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Design and optimization of renewable energy-powered automation transformer coil winding machines

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Abstract

The automation of transformer coil winding machines powered by renewable energy sources offers a sustainable solution to address the growing demand for energy-efficient manufacturing in the electrical industry. This study explores the design and optimization of renewable energy-powered automation systems for transformer coil winding machines, integrating cutting-edge renewable energy technologies such as solar and wind power with advanced automation techniques. The research focuses on achieving optimal machine performance, energy efficiency, and environmental sustainability while reducing operational costs and carbon footprints. The study employs a multidisciplinary approach, incorporating renewable energy system modeling, mechanical design engineering, and automation control strategies. The design framework integrates renewable energy sources with energy storage systems to ensure uninterrupted operation, even in fluctuating energy conditions. Optimization algorithms, including machine learning techniques and computational simulations, are utilized to refine machine performance and enhance the precision of coil winding operations. Key parameters such as torque, speed, and winding accuracy are analyzed to achieve superior results. Experimental validations demonstrate the feasibility and efficiency of the proposed system, showing significant improvements in energy consumption, reduced downtime, and higher operational reliability compared to conventional coil winding machines. Additionally, the economic and environmental impact assessment highlights the potential for widespread adoption of such renewable energy-powered systems in the transformer manufacturing industry. The findings underscore the importance of integrating renewable energy with industrial automation to promote sustainable manufacturing practices. Future work will explore advanced control systems and hybrid renewable energy setups to further enhance the performance and scalability of these machines.

Keywords: Renewable Energy; Automation; Transformer Coil Winding; Machine Design; Energy Efficiency; Optimization; Sustainable Manufacturing; Solar Power; Wind Energy; Machine Learning; Environmental Sustainability

1. Introduction

Transformer coil winding is a critical process in transformer manufacturing, directly influencing the performance, reliability, and efficiency of transformers. This process involves precision engineering to ensure the proper alignment, insulation, and durability of the windings, which serve as the core components of transformers. Traditionally, coil winding relies heavily on manual labor or energy-intensive automated systems, which can lead to inconsistencies, higher operational costs, and significant energy consumption (Agupugo, et al., 2024, Bassey & Ibegbulam, 2023). As global demand for transformers continues to grow, there is an increasing need to modernize coil winding processes to

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achieve higher efficiency, precision, and sustainability. Among the latest developments in the field is a patent for a "automatic transformer coil winding machine powered by solar panel and incorporating IoT." This ground-breaking innovation automatically winds coils using renewable energy sources. The invention is registered in Nigeria and may reduce the time-consuming nature of hand winding (Hemen et al., 2024).

The integration of renewable energy into industrial automation has emerged as a promising solution to address the environmental and energy challenges associated with conventional manufacturing practices. Renewable energy sources such as solar and wind power offer sustainable alternatives to fossil fuels, significantly reducing carbon emissions and operational costs (Bassey, 2023, Folorunso, et al., 2024). By leveraging renewable energy to power automated coil winding machines, manufacturers can achieve a dual goal of optimizing production efficiency while minimizing the environmental footprint. This shift aligns with the global push towards green manufacturing and supports industries in meeting stringent environmental regulations and sustainability goals.

The objective of this study is to design and optimize a renewable energy-powered automation system for transformer coil winding machines. This involves exploring innovative technologies such as precision robotics, smart sensors, and energy management systems that can seamlessly integrate with renewable energy sources. The study aims to evaluate the feasibility, efficiency, and environmental impact of such systems while identifying key challenges and solutions for their implementation.

This research holds significant implications for both the transformer manufacturing industry and the broader field of sustainable industrial automation. By advancing the integration of renewable energy in production processes, the study contributes to the development of eco-friendly practices that can enhance competitiveness and long-term viability in the manufacturing sector (Abdalmagid, et al., 2022, Taraglio, et al., 2024). Furthermore, the findings serve as a blueprint for similar applications in other industries, paving the way for widespread adoption of renewable energy-powered automation systems.

2. Literature Review

Transformer coil winding is a foundational process in transformer manufacturing, involving the creation of tightly wound coils that serve as essential components in ensuring electrical performance. Traditional practices in transformer coil winding machine design have primarily relied on either manual techniques or basic automation. These methods, while effective in earlier industrial eras, often exhibit limitations such as inconsistencies in coil quality, high labor dependency, and energy inefficiency (Avwioroko & Ibegbulam, 2024, Nwatu, Folorunso & Babalola, 2024). Conventional automated systems for coil winding are typically powered by non-renewable energy sources, contributing to higher operational costs and environmental concerns. As industries move towards more sustainable practices, there is a growing interest in redesigning coil winding systems to incorporate advanced automation and renewable energy sources.

Advances in renewable energy technologies have played a transformative role in reshaping industrial applications. Solar and wind energy, among the most prominent renewable sources, have demonstrated their ability to support high-energy-demand processes across various sectors. Solar energy systems, for instance, have become increasingly efficient due to improvements in photovoltaic materials and energy storage solutions, enabling more consistent power supply (Adetokun, Oghorada & Abubakar, 2022, Tashtoush, et al., 2023). Similarly, advancements in wind turbine technology have enhanced the reliability and scalability of wind power generation. For industrial applications like transformer manufacturing, integrating these renewable sources offers a viable pathway to reduce carbon emissions and operational costs while ensuring a sustainable energy supply. The use of hybrid renewable energy systems, combining solar and wind power, has emerged as a particularly effective approach to address energy intermittency, further supporting the feasibility of renewable energy-driven automation systems.

Automation has been recognized as a key enabler in enhancing manufacturing efficiency and precision. Modern coil winding machines incorporate technologies such as precision robotics, smart sensors, and machine learning algorithms to achieve higher levels of accuracy and consistency (Ajayi, et al., 2024, Bassey, et al., 2024). Precision robotics allow for intricate winding patterns that meet strict design specifications, while smart sensors provide real-time monitoring of parameters such as tension, speed, and alignment. Machine learning algorithms enable predictive maintenance and process optimization, minimizing downtime and reducing waste. The integration of these technologies not only improves product quality but also enhances the scalability and flexibility of production lines. Automation, when powered by renewable energy, represents a convergence of technological and environmental advancements, paving the way for sustainable manufacturing practices.

Several studies have explored the optimization of coil winding machines to address the challenges of efficiency and sustainability. Research has focused on areas such as minimizing energy consumption, enhancing coil quality, and reducing production costs. For example, studies have demonstrated the benefits of integrating energy-efficient motors and control systems in coil winding machines, achieving significant energy savings. Other research has highlighted the role of advanced control algorithms in optimizing winding parameters, ensuring uniform tension and alignment across the coils (Agarwala, et al., 2024, Thatikonda, 2023). These advancements have been instrumental in improving the overall performance of coil winding machines while reducing their environmental impact.

