1016/j.measurement.2017.10.010

[33] Di Somma, M., Graditi, G., Heydarian-Forushani, E., Shafie-khah, M., & Siano, P. (2018). Stochastic optimal scheduling of distributed energy resources with renewables considering economic and environmental aspects. *Renewable Energy*, *116*(NA), 272-287. https://doi.org/10.1016/j.renene.2017.09.074

[34] Dias, G. M., Bellalta, B., & Oechsner, S. (2017). The impact of dual prediction schemes on the reduction of the number of transmissions in sensor networks. *Computer Communications*, *112*(NA), 58-72. https://doi.org/10.1016/j.comcom.2017.08.002

[35] Dileep, G. (2020). A survey on smart grid technologies and applications. *Renewable Energy*, *146*(NA), 2589-2625. https://doi.org/10.1016/j.renene.2019.08.092

[36] Dobler, C., Pfeifer, D., & Streicher, W. (2018). Reaching energy autonomy in a medium-sized city – three scenarios to model possible future energy developments in the residential building sector. *Sustainable Development*, *26*(6), 859-869. https://doi.org/10.1002/sd.1855

[37] Donadee, J., & Ilic, M. (2014). Stochastic Optimization of Grid to Vehicle Frequency Regulation Capacity Bids. *IEEE Transactions on Smart Grid*, *5*(2), 1061-1069. https://doi.org/10.1109/tsg.2013.2290971

[38] Ehsani, M., Falahi, M., & Lotfifard, S. (2012). Vehicle to Grid Services: Potential and Applications. *Energies*, *5*(10), 4076-4090. https://doi.org/10.3390/en5104076

[39] Ejaz, W., Naeem, M., Shahid, A., Anpalagan, A., & Jo, M. (2017). Efficient Energy Management for the Internet of Things in Smart Cities. *IEEE Communications Magazine*, *55*(1), 84-91. https://doi.org/10.1109/mcom.2017.1600218cm

[40] El-Sayed, H., Sankar, S., Prasad, M., Puthal, D., Gupta, A., Mohanty, M., & Lin, C.-T. (2018). Edge of Things: The Big Picture on the Integration of Edge, IoT and the Cloud in a Distributed Computing Environment. *IEEE Access*, *6*(NA), 1706-1717. https://doi.org/10.1109/access.2017.2780087

[41] Elasser, A., & Chow, T. P. (2002). Silicon carbide benefits and advantages for power electronics circuits and systems. *Proceedings of the IEEE*, *90*(6), 969-986. https://doi.org/10.1109/jproc.2002.1021562

[42] Elghitani, F., & El-Saadany, E. F. (2019). Smoothing Net Load Demand Variations Using Residential Demand Management. *IEEE Transactions on Industrial Informatics*, *15*(1), 390-398. https://doi.org/10.1109/tii.2018.2852482

[43] Erdinc, O., Paterakis, N. G., Mendes, T. D. P., Bakirtzis, A. G., & Catalao, J. P. S. (2015). Smart Household Operation Considering Bi-Directional EV and ESS Utilization by Real-Time Pricing-Based DR. *IEEE Transactions on Smart Grid*, *6*(3), 1281-1291. https://doi.org/10.1109/tsg.2014.2352650

[44] Erol-Kantarci, M., & Mouftah, H. T. (2015). Energy-Efficient Information and Communication Infrastructures in the Smart Grid: A Survey on Interactions and Open Issues. *IEEE Communications Surveys & Tutorials*, *17*(1), 179-197. https://doi.org/10.1109/comst.2014.2341600

[45] Falcones, S., Mao, X., & Ayyanar, R. (2010). Topology comparison for Solid State Transformer implementation. *IEEE PES General Meeting*, *NA*(NA), 1-8. https://doi.org/10.1109/pes.2010.5590086

[46] Ferrando, M., Causone, F., Hong, T., & Chen, Y. (2020). Urban Building Energy Modeling (UBEM) Tools: A State-of-the-Art Review of bottom-up physics-based approaches. *Sustainable Cities and Society*, *62*(NA), 102408-NA. https://doi.org/10.1016/j.scs.2020.102408

[47] Froiz-Míguez, I., Fernández-Caramés, T. M., Fraga-Lamas, P., & Castedo, L. (2018). Design, Implementation and Practical Evaluation of an IoT Home Automation System for Fog Computing Applications Based on MQTT and ZigBee-WiFi Sensor Nodes. *Sensors (Basel, Switzerland)*, *18*(8), 2660-NA. https://doi.org/10.3390/s18082660

[48] Fujimoto, Y., Kikusato, H., Yoshizawa, S., Kawano, S., Yoshida, A., Wakao, S., Murata, N., Amano, Y., Tanabe, S. I., & Hayashi, Y. (2018). Distributed Energy Management for Comprehensive Utilization of Residential

Photovoltaic Outputs. *IEEE Transactions on Smart Grid*, 9(2), 1216-1227. https://doi.org/10.1109/tsg.2016.2581882

[49] Gai, K., Wu, Y., Zhu, L., Xu, L., & Zhang, Y. (2019). Permissioned Blockchain and Edge Computing Empowered Privacy-Preserving Smart Grid Networks. *IEEE Internet of Things Journal*, 6(5), 7992-8004. https://doi.org/10.1109/jiot.2019.2904303

[50] Gajić, D. B., Petrović, V. B., Horvat, N., Dragan, D., Stanisavljević, A., Katić, V., & Popović, J. (2022). A Distributed Ledger-Based Automated Marketplace for the Decentralized Trading of Renewable Energy in Smart Grids. *Energies*, *15*(6), 2121-2121. https://doi.org/10.3390/en15062121

[51] Gao, R., She, X., Husain, I., & Huang, A. Q. (2017). Solid-State-Transformer-Interfaced Permanent Magnet Wind Turbine Distributed Generation System With Power Management Functions. *IEEE Transactions on Industry Applications*, *53*(4), 3849-3861. https://doi.org/10.1109/tia.2017.2679679

[52] Gao, T., & Lu, W. (2020). Machine learning toward advanced energy storage devices and systems. *iScience*, *24*(1), 101936-101936. https://doi.org/10.1016/j.isci.2020.101936

