

# Power Transformers: Evolution, Challenges and Emerging Trends in Electrical Power Systems

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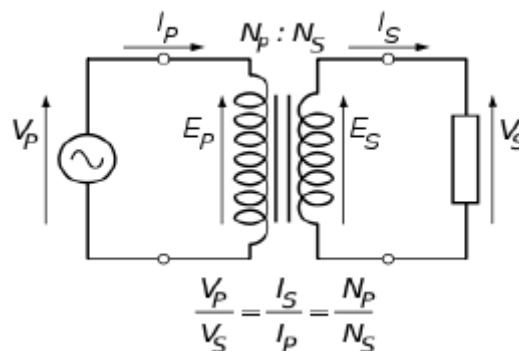
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**Abstract:** This research article presents an in-depth examination of power transformers, their evolution, market issues, and new trends in electrical power systems. Power transformers play an important role in maintaining efficient and stable electrical supply, affecting industries, infrastructure, and households. The importance of power transformers in supporting manufacturing processes, infrastructure resilience, renewable energy integration, and daily home activities is discussed in the article. It focuses on the changing landscape of power transformer technology, such as advances in core materials, insulation methods, cooling approaches, and smart grid integration. The power transformer industry's concerns, such as aging infrastructure, grid integration of renewable energy, energy efficiency, and cyber security, are addressed.

**Keywords:** Power transformers, evolution, challenges, emerging trends, electrical power systems,

## I. INTRODUCTION

A power transformer is a static electrical device that uses electromagnetic induction to transmit electrical energy between two or more electrical circuits. Its major role is to increase or decrease voltage levels while keeping the power frequency constant. Power transformers enable the effective transmission, distribution, and application of electrical energy, assuring dependable power supply to a variety of industries [1]. Power transformers are essential components of electrical power systems because they allow for the effective transmission and distribution of electricity. They are critical components that allow power generated at producing stations to be stepped up at high voltages for long-distance transmission and then stepped down to lower voltages for consumer distribution. Power transformers' principal role is to transfer electrical energy between two or more electrical circuits via electromagnetic induction. They achieve this through the use of a pair of mutually connected coils known as the primary and secondary windings [2]. The primary winding is connected to the system's high-voltage side, while the secondary winding is connected to the system's low-voltage side.



**Figure 1 Schematic Diagram of Ideal Transformer**

Power transformers work on the basis of electromagnetic induction. A fluctuating magnetic field is created when an alternating current travels through the primary winding. Through mutual induction, this magnetic field creates a voltage in the secondary winding, allowing power transfer between the windings [3]. Power transformer operating circumstances include factors such as load changes, temperature, insulation age, and electrical stressors. Transformers must be built to manage the rated voltage and current levels while staying within the temperature restrictions [4]. Cooling systems preserve the transformer operating within safe temperature levels. There are several varieties of power transformers, each designed for a certain application, such as:

**Step-Up Transformers:** These transformers increase the voltage level from the primary side to the secondary side, typically used for transmission purposes.

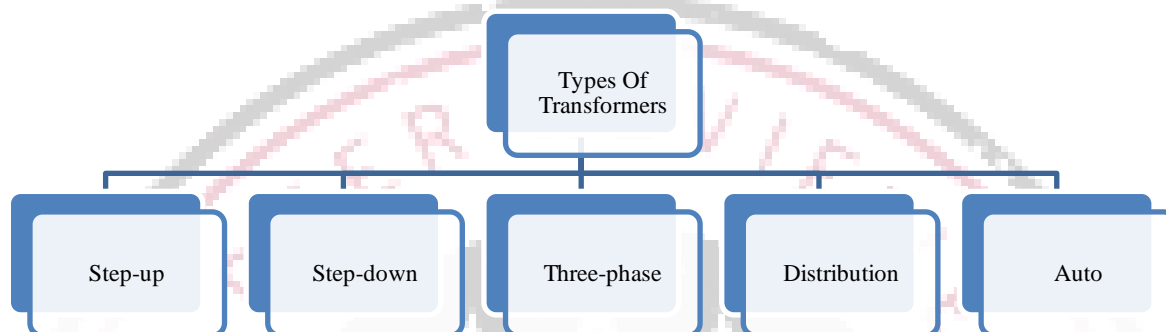
**Step-Down Transformers:** Step-down transformers decrease the voltage level from the primary side to the secondary side, suitable for distribution and utilization purposes.