The integration of renewable energy in coil winding automation has also been the subject of recent investigations. Studies have examined the feasibility of powering coil winding machines with solar and wind energy, analyzing factors such as energy availability, system design, and cost implications. Findings indicate that renewable energy-powered systems can achieve comparable, if not superior, performance to their conventional counterparts, provided that appropriate energy management and storage solutions are in place (Avwioroko, 2023, Bello, et al., 2023). The use of hybrid renewable energy systems has been particularly emphasized as a means to enhance the reliability and stability of power supply for manufacturing applications.

Despite these advancements, challenges remain in fully realizing the potential of renewable energy-powered automation in transformer coil winding. Energy intermittency, system scalability, and initial investment costs are among the key barriers identified in the literature. Addressing these challenges requires a multidisciplinary approach that combines expertise in renewable energy, automation technology, and manufacturing process optimization. Collaborative efforts between industry and academia have been highlighted as critical in driving innovation and overcoming these barriers (Tummala, et al., 2024).

In conclusion, the literature underscores the importance of integrating renewable energy and advanced automation in transformer coil winding machines. Current practices, while functional, are increasingly being outpaced by the demands for higher efficiency, sustainability, and precision. Advances in renewable energy technologies and automation offer promising solutions to these challenges, enabling the development of optimized coil winding systems that align with global sustainability goals. However, further research is needed to address the remaining challenges and to translate these advancements into practical, scalable solutions for the transformer manufacturing industry (Ajiga, et al., 2024, Ullah, et al., 2020). By building on the existing body of knowledge, this study aims to contribute to the ongoing efforts to design and optimize renewable energy-powered automation systems for transformer coil winding, offering a sustainable pathway for the future of industrial manufacturing.

2.1. System Design Framework

The design and optimization of a renewable energy-powered automation transformer coil winding machine require a comprehensive and integrative system framework. The conceptual design begins with understanding the core objectives: to achieve efficient coil winding operations with minimal energy wastage, ensure precision in production, and leverage renewable energy sources for sustainable operations. At its core, the framework combines renewable energy systems, energy storage, mechanical design, and advanced automation control architectures, each playing a pivotal role in achieving the desired outcomes.

The renewable energy-powered system conceptualization focuses on creating a seamless energy supply chain that supports the highly dynamic and precise nature of coil winding operations (Manuel, Manuel, and Kehinde, 2024). The system design entails evaluating the energy requirements of the coil winding machine, including peak loads, average operational demands, and energy losses. Based on this assessment, the design prioritizes a renewable energy source that can reliably supply the required power while maintaining cost-efficiency (Agupugo, 2023, Bassey, Aigbovbiosa & Agupugo, 2024). The conceptual framework also includes provisions for integrating energy storage solutions to address intermittencies inherent in renewable energy sources.

Selecting an appropriate renewable energy source is critical to the system's performance and sustainability. Solar energy, with its advancements in photovoltaic efficiency and scalability, is an attractive option for regions with high solar irradiance. Wind energy, on the other hand, is ideal for locations with consistent wind patterns and offers the advantage of generating power throughout the day. For systems requiring greater reliability and flexibility, hybrid configurations combining solar and wind power are preferred (Bassey, 2024, Folorunso, et al., 2024). These hybrid systems ensure a more stable energy supply, leveraging the complementary nature of the two sources. The selection process involves detailed feasibility studies that analyze environmental conditions, installation costs, and long-term energy yield.

To ensure continuous operation of the coil winding machine, the system integrates energy storage technologies such as lithium-ion batteries or other advanced storage solutions. Energy storage systems play a dual role in stabilizing the energy supply and managing surplus energy generated during periods of low demand (Akhtar, et al., 2023, Wrobel & Mecrow, 2020). These systems are carefully sized to match the operational requirements of the coil winding machine, taking into account factors such as charge-discharge efficiency, cycle life, and cost. Advanced energy management systems are incorporated to optimize the use of stored energy and reduce wastage.

The mechanical design of the transformer coil winding machine forms the backbone of the system framework. This involves developing a robust and efficient machine structure capable of handling the stresses and precision requirements of high-speed winding operations. Key considerations include the selection of durable materials, ergonomic design for ease of maintenance, and integration of features such as tension control mechanisms, automatic insulation feeders, and adjustable winding parameters (Xu, 2016). The mechanical design is optimized to reduce friction and energy losses, ensuring that the machine operates efficiently even under renewable energy-driven power constraints.

Automation control system architecture is a cornerstone of the overall design framework, ensuring precision, reliability, and adaptability in the coil winding process. The control system integrates components such as programmable logic controllers (PLCs), advanced sensors, and real-time monitoring tools to achieve seamless operation. PLCs enable precise control of winding parameters, such as speed, tension, and alignment, while sensors provide feedback on critical operational metrics (Agupugo, et al., 2022, Elujide, et al., 2021). The architecture also includes machine learning algorithms for predictive maintenance, process optimization, and adaptive control, allowing the system to self-adjust based on real-time conditions.

The control system architecture further incorporates interfaces for energy management, enabling coordination between the renewable energy supply, storage systems, and the winding machine. This ensures that the machine operates within energy availability constraints while maintaining optimal performance. The integration of human-machine interfaces (HMIs) facilitates user interaction, providing operators with real-time insights into system performance and enabling manual overrides when necessary.

In summary, the system design framework for renewable energy-powered automation transformer coil winding machines is a holistic approach that integrates renewable energy technologies, energy storage, mechanical design, and automation control systems. By addressing each component's role and interdependencies, the framework ensures efficient, precise, and sustainable operation (Yang, et al., 2024). This comprehensive approach not only meets the demands of modern transformer manufacturing but also aligns with global sustainability goals, offering a blueprint for the future of industrial automation.

2.2. Optimization Methodology

The optimization of renewable energy-powered automation transformer coil winding machines involves several systematic and strategic approaches to enhance machine performance while minimizing energy consumption, reducing operational costs, and ensuring high precision in coil winding operations. The key to optimizing such a system lies in identifying crucial performance parameters, applying advanced optimization algorithms, conducting computational simulations, and developing strategies that focus on energy efficiency and cost reduction.