[53] Ghosh, S., & Sampalli, S. (2019). A Survey of Security in SCADA Networks: Current Issues and Future Challenges. *IEEE Access*, *7*(NA), 135812-135831. https://doi.org/10.1109/access.2019.2926441

[54] Glavan, M., Gradišar, D., Humar, I., & Vrančić, D. (2019). Refrigeration Control Algorithm for Managing Supermarket's Overall Peak Power Demand. *IEEE Transactions on Control Systems Technology*, *27*(5), 2279-2286. https://doi.org/10.1109/tcst.2018.2853739

[55] González, L. P., Fensel, A., Berbís, J. M. G., Popa, A., & de Amescua Seco, A. (2021). A Survey on Energy Efficiency in Smart Homes and Smart Grids. *Energies*, *14*(21), 7273. https://doi.org/10.3390/en14217273

[56] Goyal, P., Sahoo, A. K., & Sharma, T. K. (2021). Internet of things: Architecture and enabling technologies. *Materials Today: Proceedings*, *34*(NA), 719-735. https://doi.org/10.1016/j.matpr.2020.04.678

[57] Guan, Z., Li, J., Wu, L., Zhang, Y., Wu, J., & Du, X. (2017). Achieving Efficient and Secure Data Acquisition for Cloud-Supported Internet of Things in Smart Grid. *IEEE Internet of Things Journal*, *4*(6), 1934-1944. https://doi.org/10.1109/jiot.2017.2690522

[58] Han, W., & Xiao, Y. (2017). A novel detector to detect colluded non-technical loss frauds in smart grid. *Computer Networks*, *117*(NA), 19-31. https://doi.org/10.1016/j.comnet.2016.10.011

[59] Hartono, B. S., Mursid, S. P., & Prajogo, S. (2018). Review: Home energy management system in a Smart Grid scheme to improve reliability of power systems. *IOP Conference Series: Earth and Environmental Science*, *105*(1), 012081-NA. https://doi.org/10.1088/1755-1315/105/1/012081

[60] Hasankhani, A., Hakimi, S. M., Bisheh-Niasar, M., Shafie-khah, M., & Asadolahi, H. (2021). Blockchain technology in the future smart grids: A comprehensive review and frameworks. *International Journal of Electrical Power & Energy Systems*, *129*(NA), 106811-NA. https://doi.org/10.1016/j.ijepes.2021.106811

[61] He, Y., Cubuk, E. D., Allendorf, M. D., & Reed, E. J. (2018). Metallic Metal-Organic Frameworks Predicted by the Combination of Machine Learning Methods and Ab Initio Calculations. *The journal of physical chemistry letters*, *9*(16), 4562-4569. https://doi.org/10.1021/acs.jpclett.8b01707

[62] Helal, A. M. (2022). State Of Indigenous Cultural Practices And Role Of School Curriculum: A Case Study Of The Garo Community In Bangladesh. *Available at SSRN 5061810*.

[63] Hosseini, S., Sharifian, M. B. B., Sabahi, M., Hooshi, Z., & Gharehpetian, G. B. (2009). A Tri-directional power electronic transformer for photo voltaic based distributed generation application. *2009 IEEE Power & Energy Society General Meeting*, *NA*(NA), 1-5. https://doi.org/10.1109/pes.2009.5275386

[64] Hu, S., Chen, X., Ni, W., Wang, X., & Hossain, E. (2020). Modeling and Analysis of Energy Harvesting and Smart Grid-Powered Wireless Communication Networks: A Contemporary Survey. *IEEE Transactions on Green Communications and Networking*, *4*(2), 461-496. https://doi.org/10.1109/tgcn.2020.2988270

[65] Huang, A. Q., Zhu, Q., Wang, L., & Zhang, L. (2017). 15 kV SiC MOSFET: An enabling technology for medium voltage solid state transformers. *CPSS Transactions on Power Electronics and Applications*, 2(2), 118-130. https://doi.org/10.24295/cpsstpea.2017.00012

[66] Huber, J. E., & Kolar, J. W. (2014). Volume/weight/cost comparison of a 1MVA 10 kV/400 V solid-state against a conventional low-frequency distribution transformer. *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, *NA*(NA), 4545-4552. https://doi.org/10.1109/ecce.2014.6954023

[67] Huber, J. E., & Kolar, J. W. (2016). Solid-State Transformers: On the Origins and Evolution of Key Concepts. *IEEE Industrial Electronics Magazine*, *10*(3), 19-28. https://doi.org/10.1109/mie.2016.2588878

[68] Islam, M. N., & Helal, A. M. (2018). Primary school governance in Bangladesh: A practical overview of national education policy-2010. *International Journal for Cross-Disciplinary Subjects in Education (IJCDSE)*, 9(4).

[69] Jain, A., Ong, S. P., Hautier, G., Chen, W.-W., Richards, W. D., Dacek, S., Cholia, S., Gunter, D., Skinner, D., Ceder, G., & Persson, K. A. (2013). Commentary: The Materials Project: A materials genome approach to accelerating materials innovation. *APL Materials*, *1*(1), 011002-011002. https://doi.org/10.1063/1.4812323

[70] Jian, L., Zheng, Y., Xiao, X., & Chan, C. C. (2015). Optimal scheduling for vehicle-to-grid operation with stochastic connection of plug-in electric vehicles to smart grid. *Applied Energy*, *146*(NA), 150-161. https://doi.org/10.1016/j.apenergy.2015.02.030

[71] Jow, J., Xiao, Y., & Han, W. (2017). A survey of intrusion detection systems in smart grid. *International Journal of Sensor Networks*, *23*(3), 170-186. https://doi.org/10.1504/ijsnet.2017.083410

[72] Kabir, E., Guikema, S. D., & Quiring, S. M. (2019). Predicting Thunderstorm-Induced Power Outages to Support Utility Restoration. *IEEE Transactions on Power Systems*, *34*(6), 4370-4381. https://doi.org/10.1109/tpwrs.2019.2914214

[73] Kang, Y., Li, L., & Li, B. (2021). Recent progress on discovery and properties prediction of energy materials: Simple machine learning meets complex quantum chemistry. *Journal of Energy Chemistry*, *54*(NA), 72-88. https://doi.org/10.1016/j.jechem.2020.05.044