**Three-Phase Transformers:** Three-phase transformers have three primary and three secondary windings, commonly used in three-phase power systems for efficient transmission and distribution.

**Auto-Transformers:** Auto-transformers have a shared winding acting as both the primary and secondary winding. They are more compact and cost-effective than traditional transformers but offer limited isolation between the primary and secondary sides.

**Distribution Transformers:** Distribution transformers are primarily used for voltage transformation in local distribution networks, delivering power to residential, commercial, and industrial areas [6].

**Instrument Transformers:** Instrument transformers, such as current transformers (CTs) and voltage transformers (VTs), are used to step down high currents and voltages for measurement and protection purposes.



**Figure 2 Different Types of Transformers**

The significance of power transformers lies in their ability to increase or decrease voltage levels while maintaining the power frequency. This voltage transformation is crucial for several reasons [5]:

- **Efficient Transmission:** Power transformers allow electrical energy to be transmitted at high voltages, reducing the transmission losses associated with long-distance power transmission. By stepping up the voltage, power transformers enable the use of high-voltage transmission lines, which have lower resistance and, therefore, minimize power losses.
- **Load Adaptation:** Power transformers enable the adaptation of voltage levels to suit different load requirements. They step down the high transmission voltages to lower voltages suitable for distribution to residential, commercial, and industrial consumers. This ensures that electricity is delivered at the appropriate voltage levels for safe and efficient utilization.
- **Grid Interconnection:** Power transformers facilitate the interconnection of different parts of the electrical power grid, enabling the transfer of power between regions and countries. They provide the necessary voltage transformation and synchronization required to integrate power from various generating sources and balance the load across the grid.
- **System Stability and Reliability:** Power transformers contribute to the stability and reliability of electrical power systems by providing voltage regulation, impedance matching, and fault isolation capabilities. They help maintain a steady voltage profile, protect the system from voltage fluctuations, and isolate faulty sections to minimize disruptions.

Power transformers are critical in the industrial sector for ensuring uninterrupted power distribution to support manufacturing operations, production lines, and automation. They efficiently lower high-voltage power to levels acceptable for industrial gear, so increasing productivity, reducing downtime, and improving operational efficiency. Power transformers are the backbone of electrical systems, supplying dependable power to transportation networks, healthcare facilities, telecommunications, and educational institutions [6]. They ensure that power is available for key services, emergency systems, and infrastructure resilience. Furthermore, power transformers play an important role in integrating renewable energy sources into the grid by increasing or decreasing voltage levels and synchronizing the varied outputs of solar and wind power. This allows for a more sustainable and environmentally friendly energy mix. Power transformers provide electricity to residential areas, enabling daily activities such as powering appliances, lighting, and electronic gadgets [7]. They are critical in sustaining individuals' and families' comfort, convenience, and quality of life. Overall, power transformers help to maintain grid stability and resilience by regulating voltage levels, balancing load distribution, and protecting against faults. Their importance extends beyond guaranteeing consistent power supply to supporting economic activity and improving the overall sustainability of electrical power networks.

## II. EVOLUTION OF POWER TRANSFORMER TECHNOLOGY

The evolution of power transformer technology has been a dynamic process driven by the need for increased efficiency, reliability, and environmental considerations. Over the years, several significant advancements and innovations have

shaped the field of power transformers. Here are some key aspects of the evolution of power transformer technology [8-16]:

- **Core Materials:** The development of new core materials has been instrumental in improving the efficiency of power transformers. Traditional transformer cores made of iron were replaced by more advanced materials like silicon steel, which reduced core losses and improved overall efficiency. Further advancements led to the use of amorphous and nanocrystalline materials that offer even higher efficiency and lower losses.
- **Insulation Systems:** Insulation plays a crucial role in the performance and reliability of power transformers. The evolution of insulation systems has focused on enhancing dielectric strength, thermal stability, and resistance to electrical and environmental stresses. Materials like oil-impregnated paper (OIP) and mineral oil were traditionally used, but modern transformers have seen the adoption of advanced insulation materials such as ester liquids and solid insulation systems like epoxy resin and composite materials.
- **High-Voltage Designs:** With the increasing demand for high-voltage transmission, power transformers have undergone significant developments to accommodate higher voltage levels. This includes the design of larger and more efficient windings, improvements in cooling techniques, and advancements in insulation systems to withstand higher electric fields and stresses.
- **Cooling Techniques:** Efficient cooling is vital for the optimal performance and longevity of power transformers. Traditional methods involved natural oil convection cooling or forced air cooling. However, newer cooling techniques like oil forced water cooling (OFWC) and direct liquid immersion cooling (DLIC) have emerged, offering improved heat dissipation and enhanced transformer efficiency.
- **Diagnostic and Monitoring Systems:** The evolution of power transformer technology includes the integration of advanced diagnostic and monitoring systems. These systems employ various sensors, such as temperature sensors, dissolved gas analysis (DGA), and partial discharge (PD) detectors, to monitor the condition of transformers in real-time. This allows for early detection of potential issues, predictive maintenance, and improved reliability [7, 8].
- **Eco-Friendly Designs:** Environmental considerations have played a significant role in the evolution of power transformers. There has been a growing focus on developing eco-friendly designs that reduce the environmental impact of transformers. This includes the use of alternative, biodegradable dielectric fluids such as vegetable-based oils or synthetic esters, which offer better environmental compatibility and fire safety.
- **Smart Grid Integration:** Power transformers are increasingly being integrated into smart grid systems. This involves the incorporation of communication and monitoring technologies that enable remote monitoring, control, and coordination of transformer operations. Smart grid integration improves the efficiency, reliability, and flexibility of power systems [12,13].

### III. EMERGING TRENDS – RELATED WORK

**Islam et al. (2018)** conducted a comprehensive assessment of condition monitoring methodologies and diagnostic tests for determining the lifetime of power transformers. The study underlines the need of effective condition monitoring in ensuring the dependability and lifetime of power transformers. The authors describe several approaches such as dissolved gas analysis (DGA), partial discharge (PD) measurement, thermography, and vibration analysis. They present an explanation of the principles, benefits, and limitations of each technique and emphasize the importance of integrating different techniques for accurate diagnosis and estimation of transformer health.

**Senobari et al. (2018)** concentrated on the use of frequency response analysis (FRA) in power transformer problem detection and localisation. The research looks at the ideas and methodology of FRA, which include studying a transformer's frequency response to uncover internal faults and mechanical difficulties. The authors cover several fault detection and localization methodologies, data interpretation approaches, and the obstacles associated with precise fault detection and location. They highlight FRA's promise as a non-intrusive technology for transformer diagnostics, as well as its utility in preventative maintenance programs.

**Christina et al. (2018)** did a thorough investigation into transformer breakdowns and diagnostic procedures. The study reveals a variety of transformer failure reasons, including aging, insulation deterioration, mechanical stress, and electrical problems. The authors address various diagnostic approaches such as oil analysis, DGA, PD measurement, and electrical and mechanical parameter monitoring. They underline the significance of a holistic approach to transformer diagnostics, incorporating numerous methodologies and taking into account diverse failure mechanisms in order to increase transformer dependability and longevity.

**Vinogradov et al. (2020)** present a mobile measuring complex intended for an electric network survey. Various sensors and monitoring devices are integrated into the complex to analyze the health and performance of power transformers and other network components. The authors highlight the complex's characteristics and capabilities, including as real-time data

collecting, remote monitoring, and fault detection methods. They emphasize the complex's potential for enabling condition monitoring and preventative maintenance of power transformers in electrical networks.

**Vinogradov et al. (2019)** describe a system for tracking power outages, duration, and power quality in low-voltage electrical networks. While the study does not focus primarily on transformers, it does provide insights into the monitoring and diagnostic capabilities required to keep electrical networks reliable. The authors talk about the system's design and execution, which comprises data acquisition units, communication infrastructure, and analysis tools. They underline the significance of monitoring power quality measures in order to detect potential transformer issues and improve overall network performance.

**Zhang et al. (2022)** explore the integration of buildings into distribution networks while taking power transformer loading capability and distribution network reconfiguration into account. While the study largely focuses on building integration, it emphasizes the need of analyzing transformer loads and its impact on network performance. The authors present methods for analyzing transformer loading while taking into account aspects like as building demand, distribution network topology, and operational restrictions. They underline the necessity for optimization strategies to manage transformer loading and increase distribution network energy efficiency.