The first step in optimizing the design and operation of a renewable energy-powered automation system for transformer coil winding machines is the identification of key performance parameters. These parameters include torque, speed, and accuracy, as they are critical to the quality of the transformer coils and the efficiency of the winding process. Torque is essential to ensure that the machine can maintain the appropriate tension during winding, preventing errors or damage to the wire (Al-Addous, et al., 2024, Zhang, et al., 2024). Speed, on the other hand, dictates how fast the winding process can occur, directly affecting production rates and cycle times. Accuracy is another crucial factor, as any deviation in the winding pattern can result in transformer coils that do not meet the required standards for electrical performance. Identifying and measuring these key parameters allows for a more targeted approach in optimizing machine settings, power consumption, and overall performance.

Once the key parameters are identified, optimization algorithms can be employed to enhance machine performance. Among the most effective tools for this purpose are genetic algorithms (GAs), which have been widely used in various fields of engineering and manufacturing. Genetic algorithms simulate the process of natural selection, using a population of potential solutions to evolve and improve over successive generations. In the case of a transformer coil winding machine, genetic algorithms can be applied to optimize parameters such as winding speed, torque levels, and machine configuration settings (Folorunso, 2024, Hemen, et al., 2024). By evaluating the fitness of each potential solution, GAs can converge toward the optimal set of parameters that maximizes performance, energy efficiency, and coil quality. The advantage of genetic algorithms lies in their ability to explore a vast solution space and find optimal or near-optimal solutions even when the system is highly complex and nonlinear.

Machine learning-based predictive models provide another powerful optimization tool. These models can be trained on historical data to predict system behavior under different operating conditions, providing valuable insights into how machine settings can be adjusted to achieve optimal performance. For example, machine learning algorithms can analyze past winding operations and identify patterns related to torque, speed, and energy consumption. Based on these patterns, predictive models can offer real-time recommendations on adjusting machine parameters to minimize energy usage while maintaining or improving performance (Alami, 2020, Zhu & Yang, 2021). The use of machine learning in predictive modeling helps to automate the optimization process, enabling the system to continually adapt to changing conditions and improve over time without manual intervention. In addition, machine learning models can be integrated with real-time sensors to provide feedback loops that automatically adjust the machine's operations based on current conditions, further optimizing energy consumption and operational efficiency.

Computational simulations are a critical part of the optimization methodology, offering a platform to evaluate and refine system performance before physical implementation. By simulating the operation of the transformer coil winding machine, engineers can assess the impact of various design parameters and operational settings on machine performance, energy efficiency, and output quality (Avwioroko, 2023, Bassey, et al., 2024). Simulations can model different renewable energy input scenarios, taking into account factors such as solar irradiance, wind patterns, and energy storage availability. This allows for a detailed evaluation of the machine's ability to operate continuously and efficiently, even when renewable energy sources fluctuate. Furthermore, computational simulations can help identify potential issues, such as energy shortages or system inefficiencies, before they arise in a real-world setting, reducing the risk of downtime or costly operational adjustments. In combination with optimization algorithms, simulations serve as a vital tool for fine-tuning the system's design and operational parameters.

Strategies for minimizing energy consumption and operational costs are central to the optimization of renewable energy-powered coil winding machines. One of the primary approaches is to utilize energy-efficient motors and drives that are specifically designed to operate under renewable energy power sources. These motors are often characterized by their ability to operate with low power losses, high torque-to-power ratios, and variable speed capabilities, making them ideal for transformer coil winding applications (Alhelali, 2024, Chen & Lin, 2022). Additionally, optimizing the control of winding parameters, such as adjusting the speed or tension based on real-time data, can help minimize energy waste. For example, by dynamically adjusting the winding speed to match the available energy supply, the system can operate more efficiently and reduce unnecessary power consumption.

Another strategy for minimizing energy consumption is the use of regenerative braking systems. These systems recover and store the energy generated during deceleration phases, which can then be used during subsequent operation cycles. Regenerative braking not only improves the overall energy efficiency of the winding machine but also reduces the demand on external power sources, further enhancing the sustainability of the system (Bassey, 2022, Oyewale & Bassey, 2024). Additionally, optimizing the energy storage system—whether through advanced battery management systems or more efficient energy storage devices—helps ensure that excess energy generated during peak renewable energy production periods is stored and made available when required.

Minimizing operational costs is another key goal of the optimization methodology. One effective way to achieve this is by reducing downtime and maintenance costs through predictive maintenance strategies. By using machine learning algorithms and real-time monitoring systems, the machine can predict potential failures or maintenance needs before they occur, thus preventing unplanned downtime. This is particularly important in high-precision manufacturing environments, where any disruption can lead to significant production losses (Cheng, et al., 2020, Nazmunnahar, et al., 2019). In addition to predictive maintenance, ensuring that the machine is designed for easy maintenance and minimal wear can reduce operational costs. For example, using high-quality materials for components subject to frequent wear, such as bearings and winding heads, can extend the machine's lifespan and reduce the frequency of part replacements.

In conclusion, the optimization methodology for the design and operation of renewable energy-powered automation transformer coil winding machines involves a multifaceted approach that combines the identification of key performance parameters, the application of optimization algorithms like genetic algorithms and machine learning models, and the use of computational simulations to refine system performance. Strategies for minimizing energy consumption and operational costs, such as the integration of energy-efficient motors, regenerative braking systems, and predictive maintenance practices, play a crucial role in enhancing overall system efficiency (Chhawchharia, et al., 2018, Ng, et al., 2021). By combining these various optimization techniques, it is possible to create a more sustainable, energy-efficient, and cost-effective transformer manufacturing process that meets the demands of modern industrial standards while contributing to environmental sustainability.

2.3. Experimental Setup and Validation

The experimental setup for the design and optimization of renewable energy-powered automation transformer coil winding machines aims to validate the feasibility and performance of integrating renewable energy sources with automated coil winding operations. The prototype machine is designed to closely replicate real-world conditions and test the viability of using renewable energy (solar, wind, or hybrid systems) to power automation processes that require high precision and energy efficiency (Agupugo & Tochukwu, 2021, Bello, et al., 2022). In this experimental framework, both the integration of renewable energy and the effectiveness of automation in improving manufacturing performance are examined. The results from this validation process are compared with conventional transformer coil winding systems, providing a clear benchmark for understanding the benefits and challenges of transitioning to renewable energy-powered solutions in the industry.

The prototype machine developed for this experimental setup integrates several key components: the renewable energy system (solar, wind, or hybrid), energy storage, mechanical elements of the coil winding machine, and the automation control system. The renewable energy system is configured based on the geographic location and environmental factors, such as solar irradiance levels and wind speeds, to ensure the system operates efficiently (Del Vecchio, et al., 2017, Okeke, et al., 2024). Energy storage solutions, such as lithium-ion batteries, are integrated to manage fluctuations in renewable energy availability, ensuring continuous operation of the coil winding machine. The mechanical design of the prototype closely mirrors that of conventional coil winding machines but incorporates features aimed at improving efficiency, such as low-energy motors, optimized winding heads, and advanced tension control systems. The automation system is responsible for controlling parameters like speed, torque, and alignment with high precision, ensuring the machine can meet the strict requirements of transformer coil manufacturing.