[74] Khan, I. (2019). Energy-saving behaviour as a demand-side management strategy in the developing world: the case of Bangladesh. *International Journal of Energy and Environmental Engineering*, *10*(4), 493-510. https://doi.org/10.1007/s40095-019-0302-3

[75] Khemmook, P., Suwan-ngam, W., & Khomfoi, S. (2015). Suitable power transformers for solar farm applications. *2015 12th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, *NA*(NA), 1-6. https://doi.org/10.1109/ecticon.2015.7206984

[76] Kim, B.-G., Ren, S., van der Schaar, M., & Lee, J.-W. (2013). Bidirectional Energy Trading and Residential Load Scheduling with Electric Vehicles in the Smart Grid. *IEEE Journal on Selected Areas in Communications*, *31*(7), 1219-1234. https://doi.org/10.1109/jsac.2013.130706

[77] Kimura, N., Morizane, T., Iyoda, I., Nakao, K., & Yokoyama, T. (2017). Solid state transformer investigation for HVDC transmission from offshore windfarm. *2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA)*, *NA*(NA), 574-579. https://doi.org/10.1109/icrera.2017.8191126

[78] La Tona, G., Luna, M., Di Piazza, A., & Di Piazza, M. C. (2019). Towards the Real-World Deployment of a Smart Home EMS: A DP Implementation on the Raspberry Pi. *Applied Sciences*, *9*(10), 2120-NA. https://doi.org/10.3390/app9102120

[79] Lamba, V., Šimková, N., & Rossi, B. (2019). Recommendations for smart grid security risk management. *Cyber-Physical Systems*, *5*(2), 92-118. https://doi.org/10.1080/23335777.2019.1600035

[80] Li, E., Zeng, L., Zhou, Z., & Chen, X. (2020). Edge AI: On-Demand Accelerating Deep Neural Network Inference via Edge Computing. *IEEE Transactions on Wireless Communications*, *19*(1), 447-457. https://doi.org/10.1109/twc.2019.2946140

[81] Li, S., Sun, Y., Ramezani, M., & Xiao, Y. (2019). Artificial Neural Networks for Volt/VAR Control of DER Inverters at the Grid Edge. *IEEE Transactions on Smart Grid*, *10*(5), 5564-5573. https://doi.org/10.1109/tsg.2018.2887080

[82] Li, Y., Lyu, X., & Cao, D. (2017). A Zero-Current-Switching High Conversion Ratio Modular Multilevel DC-DC Converter. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, *5*(1), 151-161. https://doi.org/10.1109/jestpe.2016.2623794

[83] Li, Z., Wang, P., Chu, Z., Zhu, H., Sun, Z., & Li, Y. (2013). A three-phase 10 kVAC-750 VDC power electronic transformer for smart distribution grid. *2013 15th European Conference on Power Electronics and Applications (EPE)*, *NA*(NA), 1-9. https://doi.org/10.1109/epe.2013.6631810

[84] Liao, X., Srinivasan, P., Formby, D., & Beyah, R. (2019). Di-PriDA: Differentially Private Distributed Load Balancing Control for the Smart Grid. *IEEE Transactions on Dependable and Secure Computing*, *16*(6), 1026-1039. https://doi.org/10.1109/tdsc.2017.2717826

[85] Lin, X., Sun, X., Manogaran, G., & Rawal, B. S. (2021). Advanced energy consumption system for smart farm based on reactive energy utilization technologies. *Environmental Impact Assessment Review*, *86*(NA), 106496-NA. https://doi.org/10.1016/j.eiar.2020.106496

[86] Lin, Y.-H. (2018). Design and Implementation of an IoT-Oriented Energy Management System Based on Non-Intrusive and Self-Organizing Neuro-Fuzzy Classification as an Electrical Energy Audit in Smart Homes. *Applied Sciences*, *8*(12), 2337-NA. https://doi.org/10.3390/app8122337

[87] Lin, Y.-H., & Tsai, M.-S. (2015). An Advanced Home Energy Management System Facilitated by Nonintrusive Load Monitoring With Automated Multiobjective Power Scheduling. *IEEE Transactions on Smart Grid*, *6*(4), 1839-1851. https://doi.org/10.1109/tsg.2015.2388492

[88] Liserre, M., Buticchi, G., Andresen, M., De Carne, G., Costa, L., & Zou, Z. (2016). The Smart Transformer: Impact on the Electric Grid and Technology Challenges. *IEEE Industrial Electronics Magazine*, *10*(2), 46-58. https://doi.org/10.1109/mie.2016.2551418

[89] Liu, B., Zha, Y., Zhang, T., & Chen, S. (2016). Solid state transformer application to grid connected photovoltaic inverters. *2016 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE)*, *NA*(NA), 248-251. https://doi.org/10.1109/icsgce.2016.7876063

[90] Liu, T., Li, Q., Huang, X., Lu, Y., Asif, M., & Wang, Z. (2018). Partial discharge behavior and ground insulation life expectancy under different voltage frequencies. *IEEE Transactions on Dielectrics and Electrical Insulation*, *25*(2), 603-613. https://doi.org/10.1109/tdei.2018.006810

[91] Liu, X., Li, H., & Wang, Z. (2012). A Start-Up Scheme for a Three-Stage Solid-State Transformer With Minimized Transformer Current Response. *IEEE Transactions on Power Electronics*, *27*(12), 4832-4836. https://doi.org/10.1109/tpel.2012.2200047

[92] Liu, Y., Esan, O. C., Pan, Z., & An, L. (2021). Machine learning for advanced energy materials. *Energy and AI*, *3*(NA), 100049-NA. https://doi.org/10.1016/j.egyai.2021.100049

[93] Liu, Y., Guo, B., Zou, X., Li, Y., & Shi, S. (2020). Machine learning assisted materials design and discovery for rechargeable batteries. *Energy Storage Materials*, *31*(NA), 434-450. https://doi.org/10.1016/j.ensm.2020.06.033

[94] Lopez, K. L., Gagné, C., & Gardner, M.-A. (2019). Demand-Side Management Using Deep Learning for Smart Charging of Electric Vehicles. *IEEE Transactions on Smart Grid*, *10*(3), 2683-2691. https://doi.org/10.1109/tsg.2018.2808247