**Yue et al. (2018)** provide an all-encompassing power losses model for electronic power transformers. The research focuses on precisely modeling and estimating power losses in electronic power transformers while taking into account a variety of parameters such as magnetic core materials, winding structures, and operating circumstances. The authors cover the formulation of the loss model and its experimental confirmation. They underline the significance of accurate loss modeling in the design and optimization of electronic power transformers, which leads to higher efficiency and performance.

**Karimov (2020)** conducts research on the current state of the subject of improving the quality of electricity in power supply networks. While the study does not particularly target power transformers, it does cover the broader topic of enhancing electric energy quality. The author examines numerous power quality issues such as harmonics, voltage fluctuations, and power factor, as well as approaches and technology to improve power quality. The study emphasizes the significance of maintaining a consistent and high-quality electric power supply, which influences the performance and longevity of power transformers indirectly.

**Afrasiabi et al. (2019)** investigate the integration of an accelerated deep neural network into power transformer differential protection. The study addresses the challenge of accurately detecting internal faults in power transformers using differential protection schemes. The authors propose a deep neural network-based approach to enhance the accuracy and efficiency of differential protection. They discuss the architecture of the network, training methodologies, and validation results. The study demonstrates the potential of deep learning techniques in improving the reliability and sensitivity of power transformer differential protection.

**Murugan and Ramasamy (2019)** concentrate on understanding power transformer component failures for health index-based maintenance planning in electric utilities. The study studies the failure modes and patterns of power transformer components such as windings, insulation systems, and cooling systems in order to provide a thorough understanding of failure mechanisms. The authors underline the relevance of condition monitoring and health index-based maintenance planning in ensuring the dependability and durability of power transformers. They go over the procedures for calculating health indicators and establishing maintenance programs based on criticality and risk assessment.

**Aizpurua et al. (2018)** propose a methodology for power transformer dissolved gas analysis (DGA) using Bayesian networks and hypothesis testing. The study focuses on analyzing the gases dissolved in transformer oil as an indicator of potential faults or abnormalities. The authors discuss the development of Bayesian network models to infer fault probabilities based on DGA data. They also present a hypothesis testing framework to validate the accuracy and reliability of the fault diagnosis. The study demonstrates the effectiveness of the proposed approach in enhancing the reliability and efficiency of power transformer condition monitoring.

**Lin et al. (2018)** propose a prediction method for power transformer running state based on a Long Short-Term Memory (LSTM) Deep Belief Network (DBN). The study focuses on developing an accurate and reliable prediction model for power transformer conditions. The authors discuss the architecture and training process of the LSTM\_DBN network, which incorporates deep learning techniques to capture temporal dependencies in transformer operating data. The study demonstrates the effectiveness of the proposed method in predicting power transformer conditions, facilitating proactive maintenance and ensuring reliable operation.

**Roncero-Clemente and Roanes-Lozano (2018)** present a multi-criteria computer package for power transformer fault detection and diagnosis. The study addresses the challenge of effectively detecting and diagnosing faults in power transformers by integrating multiple criteria and analytical techniques. The authors discuss the design and implementation of the computer package, which includes fault detection algorithms, fault diagnosis modules, and decision-making tools. The study emphasizes the importance of a comprehensive approach that considers multiple criteria, such as insulation condition, DGA results, and electrical parameters, for accurate fault detection and diagnosis.