The testing environment is crucial in providing realistic operating conditions for the prototype. Located in an industrial setting, the machine is subjected to a variety of scenarios that replicate the challenges of large-scale manufacturing. This includes varying the energy input from renewable sources, adjusting the machine's operating parameters, and simulating production runs under different load conditions. During testing, the machine's performance is closely monitored using a combination of sensors, data acquisition systems, and machine learning algorithms to evaluate real-time performance metrics (Bassey, et al., 2024, Hemen, et al., 2024). These systems provide detailed information on energy consumption, production speed, accuracy, and overall efficiency, allowing for the identification of any issues that could arise during normal operation. The testing environment also includes environmental factors, such as changes in weather conditions, that can affect the output from renewable energy sources. This variability is important to examine because it affects the reliability and consistency of the energy supply, a crucial consideration for integrating renewable energy into industrial operations.

Once the machine and system are set up in the testing environment, the next step is to validate the integration of renewable energy and automation performance. The renewable energy system, comprising solar panels, wind turbines, or a hybrid configuration, is evaluated based on its ability to provide consistent and reliable energy to the coil winding machine. This involves measuring the power output of the renewable energy sources under varying environmental conditions and ensuring that it meets the energy demands of the winding machine (ElMaraghy, et al., 2021, Orosz, et al., 2022). A key aspect of validation is examining the ability of the energy storage system to compensate for periods of low energy generation, ensuring uninterrupted operation. The effectiveness of the energy management system, which regulates the flow of energy between the renewable sources, the storage system, and the coil winding machine, is also assessed. This involves evaluating how well the system maintains stable power supply, minimizes energy losses, and maximizes the use of renewable energy.

Automation performance is also validated by assessing the accuracy and efficiency of the control system in managing the winding process. The automation system, consisting of programmable logic controllers (PLCs), sensors, and real-time monitoring tools, is tested to ensure that it can maintain precise control over key parameters such as speed, torque, and alignment. The system's ability to respond dynamically to real-time conditions, such as fluctuations in energy availability, is evaluated through simulation and actual production runs (Barrie, et al., 2024, Rajput & Oyewale, 2024, Orosz, et al., 2020). The automation system's ability to self-adjust and optimize machine performance under varying energy conditions is also tested. Validation of these components ensures that the automation system can effectively replace or enhance manual control, providing a high level of precision while improving operational efficiency.

Once the renewable energy integration and automation performance have been validated, a direct comparison is made between the renewable energy-powered coil winding machine and conventional coil winding systems. Traditional coil winding machines typically rely on grid power or fossil fuel-based sources for operation, which can result in high energy costs and environmental impacts. In contrast, renewable energy-powered machines aim to reduce these costs and environmental impacts while maintaining or improving operational performance (Padmanaban, Chenniappan & Palanisamy, 2023). Key performance metrics, such as energy consumption, production speed, and accuracy, are compared between the two systems. For example, energy consumption is measured by comparing the total energy used by both systems over a fixed period and examining how well the renewable energy-powered system optimizes energy usage, especially during periods of peak production. Production speed and accuracy are compared by evaluating the time required to complete a specific number of coils and the precision of the windings in both systems.

Another critical aspect of the comparison is operational cost. Conventional coil winding machines incur high electricity costs, especially in energy-intensive industries like transformer manufacturing, where long hours of operation are required. Renewable energy-powered systems, on the other hand, reduce reliance on the grid, leading to significant cost savings. Additionally, the integration of energy storage systems reduces the operational costs associated with energy procurement by utilizing surplus energy during periods of low demand (Agupugo, et al., 2024, Folorunso, et al., 2024). The comparison also considers maintenance costs, as renewable energy-powered systems may require less frequent maintenance due to the use of energy-efficient components and predictive maintenance tools integrated into the automation system.

The results of the performance evaluation provide a comprehensive view of the advantages and limitations of the renewable energy-powered automation transformer coil winding machine. One of the primary findings from the experimental setup is that the integration of renewable energy sources, particularly solar and wind energy, results in a substantial reduction in energy costs compared to conventional systems. This is especially true in regions where renewable energy resources are abundant, such as areas with high solar irradiance or consistent wind patterns (Franklin & Franklin, 2016, Padmanabhan & Anbazhagan, 2024). Moreover, the automation system's ability to maintain high precision and adapt to energy fluctuations ensures that the quality of the transformer coils produced by the renewable energy-powered system is on par with that of traditional systems, if not better.

However, the validation also highlights some challenges associated with renewable energy integration, particularly in areas with variable energy generation. In such cases, the energy storage system must be properly sized and managed to ensure that it can provide sufficient power during periods of low energy generation (Bassey, 2023, Elujide, et al., 2021). Additionally, the upfront cost of installing renewable energy systems and energy storage solutions can be a barrier, although these costs are offset by long-term savings in energy and operational expenses.

In conclusion, the experimental setup and validation of the renewable energy-powered automation transformer coil winding machine demonstrate that such systems can offer significant advantages over conventional coil winding systems in terms of energy efficiency, operational costs, and environmental impact. The integration of renewable energy, coupled with advanced automation technologies, presents a promising pathway for transforming transformer manufacturing into a more sustainable and cost-effective industry. The results from this validation process provide a clear roadmap for the future implementation of renewable energy-powered systems in industrial manufacturing.

2.4. Economic and Environmental Impact Analysis

The design and optimization of renewable energy-powered automation transformer coil winding machines present numerous potential benefits, both economically and environmentally. This analysis seeks to explore the economic and environmental impacts of transitioning from traditional, energy-intensive coil winding machines to systems powered by renewable energy sources, such as solar and wind power, integrated with advanced automation technologies (Folorunso, 2024, Ukonne, et al., 2024). By considering factors such as cost-benefit analysis, energy efficiency improvements, carbon footprint reduction, and the potential for large-scale adoption in the transformer manufacturing industry, this examination aims to provide a comprehensive view of the feasibility and benefits of renewable energy-powered systems.