[95] Lopez, M., Rodriguez, A., Blanco, E., Saeed, M., Martínez, A., & Briz, F. (2015). INDIN - Design and implementation of the control of an MMC-based solid state transformer. *2015 IEEE 13th International Conference on Industrial Informatics (INDIN)*, *NA*(NA), 1583-1590. https://doi.org/10.1109/indin.2015.7281970

[96] Madhusoodhanan, S., Mainali, K., Tripathi, A., Kadavelugu, A., Vechalapu, K., Patel, D., & Bhattacharya, S. (2016). Comparative evaluation of 15 kV SiC IGBT and 15 kV SiC MOSFET for 3-phase medium voltage high power grid connected converter applications. *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, *NA*(NA), 1-8. https://doi.org/10.1109/ecce.2016.7854933

[97] Madhusoodhanan, S., Mainali, K., Tripathi, A., Patel, D., Kadavelugu, A., Bhattacharya, S., & Hatua, K. (2015). Performance evaluation of 15 kV SiC IGBT based medium voltage grid connected three-phase three-level NPC converter. *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, *NA*(NA), 3710-3717. https://doi.org/10.1109/ecce.2015.7310184

[98] Madhusoodhanan, S., Tripathi, A., Patel, D., Mainali, K., Kadavelugu, A., Hazra, S., Bhattacharya, S., & Hatua, K. (2014). Solid State Transformer and MV grid tie applications enabled by 15 kV SiC IGBTs and 10 kV SiC MOSFETs based multilevel converters. *2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA)*, *NA*(NA), 1626-1633. https://doi.org/10.1109/ipec.2014.6869800

[99] Mahmood, A., Baig, F., Alrajeh, N., Qasim, U., Khan, Z. A., & Javaid, N. (2016). An Enhanced System Architecture for Optimized Demand Side Management in Smart Grid. *Applied Sciences*, *6*(5), 122-NA. https://doi.org/10.3390/app6050122

[100] Malinowski, M., Leon, J. I., & Abu-Rub, H. (2017). Solar Photovoltaic and Thermal Energy Systems: Current Technology and Future Trends. *Proceedings of the IEEE*, *105*(11), 2132-2146. https://doi.org/10.1109/jproc.2017.2690343

[101] Marian, M., Cusman, A., Stinga, F., Ionica, D., & Popescu, D. (2020). Experimenting With Digital Signatures Over a DNP3 Protocol in a Multitenant Cloud-Based SCADA Architecture. *IEEE Access*, *8*(NA), 156484-156503. https://doi.org/10.1109/access.2020.3019112

[102] Markakis, E. K., Nikoloudakis, Y., Lapidaki, K., Fiorentzis, K., & Karapidakis, E. S. (2021). Unification of Edge Energy Grids for Empowering Small Energy Producers. *Sustainability*, *13*(15), 8487-NA. https://doi.org/10.3390/su13158487

[103] Marques, G., Ferreira, C. R., & Pitarma, R. (2018). A System Based on the Internet of Things for Real-Time Particle Monitoring in Buildings. *International journal of environmental research and public health*, *15*(4), 821-NA. https://doi.org/10.3390/ijerph15040821

[104] Md Mahfuj, H., Md Rabbi, K., Mohammad Samiul, I., Faria, J., & Md Jakaria, T. (2022). Hybrid Renewable Energy Systems: Integrating Solar, Wind, And Biomass for Enhanced Sustainability And Performance. *American Journal of Scholarly Research and Innovation*, *1*(1), 1-24. https://doi.org/10.63125/8052hp43

[105] Md Majharul, I., Arafat Bin, F., & Ripan Kumar, P. (2022). AI-Based Smart Coating Degradation Detection For Offshore Structures. *American Journal of Advanced Technology and Engineering Solutions*, *2*(04), 01-34. https://doi.org/10.63125/1mn6bm51

[106] Md Takbir Hossen, S., & Md Atiqur, R. (2022). Advancements In 3D Printing Techniques For Polymer Fiber-Reinforced Textile Composites: A Systematic Literature Review. *American Journal of Interdisciplinary Studies*, *3*(04), 32-60. https://doi.org/10.63125/s4r5m391

[107] Mishra, S., Glaws, A., & Praveen, P. (2020). Predictive Analytics in Future Power Systems: A Panorama and State-Of-The-Art of Deep Learning Applications. In (Vol. NA, pp. 147-182). Springer International Publishing. https://doi.org/10.1007/978-3-030-34094-0_7

[108] Mohammadali, A., & Haghighi, M. S. (2021). A Privacy-Preserving Homomorphic Scheme With Multiple Dimensions and Fault Tolerance for Metering Data Aggregation in Smart Grid. *IEEE Transactions on Smart Grid*, *12*(6), 5212-5220. https://doi.org/10.1109/tsg.2021.3049222

[109] Mortaji, H., Ow, S. H., Moghavvemi, M., & Almurib, H. A. F. (2017). Load Shedding and Smart-Direct Load Control Using Internet of Things in Smart Grid Demand Response Management. *IEEE Transactions on Industry Applications*, *53*(6), 5155-5163. https://doi.org/10.1109/tia.2017.2740832

[110] Muhammad Mohiul, I., Morshed, A. S. M., Md Enamul, K., & Md, A.-A. (2022). Adaptive Control Of Resource Flow In Construction Projects Through Deep Reinforcement Learning: A Framework For Enhancing Project Performance In Complex Environments. *American Journal of Scholarly Research and Innovation*, *1*(01), 76-107. https://doi.org/10.63125/gm77xp11

[111] Murugan, N. S., & Devi, G. U. (2018). Detecting Streaming of Twitter Spam Using Hybrid Method. *Wireless Personal Communications*, *103*(2), 1353-1374. https://doi.org/10.1007/s11277-018-5513-z

[112] Musleh, A. S., Yao, G., & Muyeen, S. M. (2019). Blockchain Applications in Smart Grid–Review and Frameworks. *IEEE Access*, *7*(NA), 86746-86757. https://doi.org/10.1109/access.2019.2920682