**Table 1 Summary of the related work**

Study	Application	Work Done	Result Outcome	Limitations
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1) Islam, M. M., et al. (2018)	Lifetime estimation of power transformers	Review of condition monitoring techniques and diagnostic tests	Identification of effective techniques for lifetime estimation	Limited focus on condition monitoring techniques
2) Vinogradov, A., et al. (2020)	Electric network survey	Development of a mobile measuring complex	Improved efficiency in conducting electric network surveys	Limited discussion on renewable energy integration
3) Vinogradov, A., et al. (2019)	Power outage monitoring and power quality in 0.38 kV networks	Development of a monitoring system	Enhanced monitoring of power outages and power quality	Narrow focus on power quality in 0.38 kV networks
4) Senobari, R. K., et al. (2018)	Fault detection and location in transformers	Review of frequency response analysis (FRA)	Identification of FRA as an effective fault detection tool	Limited discussion on other fault detection methods
5) Christina, A., et al. (2018)	Transformer failure causes and diagnostic methods	Review of transformer failure causes and diagnostic methods	Comprehensive understanding of transformer failures	Limited discussion on advanced diagnostic methods
6) Zhang, Y., et al. (2022)	Buildings-to-distribution-network integration	Proposal of an integrated approach	Consideration of power transformer loading capability	Limited focus on distribution network reconfiguration
7) Yue, Q., et al. (2018)	Electronic power transformer power losses model	Development of a comprehensive power losses model	Accurate estimation of power losses in electronic transformers	Limited focus on other power transformer components
8) Karimov, R. (2020)	Increasing the quality of electric energy in power systems	Study of improving the quality of electric energy	Enhanced understanding of power quality improvement	Limited focus on specific power system improvement methods
9) Afrasiabi, S., et al. (2019)	Power transformer differential protection using deep neural network	Integration of deep neural network into differential protection	Improved accuracy and performance in differential protection	Limited discussion on other methods of power transformer protection
10) Murugan, R., & Ramasamy, R. (2019)	Health index-based maintenance planning in electric utilities	Investigation of power transformer component failures	Effective health index-based maintenance planning	Limited discussion on other maintenance planning approaches
11) Aizpurua, J. I., et al. (2018)	Power transformer dissolved gas analysis	Application of Bayesian networks and hypothesis testing	Improved fault detection through dissolved gas analysis	Limited discussion on other transformer diagnostic techniques
12) Lin, J., et al. (2018)	Power transformer state prediction using LSTM_DBN network	Proposal of a prediction method using LSTM_DBN network	Accurate prediction of power transformer running state	Limited evaluation of the proposed prediction method
13) Roncero-Clemente, C., & Roanes-Lozano, E. (2018)	Power transformer fault detection and diagnosis	Development of a computer package for fault detection	Multi-criteria approach for fault detection and diagnosis	Limited evaluation of the developed computer package

#### IV. CURRENT CHALLENGES

- **Aging Infrastructure:** The power transformer industry faces the challenge of dealing with aging infrastructure, as many transformers reach the end of their operational life. This requires proactive management strategies, including condition assessment, maintenance, and replacement programs [11].

- **Grid Integration of Renewable Energy:** The increasing penetration of renewable energy sources, such as solar and wind, presents challenges in integrating these intermittent sources into the grid. Power transformers need to accommodate bidirectional power flow, voltage regulation, and grid stability issues associated with variable generation. Anees (2012) in [12] highlights challenges and issues related to integrating renewable energy into the grid, including intermittency, voltage fluctuations, and regulatory considerations. The study suggests solutions such as grid infrastructure upgrades, energy storage systems, and advanced control strategies. Bizhani et al. (2021) in [13] evaluate the performance of a power converter used for grid integration, emphasizing the importance of accurate modeling, advanced control techniques, and design considerations to optimize efficiency and minimize losses.
- **Energy Efficiency and Environmental Regulations:** Meeting energy efficiency standards and complying with environmental regulations is a significant challenge for power transformers. Manufacturers need to develop designs that minimize losses, reduce environmental impact, and comply with regulations related to materials, emissions, and disposal.
- **Cybersecurity:** With the digitization and interconnectedness of power systems, cybersecurity becomes crucial. Power transformers are potential targets for cyber-attacks that could disrupt grid operations, compromise data integrity, and pose risks to the overall system reliability.

From the above graph of comparative results for the temperature difference at different flow rate, it has been observed that the maximum variation of temperature difference of 1.11 times for Al<sub>2</sub>O<sub>3</sub> nanofluid mixture of ethylene glycol & water (60:40), 1.18% times for graphene/water-ethylene glycol (60:40) and 1.67 times enhanced for ZnO nanofluid mixture of ethylene glycol & water (50:50) at 300 LPH.

## V. CONCLUSION

Power transformers are essential components in electrical power systems, ensuring efficient and reliable electricity supply. This review paper has provided a comprehensive overview of the evolution, challenges, and emerging trends in power transformer technology. The aging infrastructure, grid integration of renewable energy, energy efficiency, and cybersecurity pose significant challenges to the industry. However, emerging trends such as smart grid integration, digitalization, eco-friendly designs, and advanced materials offer opportunities for improved performance and sustainability. By embracing these trends and addressing the challenges, the power transformer industry can enhance grid reliability, optimize asset performance, and contribute to the transition towards a more sustainable energy future. Continued research, innovation, and collaboration among stakeholders are crucial for the development of advanced power transformer solutions that meet the evolving needs of modern electrical power systems.

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