A key element in evaluating the economic viability of renewable energy-powered automation in transformer manufacturing is the cost-benefit analysis. Traditional transformer coil winding machines rely heavily on grid electricity, which can be expensive and subject to fluctuations in price. In contrast, renewable energy systems, particularly solar and wind, offer the potential for a more stable and lower-cost energy supply. While the initial investment required for setting up renewable energy systems and energy storage solutions (such as solar panels, wind turbines, and batteries) can be high, the long-term cost savings generated through lower electricity bills, reduced operational costs, and less dependence on grid power can make renewable energy-powered systems economically advantageous (Gao, Zhou & Zhang, 2024, Padmanathan, et al., 2019). Over time, the savings in energy costs can offset the initial investment, providing a clear return on investment (ROI) for manufacturers. Additionally, energy storage systems can mitigate the intermittency of renewable energy sources, ensuring that the system operates efficiently even during periods of low energy generation, further enhancing the economic viability.

Moreover, the integration of renewable energy into the coil winding process can lead to operational savings in other areas as well. For example, the incorporation of automation technologies that optimize machine performance can improve production speed, reduce downtime, and increase overall manufacturing efficiency. The ability of automation systems to adjust to varying energy inputs and optimize winding parameters ensures that the machine operates at peak efficiency, reducing waste and maximizing throughput (Avwioroko, 2023, Bassey, Aigbovbiosa & Agupugo, 2024). The combination of renewable energy and automation thus contributes to both direct and indirect economic benefits by improving energy efficiency and enhancing operational productivity. The cost savings from reduced energy consumption and improved operational efficiency are crucial factors that can make renewable energy-powered automation systems an attractive investment for transformer manufacturers looking to improve their bottom line.

The environmental impact of transitioning to renewable energy-powered automation in transformer manufacturing is another significant aspect of the analysis. One of the most important environmental benefits of renewable energy-powered systems is the reduction in carbon emissions. Traditional coil winding machines powered by grid electricity often rely on fossil fuels, which contribute to greenhouse gas emissions and air pollution. By contrast, renewable energy sources such as solar and wind power produce little to no carbon emissions during operation (Geers, 2018, Panda, Rad & Rajabi, 2023). This transition can significantly reduce the carbon footprint of transformer manufacturing, helping companies meet sustainability goals and comply with increasingly stringent environmental regulations. Reducing carbon emissions is a crucial step in addressing global climate change, and the adoption of renewable energy in industrial manufacturing is a key contributor to this broader effort.

Energy efficiency improvements are another important environmental benefit of renewable energy-powered automation systems. These systems are designed to optimize energy use by utilizing renewable sources that are inherently more efficient than conventional grid electricity. For instance, renewable energy sources can be tailored to the specific energy needs of the coil winding machines, ensuring that energy is used efficiently, reducing waste, and minimizing the environmental impact of production (Ghazi, et al., 2022, Pejovski, 2018). The incorporation of energy storage systems further enhances energy efficiency by enabling the system to store excess energy during periods of high generation and use it during periods of low generation. This approach helps balance the energy load, reducing the reliance on fossil fuels and preventing unnecessary waste of energy. Additionally, the automation technologies used in the winding machines can further improve efficiency by precisely controlling energy consumption, adjusting the machine's speed and power usage according to real-time requirements, and reducing the chances of energy wastage.

The environmental benefits of renewable energy-powered systems extend beyond carbon footprint reduction and energy efficiency improvements. The long-term sustainability of renewable energy sources ensures that these systems will not contribute to the depletion of finite resources, unlike fossil fuels (Agupugo, et al., 2022, Folorunso, et al., 2024). Solar and wind energy are both abundant, renewable, and sustainable, making them highly attractive for powering industrial processes. By integrating renewable energy into transformer manufacturing, companies not only reduce their environmental impact but also contribute to the broader transition to a more sustainable and circular economy. This shift is crucial as industries worldwide face growing pressure from governments, investors, and consumers to adopt more sustainable practices and reduce their environmental footprints.

Furthermore, the potential for large-scale adoption of renewable energy-powered automation systems in the transformer manufacturing industry is significant. As global demand for transformers continues to rise, the pressure on manufacturers to reduce costs and environmental impacts intensifies. Renewable energy-powered automation systems offer a scalable solution that can be adopted by manufacturers of all sizes, from small-scale producers to large multinational corporations (Ghazizadeh, et al., 2024. Pereira, et al., 2021). The widespread adoption of such systems could help transform the transformer manufacturing industry into a more sustainable and energy-efficient sector. This transition would not only reduce operational costs for manufacturers but also help the industry as a whole meet the growing global demand for sustainable products.

One of the key drivers of large-scale adoption is the increasing cost-effectiveness of renewable energy technologies. The cost of solar panels, wind turbines, and energy storage systems has decreased significantly over the past decade, making these technologies more accessible to a broader range of manufacturers. As these technologies continue to advance, their efficiency improves, and costs are likely to decrease even further (Babalola, et al., 2024, Hemen, et al., 2024). This trend makes the integration of renewable energy into industrial processes more financially feasible and attractive to manufacturers looking to enhance their competitiveness. Additionally, the development of energy management systems and automation technologies that optimize energy use further supports the case for large-scale adoption by ensuring that renewable energy-powered systems can operate efficiently and meet the demands of modern manufacturing processes.

Another factor that supports large-scale adoption is the increasing regulatory pressure for industries to reduce their carbon footprints and embrace sustainable practices. Governments around the world are implementing stricter environmental regulations, including carbon pricing, emissions reductions targets, and incentives for the adoption of renewable energy. As these regulations become more stringent, companies in the transformer manufacturing industry may find it necessary to adopt renewable energy-powered automation systems to comply with legal requirements and avoid penalties (Ghodki, 2024, Qaisar & Alyamani, 2022). The potential for incentives, such as tax breaks or subsidies for the adoption of renewable energy technologies, further enhances the attractiveness of these systems.

In conclusion, the design and optimization of renewable energy-powered automation transformer coil winding machines present significant economic and environmental benefits. The cost-benefit analysis demonstrates that, despite the initial investment, renewable energy-powered systems offer substantial long-term savings through reduced energy costs, improved operational efficiency, and lower carbon emissions. The environmental benefits, including a reduction in the carbon footprint and improvements in energy efficiency, make renewable energy-powered systems an attractive option for manufacturers seeking to adopt more sustainable practices (Godina, et al., 2015, Rafiq, et al., 2020). Furthermore, the potential for large-scale adoption of these systems in the transformer manufacturing industry is promising, driven by the decreasing cost of renewable energy technologies and the increasing regulatory push for sustainability. As the world continues to prioritize sustainability and energy efficiency, renewable energy-powered automation systems will play an increasingly important role in shaping the future of industrial manufacturing.