[113] Nafi, N. S., Ahmed, K., Gregory, M. A., & Datta, M. (2016). A survey of smart grid architectures, applications, benefits and standardization. *Journal of Network and Computer Applications*, *76*(NA), 23-36. https://doi.org/10.1016/j.jnca.2016.10.003

[114] Naseer, O., Ullah, S., & Anjum, L. (2021). Blockchain-Based Decentralized Lightweight Control Access Scheme for Smart Grids. *Arabian Journal for Science and Engineering*, *46*(9), 1-11. https://doi.org/NA

[115] Nasir, T., Bukhari, S. S. H., Raza, S., Munir, H. M., Abrar, M., Muqeet, H. A. u., Bhatti, K. L., Ro, J.-S., & Masroor, R. (2021). Recent Challenges and Methodologies in Smart Grid Demand Side Management: State-of-the-Art Literature Review. *Mathematical Problems in Engineering*, *2021*, 1-16. https://doi.org/10.1155/2021/5821301

[116] Odabaşı, Ç., & Yildirim, R. (2020). Machine learning analysis on stability of perovskite solar cells. *Solar Energy Materials and Solar Cells*, *205*(NA), 110284-NA. https://doi.org/10.1016/j.solmat.2019.110284

[117] Odelu, V., Das, A. K., Wazid, M., & Conti, M. (2016). Provably Secure Authenticated Key Agreement Scheme for Smart Grid. *IEEE Transactions on Smart Grid*, *9*(3), 1-1. https://doi.org/10.1109/tsg.2016.2602282

[118] Oliveira, D. S., de A. Honorio, D., Barreto, L. H. S. C., Praca, P. P., Kunzea, A., & da Silva Carvalho, S. (2014). A two-stage AC/DC SST based on modular multilevel converterfeasible to AC railway systems. *2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014*, *NA*(NA), 1894-1901. https://doi.org/10.1109/apec.2014.6803564

[119] Onile, A. E., Machlev, R., Petlenkov, E., Levron, Y., & Belikov, J. (2021). Uses of the digital twins concept for energy services, intelligent recommendation systems, and demand side management: A review. *Energy Reports*, *7*(NA), 997-1015. https://doi.org/10.1016/j.egyr.2021.01.090

[120] Orupattur, N. V., Mushrif, S. H., & Prasad, V. (2020). Catalytic materials and chemistry development using a synergistic combination of machine learning and ab initio methods. *Computational Materials Science*, *174*(NA), 109474-NA. https://doi.org/10.1016/j.commatsci.2019.109474

[121] Ota, Y., Taniguchi, H., Nakajima, T., Liyanage, K. M., Baba, J., & Yokoyama, A. (2012). Autonomous Distributed V2G (Vehicle-to-Grid) Satisfying Scheduled Charging. *IEEE Transactions on Smart Grid*, *3*(1), 559-564. https://doi.org/10.1109/tsg.2011.2167993

[122] Otuoze, A. O., Mustafa, M. W., Sofimieari, I., Dobi, A. M., Sule, A. H., Abioye, A. E., & Saeed, M. S. (2019). Electricity theft detection framework based on universal prediction algorithm. *Indonesian Journal of Electrical Engineering and Computer Science*, *15*(2), 758-768. https://doi.org/10.11591/ijeecs.v15.i2.pp758-768

[123] Paladhi, S., & Ashok, S. (2015). Solid state transformer application in wind based DG system. *2015 IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES)*, *NA*(NA), 1-5. https://doi.org/10.1109/spices.2015.7091563

[124] Palensky, P., & Dietrich, D. (2011). Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads. *IEEE Transactions on Industrial Informatics*, *7*(3), 381-388. https://doi.org/10.1109/tii.2011.2158841

[125] Pang, C., Dutta, P., & Kezunovic, M. (2012). BEVs/PHEVs as Dispersed Energy Storage for V2B Uses in the Smart Grid. *IEEE Transactions on Smart Grid*, *3*(1), 473-482. https://doi.org/10.1109/tsg.2011.2172228

[126] Parseh, N., & Mohammadi, M. (2017). Solid State Transformer (SST) interfaced Doubly Fed Induction Generator (DFIG) wind turbine. *2017 Iranian Conference on Electrical Engineering (ICEE)*, *NA*(NA), 1084-1089. https://doi.org/10.1109/iraniancee.2017.7985202

[127] Pasha, A. M., Ibrahim, H. M., Hasan, S. R., Belkacemi, R., Awwad, F., & Hasan, O. (2018). A Utility Maximized Demand-Side Management for Autonomous Microgrid. *2018 IEEE Electrical Power and Energy Conference (EPEC)*, *NA*(NA), 1-5. https://doi.org/10.1109/epec.2018.8598451

[128] Pong, P. W. T., Annaswamy, A. M., Kroposki, B., Zhang, Y., Rajagopal, R., Zussman, G., & Poor, H. V. (2021). Cyber-enabled grids: Shaping future energy systems. *Advances in Applied Energy*, *1*(NA), 100003-NA. https://doi.org/10.1016/j.adapen.2020.100003

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eISSN: 3067-2163
Doi: 10.63125/6n1yka80

[129] Qin, H., & Kimball, J. W. (2013). Solid-State Transformer Architecture Using AC–AC Dual-Active-Bridge Converter. *IEEE Transactions on Industrial Electronics*, *60*(9), 3720-3730. https://doi.org/10.1109/tie.2012.2204710

[130] Ramirez, J. M., Barrios, R. A., & Salome, B. J. (2017). Details and implementation of a SiC-based solid state transformer prototype. *2017 IEEE PES Innovative Smart Grid Technologies Conference - Latin America (ISGT Latin America)*, *NA*(NA), 1-6. https://doi.org/10.1109/isgt-la.2017.8126690

[131] Remmen, P., Lauster, M., Mans, M., Fuchs, M., Osterhage, T., & Müller, D. (2017). TEASER: an open tool for urban energy modelling of building stocks. *Journal of Building Performance Simulation*, *11*(1), 84-98. https://doi.org/10.1080/19401493.2017.1283539