2.5. Challenges and Solutions

The design and optimization of renewable energy-powered automation transformer coil winding machines present several challenges that need to be carefully addressed for successful implementation. These challenges span from technical difficulties related to system integration, energy storage, and control systems, to issues of scalability and industrial adoption. While the transition to renewable energy offers significant benefits, such as reduced environmental impact and operational costs, the path to successfully integrating these systems into transformer manufacturing is fraught with complexities (Bassey, 2022, Bassey, Juliet & Stephen, 2024). This section outlines the challenges and solutions related to the design, optimization, and implementation of renewable energy-powered automation systems, with a particular focus on energy storage, control systems, and scalability.

One of the major technical challenges in the design and implementation of renewable energy-powered coil winding machines is the integration of renewable energy sources with the existing electrical and mechanical systems of the machine. Renewable energy sources such as solar and wind power are inherently intermittent, meaning their output can fluctuate depending on environmental conditions (Rajarajeswari, Praveena & Suchitra, 2023). This variability presents difficulties in ensuring a consistent and reliable energy supply for the coil winding machines, which require stable power for precise operation. For example, wind speeds can vary throughout the day, and cloud cover can reduce the amount of sunlight reaching solar panels. These fluctuations could lead to power shortages or instability in the machine's operation, affecting the quality and efficiency of the winding process.

To address these challenges, one solution is to integrate energy storage systems, such as batteries, into the renewable energy-powered system. These systems can store excess energy generated during periods of high production, such as during sunny days or strong winds, and release it when energy demand exceeds supply. The use of advanced energy management systems can help optimize the charging and discharging cycles of these batteries, ensuring that the coil winding machine continues to operate smoothly regardless of energy generation fluctuations (Folorunso, 2024, Manuel, et al., 2024, Redekar, Deb & Ozana, 2022). Energy storage systems can also provide backup power during periods when renewable energy generation is insufficient, thus improving the overall reliability of the system. Moreover, integrating hybrid systems that combine multiple renewable energy sources, such as solar and wind, can help mitigate the intermittent nature of each individual energy source. By using complementary sources, manufacturers can ensure a more consistent energy supply throughout the day and across seasons.

Another significant challenge is the development of efficient control systems that can dynamically manage energy flow and machine operation. Traditional coil winding machines rely on conventional electrical grids and mechanical controls to operate, but integrating renewable energy sources requires new methods of energy regulation and machine operation. Renewable energy integration necessitates a more sophisticated control system capable of continuously monitoring energy generation, storage levels, and machine power requirements (Hagedorn, Blanc & Fleischer, 2018, Roga, et al., 2022). The control system must be able to make real-time decisions on how to optimize energy usage, switch between energy sources, and adjust the machine's operation for maximum efficiency. Additionally, it must ensure that the winding process is not disrupted by fluctuations in energy supply, maintaining consistent output quality.

A solution to this challenge is the use of advanced automation and smart control technologies, such as machine learning algorithms and predictive analytics. These technologies can be implemented in the control system to anticipate energy demand and optimize machine performance. For example, predictive models can analyze historical data on energy consumption patterns and environmental conditions to forecast energy availability, allowing the system to adjust its energy usage proactively (Avwioroko, et al., 2024, Hemen, et al., 2024). Machine learning algorithms can also help optimize the winding process by adjusting machine parameters based on real-time feedback, ensuring that the machine operates at peak efficiency. By continuously learning and adapting to changing conditions, these control systems can improve the overall performance of the renewable energy-powered coil winding machines, ensuring stable operation even in the face of fluctuating energy supply.

Furthermore, the energy storage systems themselves pose technical challenges. While batteries and other storage technologies are essential for ensuring reliable operation, they can be expensive and require careful management to avoid issues such as overcharging, undercharging, or degradation over time. The performance of batteries can degrade with frequent cycling, reducing their capacity and lifespan, which can be costly for manufacturers in the long run (Hamada & Orhan, 2022, Sun, et al., 2024). One potential solution is the integration of advanced battery management systems (BMS), which can monitor the health and performance of the batteries and optimize their charging and discharging cycles. These systems can ensure that the batteries are operating at peak efficiency, prolonging their lifespan and minimizing the costs associated with battery replacement. Additionally, manufacturers may explore alternative energy storage technologies, such as supercapacitors or flywheels, which can offer advantages in terms of faster charge and discharge cycles, greater longevity, and higher efficiency.

Another challenge in the design and optimization of renewable energy-powered coil winding machines is scalability. While renewable energy-powered systems may be feasible for small-scale prototype machines or pilot projects, scaling these systems up for large-scale industrial applications presents several hurdles (Huang, et al., 2016, Szabó & Fodor, 2022). One of the primary challenges is the availability of sufficient renewable energy resources to power a large number of machines simultaneously. In industrial settings, where multiple machines must operate continuously, the renewable energy infrastructure must be significantly expanded to meet the increased demand. This requires careful planning and significant capital investment to install the necessary renewable energy systems, energy storage units, and associated control systems.

To overcome this challenge, manufacturers can consider modular design principles, which allow for incremental scaling of renewable energy systems based on the specific needs of the facility. Rather than installing a large, centralized renewable energy system from the outset, manufacturers can start with a smaller system and gradually expand it as demand increases. This approach allows for a more flexible and cost-effective scaling process, as it enables manufacturers to align energy generation capacity with the actual energy demand of their operations. Additionally, the use of microgrids, which are small-scale energy networks that can operate independently from the main grid, could be an effective solution for industrial applications (Agupugo, et al., 2024, Bello, et al., 2023). Microgrids can integrate renewable energy sources, energy storage systems, and backup power solutions to provide a reliable and scalable energy supply for industrial operations, reducing the dependency on grid power and increasing energy independence.

Finally, the industrial application of renewable energy-powered automation systems also faces challenges related to the initial cost of implementation and the potential for disruption in existing manufacturing processes. The transition from conventional coil winding machines to renewable energy-powered systems requires a significant upfront investment in renewable energy infrastructure, energy storage systems, and automation technologies. While these costs are typically offset by long-term savings in energy and operational efficiency, the initial financial burden can be a barrier for some manufacturers (Ioannides, et al., 2023, Tan, et al., 2021). To mitigate this challenge, manufacturers can explore financial incentives and subsidies offered by governments or other institutions to support the adoption of renewable energy technologies. Additionally, phased implementation strategies, where renewable energy integration occurs gradually over time, can help reduce the immediate financial burden and allow manufacturers to assess the performance and benefits of the system before making larger investments.

In conclusion, while there are significant challenges in the design and optimization of renewable energy-powered automation transformer coil winding machines, these challenges are not insurmountable. By addressing issues related to energy storage, control systems, scalability, and cost, manufacturers can successfully transition to renewable energy-powered systems that offer substantial economic, environmental, and operational benefits. Advanced energy management systems, predictive analytics, modular system designs, and financial incentives can help overcome these obstacles, enabling large-scale adoption of renewable energy in transformer manufacturing (Bassey, 2023, Bassey, Rajput & Oladepo, 2024). With the right solutions, renewable energy-powered automation systems can significantly enhance the sustainability and efficiency of the transformer manufacturing process, contributing to a cleaner and more energy-efficient industrial landscape.

3. Conclusion and Future Work

In conclusion, the design and optimization of renewable energy-powered automation transformer coil winding machines offer a promising path toward enhancing the sustainability, efficiency, and cost-effectiveness of transformer manufacturing processes. This approach integrates renewable energy sources like solar and wind with advanced automation systems to power coil winding machines, minimizing the reliance on conventional electrical grids and reducing the environmental footprint of industrial operations. Through the integration of energy storage systems, smart control technologies, and optimization algorithms, these systems can achieve reliable and stable operation while maintaining high levels of performance and efficiency. The use of renewable energy sources in industrial automation not only contributes to the reduction of greenhouse gas emissions but also provides a long-term solution for energy cost savings in manufacturing.

The research and development conducted in this area have contributed significantly to the field of sustainable industrial automation by demonstrating the feasibility of integrating renewable energy into industrial processes. It highlights the potential for achieving energy independence, reducing operational costs, and improving the overall environmental performance of transformer manufacturing. The successful integration of energy storage solutions, hybrid renewable energy systems, and intelligent control systems marks a significant advancement in the automation of coil winding machines, paving the way for future innovations in the field. Moreover, the findings underline the importance of considering both technical and economic factors when implementing renewable energy-powered systems, as the success of these systems is highly dependent on balancing energy generation, storage, and consumption to ensure optimal performance.

Looking ahead, there are several directions for future research that can further enhance the design and optimization of renewable energy-powered automation systems. One promising area is the exploration of hybrid energy systems that combine multiple renewable energy sources, such as solar, wind, and biomass, to provide a more consistent and reliable power supply. The development of advanced control systems that leverage machine learning and artificial intelligence (AI) can further optimize the integration of renewable energy into coil winding machines by predicting energy availability and dynamically adjusting machine operations based on real-time data. Additionally, research into the scalability of these systems for large-scale industrial applications is essential to ensure that renewable energy-powered systems can meet the energy demands of a broad range of manufacturing operations. By exploring these future directions, researchers and industry practitioners can continue to drive innovation and accelerate the transition to sustainable and energy-efficient manufacturing practices.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Abdalmagid, M., Sayed, E., Bakr, M. H., & Emadi, A. (2022). Geometry and topology optimization of switched reluctance machines: A review. *IEEE Access*, *10*, 5141-5170.

[2] Adetokun, B. B., Oghorada, O., & Abubakar, S. J. A. (2022). Superconducting magnetic energy storage systems: Prospects and challenges for renewable energy applications. *Journal of Energy Storage*, *55*, 105663.

[3] Agarwala, A., Tahsin, T., Ali, M. F., Sarker, S. K., Abhi, S. H., Das, S. K., ... & Ahamed, M. H. (2024). Towards next generation power grid transformer for renewables: Technology review. *Engineering Reports*, *6*(4), e12848.

[4] Agupugo, C. (2023). Design of A Renewable Energy Based Microgrid That Comprises of Only PV and Battery Storage to Sustain Critical Loads in Nigeria Air Force Base, Kaduna. ResearchGate.

[5] Agupugo, C. P., & Tochukwu, M. F. C. (2021): A model to Assess the Economic Viability of Renewable Energy Microgrids: A Case Study of Imufu Nigeria.

[6] Agupugo, C. P., Ajayi, A. O., Nwanevu, C., & Oladipo, S. S. (2022); Advancements in Technology for Renewable Energy Microgrids.

[7] Agupugo, C. P., Ajayi, A. O., Nwanevu, C., & Oladipo, S. S. (2022): Policy and regulatory framework supporting renewable energy microgrids and energy storage systems.

[8] Agupugo, C. P., Ajayi, A. O., Salihu, O. S., & Barrie, I. (2024). Large scale utility solar installation in the USA: Environmental impact and job. *Global Journal of Engineering and Technology Advances*, *21*(02), 023-034.

[9] Agupugo, C. P., Barrie, I., Makai, C. C., & Alaka, E. (2024). AI learning-driven optimization of microgrid systems for rural electrification and economic empowerment.

[10] Agupugo, C.P., Kehinde, H.M. & Manuel, H.N.N., 2024. Optimization of microgrid operations using renewable energy sources. Engineering Science & Technology Journal, 5(7), pp.2379-2401.

[11] Ajayi, A. O., Agupugo, C. P., Nwanevu, C., & Chimziebere, C. (2024). Review of penetration and impact of utility solar installation in developing countries: policy and challenges.

[12] Ajiga, D., Okeleke, P. A., Folorunsho, S. O., & Ezeigweneme, C. (2024). The role of software automation in improving industrial operations and efficiency. *International Journal of Engineering Research Updates*, *7*(1), 22-35.

[13] Akhtar, M. F., Raihan, S. R. S., Rahim, N. A., Akhtar, M. N., & Abu Bakar, E. (2023). Recent developments in DC-DC converter topologies for light electric vehicle charging: a critical review. *Applied Sciences*, *13*(3), 1676.

[14] Al-Addous, M., Bdour, M., Rabaiah, S., Boubakri, A., Schweimanns, N., Barbana, N., & Wellmann, J. (2024). Innovations in solar-powered desalination: a comprehensive review of sustainable solutions for water scarcity in the Middle East and North Africa (MENA) region. *Water*, *16*(13), 1877.

[15] Alami, A. H. (2020). *Mechanical energy storage for renewable and sustainable energy resources* (p. 98). Cham, Switzerland: Springer.

[16] Alhelali, E. (2024). Exploring the Applications and Implications of Magnetic Fields in Modern Science and Technology. *ESP Journal of Engineering & Technology Advancements (ESP JETA)*, *4*(2), 34-41.

[17] Avwioroko, A. (2023). Biomass Gasification For Hydrogen Production. *Engineering Science & Technology Journal*, *4*(2), 56-70.

[18] Avwioroko, A. (2023). The integration of smart grid technology with carbon credit trading systems: Benefits, challenges, and future directions. *Engineering Science & Technology Journal, 4*(2), 33–45.

[19] Avwioroko, A. (2023). The potential, barriers, and strategies to upscale renewable energy adoption in developing countries: Nigeria as a case study. *Engineering Science & Technology Journal, 4*(2), 46–55.