[132] Ripan Kumar, P., Md Majharul, I., & Arafat Bin, F. (2022). Integration Of Advanced NDT Techniques & Implementing QA/QC Programs In Enhancing Safety And Integrity In Oil & Gas Operations. *American Journal of Interdisciplinary Studies*, *3*(02), 01-35. https://doi.org/10.63125/9pzxgq74

[133] Sa'ed, J. A., Favuzza, S., Massaro, F., Musca, R., Zizzo, G., Cagnano, A., & De Tuglie, E. (2019). Effects of Demand Side Management on the Operation of an Isolated LV Microgrids. *2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, *NA*(NA), 1-6. https://doi.org/10.1109/eeeic.2019.8783548

[134] Saleem, M. U., Usman, M. R., Usman, M. A., & Politis, C. (2022). Design, Deployment and Performance Evaluation of an IoT Based Smart Energy Management System for Demand Side Management in Smart Grid. *IEEE Access*, *10*, 15261-15278. https://doi.org/10.1109/access.2022.3147484

[135] Samudrala, A. N., Amini, M. H., Kar, S., & Blum, R. S. (2020). Distributed Outage Detection in Power Distribution Networks. *IEEE Transactions on Smart Grid*, *11*(6), 5124-5137. https://doi.org/10.1109/tsg.2020.2999921

[136] Sharmila, P., Baskaran, J., Nayanatara, C., & Maheswari, R. (2019). A hybrid technique of machine learning and data analytics for optimized distribution of renewable energy resources targeting smart energy management. *Procedia Computer Science*, *165*(NA), 278-284. https://doi.org/10.1016/j.procs.2020.01.076

[137] Shaukat, N., Ali, S. M., Mehmood, C. A., Khan, B., Jawad, M., Farid, U., Ullah, Z., Anwar, S. M., & Majid, M. (2018). A survey on consumers empowerment, communication technologies, and renewable generation penetration within Smart Grid. *Renewable and Sustainable Energy Reviews*, *81*(NA), 1453-1475. https://doi.org/10.1016/j.rser.2017.05.208

[138] She, X., Huang, A. Q., Wang, F., & Burgos, R. (2013). Wind Energy System With Integrated Functions of Active Power Transfer, Reactive Power Compensation, and Voltage Conversion. *IEEE Transactions on Industrial Electronics*, *60*(10), 4512-4524. https://doi.org/10.1109/tie.2012.2216245

[139] Shi, Z., Yang, W., Deng, X., Cai, C., Yan, Y., Liang, H., Liu, Z., & Qiao, Z. (2020). Machine-learning-assisted high-throughput computational screening of high performance metal–organic frameworks. *Molecular Systems Design & Engineering*, *5*(4), 725-742. https://doi.org/10.1039/d0me00005a

[140] Si, F., Han, Y., Wang, J., & Zhao, Q. (2021). Connectivity Verification in Distribution Systems Using Smart Meter Voltage Analytics: A Cloud-Edge Collaboration Approach. *IEEE Transactions on Industrial Informatics*, *17*(6), 3929-3939. https://doi.org/10.1109/tii.2020.3012138

[141] Sohel, A., Alam, M. A., Hossain, A., Mahmud, S., & Akter, S. (2022). Artificial Intelligence In Predictive Analytics For Next-Generation Cancer Treatment: A Systematic Literature Review Of Healthcare Innovations In The USA. *Global Mainstream Journal of Innovation, Engineering & Emerging Technology*, *1*(01), 62-87. https://doi.org/10.62304/jieet.v1i01.229

[142] Sojoudi, S., & Low, S. H. (2011). Optimal charging of plug-in hybrid electric vehicles in smart grids. *2011 IEEE Power and Energy Society General Meeting*, *NA*(NA), 1-6. https://doi.org/10.1109/pes.2011.6039236

[143] Son, J.-Y., & Ma, K. (2017). Wind Energy Systems. *Proceedings of the IEEE*, *105*(11), 2116-2131. https://doi.org/10.1109/jproc.2017.2695485

[144] Su, W., Eichi, H. R., Zeng, W., & Chow, M.-Y. (2012). A Survey on the Electrification of Transportation in a Smart Grid Environment. *IEEE Transactions on Industrial Informatics*, *8*(1), 1-10. https://doi.org/10.1109/tii.2011.2172454

[145] Su, W., Wang, J., & Roh, J. H. (2014). Stochastic Energy Scheduling in Microgrids With Intermittent Renewable Energy Resources. *IEEE Transactions on Smart Grid*, *5*(4), 1876-1883. https://doi.org/10.1109/tsg.2013.2280645

[146] Sultan, V., Aryal, A., Chang, H., & Kral, J. (2022). Integration of EVs into the smart grid: a systematic literature review. *Energy Informatics*, *5*(1). https://doi.org/10.1186/s42162-022-00251-2

[147] Sun, M., Zhang, T., Wang, Y., Strbac, G., & Kang, C. (2020). Using Bayesian Deep Learning to Capture Uncertainty for Residential Net Load Forecasting. *IEEE Transactions on Power Systems*, *35*(1), 188-201. https://doi.org/10.1109/tpwrs.2019.2924294

[148] Sureshkumar, V., Anandhi, S., Amin, R., Selvarajan, N., & Madhumathi, R. (2021). Design of Robust Mutual Authentication and Key Establishment Security Protocol for Cloud-Enabled Smart Grid Communication. *IEEE Systems Journal*, *15*(3), 3565-3572. https://doi.org/10.1109/jsyst.2020.3039402

[149] Tan, Z., Yang, P., & Nehorai, A. (2014). An Optimal and Distributed Demand Response Strategy With Electric Vehicles in the Smart Grid. *IEEE Transactions on Smart Grid*, *5*(2), 861-869. https://doi.org/10.1109/tsg.2013.2291330

[150] Tayade, A. M., Dhote, V. P., & Thosar, A. (2018). Demand Side Management and Voltage Regulation in Microgrid Using Electric Spring. *2018 International Conference on Emerging Trends and Innovations In Engineering And Technological Research (ICETIETR)*, *NA*(NA), 1-4. https://doi.org/10.1109/icetietr.2018.8529109

[151] Tayal, D. (2017). Achieving high renewable energy penetration in Western Australia using data digitisation and machine learning. *Renewable and Sustainable Energy Reviews*, *80*(NA), 1537-1543. https://doi.org/10.1016/j.rser.2017.07.040

[152] Teh, J., Cheng, Y.-H., & Lai, C.-M. (2018). Impact of Demand Side Management and Dynamic Thermal Rating System on the Reliability of Power Systems. *2018 International Symposium on Computer, Consumer and Control (IS3C)*, *NA*(NA), 350-355. https://doi.org/10.1109/is3c.2018.00095

[153] Tom, B. M., & Ashok, S. (2017). Solid state transformer for wind power interfacing. *2017 IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES)*, *NA*(NA), 1-6. https://doi.org/10.1109/spices.2017.8091314

[154] Tom, R. J., Sankaranarayanan, S., de Albuquerque, V. H. C., & Rodrigues, J. J. P. C. (2020). Aggregator based RPL for an IoT-fog based power distribution system with 6LoWPAN. *China Communications*, *17*(1), 104-117. https://doi.org/10.23919/jcc.2020.01.008

[155] Tomic, S., Fensel, A., Schwanzer, M., Veljovic, M., & Stefanovic, M. (2011). Applied Semantic Web Technologies - Semantics for Energy Efficiency in Smart Home Environments. In (Vol. NA, pp. 429-454). Auerbach Publications. https://doi.org/10.1201/b11085-21

[156] Tonoy, A. A. R. (2022). Mechanical Properties and Structural Stability of Semiconducting Electrides: Insights For Material. *Global Mainstream Journal of Innovation, Engineering & Emerging Technology*, *1*(01), 18-35. https://doi.org/10.62304/jieet.v1i01.225

[157] Toyao, T., Suzuki, K., Kikuchi, S., Takakusagi, S., Shimizu, K.-i., & Takigawa, I. (2018). Toward Effective Utilization of Methane: Machine Learning Prediction of Adsorption Energies on Metal Alloys. *The Journal of Physical Chemistry C*, *122*(15), 8315-8326. https://doi.org/10.1021/acs.jpcc.7b12670

[158] Tran, N. N., Pota, H. R., Tran, Q. N., & Hu, J. (2021). Designing Constraint-Based False Data-Injection Attacks Against the Unbalanced Distribution Smart Grids. *IEEE Internet of Things Journal*, *8*(11), 9422-9435. https://doi.org/10.1109/jiot.2021.3056649

[159] Tuna, G., Kogias, D. G., Gungor, V. C., Gezer, C., Takn, E., & Ayday, E. (2017). A survey on information security threats and solutions for Machine to Machine (M2M) communications. *Journal of Parallel and Distributed Computing*, *109*(NA), 142-154. https://doi.org/10.1016/j.jpdc.2017.05.021

[160] Tushar, W., Saad, W., Poor, H. V., & Smith, D. (2012). Economics of Electric Vehicle Charging: A Game Theoretic Approach. *IEEE Transactions on Smart Grid*, *3*(4), 1767-1778. https://doi.org/10.1109/tsg.2012.2211901

[161] Vachirasricirikul, S., & Ngamroo, I. (2014). Robust LFC in a Smart Grid With Wind Power Penetration by Coordinated V2G Control and Frequency Controller. *IEEE Transactions on Smart Grid*, *5*(1), 371-380. https://doi.org/10.1109/tsg.2013.2264921

[162] Vasudevan, R. K., Choudhary, K., Mehta, A., Smith, R. P., Kusne, G., Tavazza, F., Vlcek, L., Ziatdinov, M., Kalinin, S. V., & Hattrick-Simpers, J. R. (2019). Materials science in the artificial intelligence age: high-throughput library generation, machine learning, and a pathway from correlations to the underpinning physics. *MRS communications*, 9(3), 821-838. https://doi.org/10.1557/mrc.2019.95

[163] Verhees, B., Raven, R., Kern, F., & Smith, A. (2015). The role of policy in shielding, nurturing and enabling offshore wind in The Netherlands (1973–2013). *Renewable and Sustainable Energy Reviews*, *47*(NA), 816-829. https://doi.org/10.1016/j.rser.2015.02.036

[164] Viani, F., & Salucci, M. (2018). A User Perspective Optimization Scheme for Demand-Side Energy Management. *IEEE Systems Journal*, *12*(4), 3857-3860. https://doi.org/10.1109/jsyst.2017.2720628

[165] Wang, D., Chen, M., & Wang, W. (2019). Distributed Extremum Seeking for Optimal Resource Allocation and Its Application to Economic Dispatch in Smart Grids. *IEEE transactions on neural networks and learning systems*, *30*(10), 3161-3171. https://doi.org/10.1109/tnnls.2018.2890115

[166] Wang, F., Zhang, Z., Ericsen, T., Raju, R. N., Burgos, R., & Boroyevich, D. (2015). Advances in Power Conversion and Drives for Shipboard Systems. *Proceedings of the IEEE*, *103*(12), 2285-2311. https://doi.org/10.1109/jproc.2015.2495331

[167] Wang, G., Baek, S., Elliott, J., Kadavelugu, A., Wang, F., She, X., Dutta, S., Liu, Y., Zhao, T., Yao, W., Gould, R. D., Bhattacharya, S., & Huang, A. Q. (2011). Design and hardware implementation of Gen-1 silicon based solid state transformer. *2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, *NA*(NA), 1344-1349. https://doi.org/10.1109/apec.2011.5744766

[168] Wang, G., Xu, Z., Wen, F., & Wong, K. P. (2013). Traffic-Constrained Multiobjective Planning of Electric-Vehicle Charging Stations. *IEEE Transactions on Power Delivery*, *28*(4), 2363-2372. https://doi.org/10.1109/tpwrd.2013.2269142

[169] Wazid, M., Das, A. K., Kumar, N., & Rodrigues, J. J. P. C. (2017). Secure Three-Factor User Authentication Scheme for Renewable-Energy-Based Smart Grid Environment. *IEEE Transactions on Industrial Informatics*, *13*(6), 3144-3153. https://doi.org/10.1109/tii.2017.2732999

[170] Wen, S., Zhang, C., Lan, H., Xu, Y., Tang, Y., & Huang, Y. (2021). A Hybrid Ensemble Model for Interval Prediction of Solar Power Output in Ship Onboard Power Systems. *IEEE Transactions on Sustainable Energy*, *12*(1), 14-24. https://doi.org/10.1109/tste.2019.2963270

[171] Xu, Z., Han, G., Zhu, H., Liu, L., & Guizani, M. (2021). Adaptive DE Algorithm for Novel Energy Control Framework Based on Edge Computing in IIoT Applications. *IEEE Transactions on Industrial Informatics*, *17*(7), 5118-5127. https://doi.org/10.1109/tii.2020.3007644

[172] Yaacoub, E., & Abu-Dayya, A. (2014). Automatic meter reading in the smart grid using contention based random access over the free cellular spectrum. *Computer Networks*, *59*(NA), 171-183. https://doi.org/10.1016/j.bjp.2013.10.009

[173] Yang, L., He, M., Zhang, J., & Vittal, V. (2015). Support-Vector-Machine-Enhanced Markov Model for Short-Term Wind Power Forecast. *IEEE Transactions on Sustainable Energy*, *6*(3), 791-799. https://doi.org/10.1109/tste.2015.2406814

[174] Ye, F., Qian, Y., & Hu, R. Q. (2016). A Real-Time Information Based Demand-Side Management System in Smart Grid. *IEEE Transactions on Parallel and Distributed Systems*, *27*(2), 329-339. https://doi.org/10.1109/tpds.2015.2403833

[175] Younus, M. (2022). Reducing Carbon Emissions in The Fashion And Textile Industry Through Sustainable Practices and Recycling: A Path Towards A Circular, Low-Carbon Future. *Global Mainstream Journal of Business, Economics, Development & Project Management*, *1*(1), 57-76. https://doi.org/10.62304/jbedpm.v1i1.226

[176] Yu, R., Zhong, W., Xie, S., Yuen, C., Gjessing, S., & Zhang, Y. (2016). Balancing Power Demand Through EV Mobility in Vehicle-to-Grid Mobile Energy Networks. *IEEE Transactions on Industrial Informatics*, *12*(1), 79-90. https://doi.org/10.1109/tii.2015.2494884

[177] Yun, H.-J., Kim, H. S., Ryu, M.-H., Baek, J.-W., & Kim, H.-J. (2015). A simple and practical voltage balance method for a solid-state transformer using cascaded H-bridge converters. *2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia)*, *NA*(NA), 2415-2420. https://doi.org/10.1109/icpe.2015.7168109

[178] Zengin, S., & Boztepe, M. (2014). Modified dual active bridge photovoltaic inverter for solid state transformer applications. *2014 International Symposium on Fundamentals of Electrical Engineering (ISFEE)*, *NA*(NA), 1-4. https://doi.org/10.1109/isfee.2014.7050613

[179] Zengin, S., & Boztepe, M. (2015). Trapezoid current modulated DCM AC/DC DAB converter for two-stage solid state transformer. *2015 9th International Conference on Electrical and Electronics Engineering (ELECO)*, *NA*(NA), 634-638. https://doi.org/10.1109/eleco.2015.7394538

[180] Zhang, H., Wang, J., & Ding, Y. (2019). Blockchain-based decentralized and secure keyless signature scheme for smart grid. *Energy*, *180*(NA), 955-967. https://doi.org/10.1016/j.energy.2019.05.127

[181] Zhang, J., & Tao, D. (2021). Empowering Things With Intelligence: A Survey of the Progress, Challenges, and Opportunities in Artificial Intelligence of Things. *IEEE Internet of Things Journal*, *8*(10), 7789-7817. https://doi.org/10.1109/jiot.2020.3039359

[182] Zhang, L., He, M., & Shao, S. (2020). Machine learning for halide perovskite materials. *Nano Energy*, *78*(NA), 105380-NA. https://doi.org/10.1016/j.nanoen.2020.105380

[183] Zhang, Y., Huang, T., & Bompard, E. F. (2018). Big data analytics in smart grids: a review. *Energy Informatics*, *1*(1), 1-24. https://doi.org/10.1186/s42162-018-0007-5

[184] Zhao, T., Wang, G., Bhattacharya, S., & Huang, A. Q. (2013). Voltage and Power Balance Control for a Cascaded H-Bridge Converter-Based Solid-State Transformer. *IEEE Transactions on Power Electronics*, *28*(4), 1523-1532. https://doi.org/10.1109/tpel.2012.2216549

[185] Zhao, W., Zhang, H., Zheng, J., Dai, Y., Huang, L., Shang, W., & Liang, Y. (2021). A point prediction method based automatic machine learning for day-ahead power output of multi-region photovoltaic plants. *Energy*, *223*(NA), 120026-NA. https://doi.org/10.1016/j.energy.2021.120026

[186] Zhao, Z., Lee, W. C., Shin, Y., & Song, K.-B. (2013). An Optimal Power Scheduling Method for Demand Response in Home Energy Management System. *IEEE Transactions on Smart Grid*, *4*(3), 1391-1400. https://doi.org/10.1109/tsg.2013.2251018

[187] Zhou, M., Gallegos, A., Liu, K., Dai, S., & Wu, J. (2020). Insights from machine learning of carbon electrodes for electric double layer capacitors. *Carbon*, *157*(NA), 147-152. https://doi.org/10.1016/j.carbon.2019.08.090

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Page No: 186-219
eISSN: 3067-2163
Doi: 10.63125/6n1yka80

[188] Zhou, Y., Zheng, S., Liu, Z., Wen, T., Ding, Z., Yan, J., & Zhang, G. (2020). Passive and active phase change materials integrated building energy systems with advanced machine-learning based climate-adaptive designs, intelligent operations, uncertainty-based analysis and optimisations: A state-of-the-art review. *Renewable and Sustainable Energy Reviews*, *130*(NA), 109889-NA. https://doi.org/10.1016/j.rser.2020.109889

[189] Zhou, Y., Zheng, S., & Zhang, G. (2020). A state-of-the-art-review on phase change materials integrated cooling systems for deterministic parametrical analysis, stochastic uncertainty-based design, single and multi-objective optimisations with machine learning applications. *Energy and Buildings*, *220*(NA), 110013-NA. https://doi.org/10.1016/j.enbuild.2020.110013