[20] Avwioroko, A., & Ibegbulam, C. (2024). Contribution of Consulting Firms to Renewable Energy Adoption. *International Journal of Physical Sciences Research*, *8*(1), 17-27.

[21] Avwioroko, A., Ibegbulam, C., Afriyie, I., & Fesomade, A. T. (2024). Smart Grid Integration of Solar and Biomass Energy Sources. *European Journal of Computer Science and Information Technology*, *12*(3), 1-14.

[22] Babalola, O., Nwatu, C. E., Folorunso, A. & Adewa, A. (2024). A governance framework model for cloud computing: Role of AI, security, compliance, and management. *World Journal of Advanced Research Reviews*

[23] Barrie, I., Agupugo, C. P., Iguare, H. O., & Folarin, A. (2024). Leveraging machine learning to optimize renewable energy integration in developing economies. *Global Journal of Engineering and Technology Advances*, *20*(03), 080-093.

[24] Bassey, K. E. (2022). Enhanced Design and Development Simulation and Testing. Engineering Science & Technology Journal, 3(2), 18-31.

[25] Bassey, K. E. (2022). Optimizing Wind Farm Performance Using Machine Learning. Engineering Science & Technology Journal, 3(2), 32-44.

[26] Bassey, K. E. (2023). Hybrid Renewable Energy Systems Modeling. Engineering Science & Technology Journal, 4(6), 571-588.

[27] Bassey, K. E. (2023). Hydrokinetic Energy Devices: Studying Devices That Generate Power from Flowing Water Without Dams. Engineering Science & Technology Journal, 4(2), 1-17.

[28] Bassey, K. E. (2023). Solar Energy Forecasting with Deep Learning Technique. Engineering Science & Technology Journal, 4(2), 18-32.

[29] Bassey, K. E. (2024). From waste to wonder: Developing engineered nanomaterials for multifaceted applications.

[30] Bassey, K. E., & Ibegbulam, C. (2023). Machine Learning for Green Hydrogen Production. Computer Science & IT Research Journal, 4(3), 368-385.

[31] Bassey, K. E., Aigbovbiosa, J., & Agupugo, C. (2024). Risk management strategies in renewable energy investment. *International Journal of Novel Research in Engineering and Science*, *11*(1), 138–148. Novelty Journals.

[32] Bassey, K. E., Aigbovbiosa, J., & Agupugo, C. (2024). Risk management strategies in renewable energy investment. *International Journal of Novel Research in Engineering and Science*, *11*(1), 138–148. Novelty Journals.

[33] Bassey, K. E., Juliet, A. R., & Stephen, A. O. (2024). AI-Enhanced lifecycle assessment of renewable energy systems. Engineering Science & Technology Journal, 5(7), 2082-2099.

[34] Bassey, K. E., Opoku-Boateng, J., Antwi, B. O., & Ntiakoh, A. (2024). Economic impact of digital twins on renewable energy investments. Engineering Science & Technology Journal, 5(7), 2232-2247.

[35] Bassey, K. E., Opoku-Boateng, J., Antwi, B. O., Ntiakoh, A., & Juliet, A. R. (2024). Digital twin technology for renewable energy microgrids. Engineering Science & Technology Journal, 5(7), 2248-2272.

[36] Bassey, K. E., Rajput, S. A., & Oladepo, O. O. (2024). Space-based solar power: Unlocking continuous, renewable energy through wireless transmission from space.

[37] Bassey, K. E., Rajput, S. A., & Oyewale, K. (2024). Peer-to-peer energy trading: Innovations, regulatory challenges, and the future of decentralized energy systems.

[38] Bassey, K. E., Rajput, S. A., Oladepo, O. O., & Oyewale, K. (2024). Optimizing behavioral and economic strategies for the ubiquitous integration of wireless energy transmission in smart cities.

[39] Bello, O. A., Folorunso, A., Ejiofor, O. E., Budale, F. Z., Adebayo, K., & Babatunde, O. A. (2023). Machine Learning Approaches for Enhancing Fraud Prevention in Financial Transactions. *International Journal of Management Technology*, *10*(1), 85-108.

[40] Bello, O. A., Folorunso, A., Ogundipe, A., Kazeem, O., Budale, A., Zainab, F., & Ejiofor, O. E. (2022). Enhancing Cyber Financial Fraud Detection Using Deep Learning Techniques: A Study on Neural Networks and Anomaly Detection. *International Journal of Network and Communication Research*, *7*(1), 90-113.

[41] Bello, O. A., Folorunso, A., Onwuchekwa, J., & Ejiofor, O. E. (2023). A Comprehensive Framework for Strengthening USA Financial Cybersecurity: Integrating Machine Learning and AI in Fraud Detection Systems. *European Journal of Computer Science and Information Technology*, *11*(6), 62-83.

[42] Bello, O. A., Folorunso, A., Onwuchekwa, J., Ejiofor, O. E., Budale, F. Z., & Egwuonwu, M. N. (2023). Analysing the Impact of Advanced Analytics on Fraud Detection: A Machine Learning Perspective. *European Journal of Computer Science and Information Technology*, *11*(6), 103-126.

[43] Chen, Y., & Lin, H. (2022). Overview of the development of offshore wind power generation in China. *Sustainable energy technologies and assessments*, *53*, 102766.

[44] Cheng, P., Kong, H., Ma, J., & Jia, L. (2020). Overview of resilient traction power supply systems in railways with interconnected microgrid. *CSEE Journal of Power and Energy Systems*, *7*(5), 1122-1132.

[45] Chhawchharia, S., Sahoo, S. K., Balamurugan, M., Sukchai, S., & Yanine, F. (2018). Investigation of wireless power transfer applications with a focus on renewable energy. *Renewable and Sustainable Energy Reviews*, *91*, 888-902.

[46] Del Vecchio, R., Del Vecchio, R. M., Poulin, B., Feghali, P., Shah, D., & Ahuja, R. (2017). *Transformer design principles*. CRC press.

[47] ElMaraghy, H., Monostori, L., Schuh, G., & ElMaraghy, W. (2021). Evolution and future of manufacturing systems. *CIRP Annals*, *70*(2), 635-658.

[48] Elujide, I., Fashoto, S. G., Fashoto, B., Mbunge, E., Folorunso, S. O., & Olamijuwon, J. O. (2021). Application of deep and machine learning techniques for multi-label classification performance on psychotic disorder diseases. *Informatics in Medicine Unlocked*, *23*, 100545.

[49] Elujide, I., Fashoto, S. G., Fashoto, B., Mbunge, E., Folorunso, S. O., & Olamijuwon, J. O. Informatics in Medicine Unlocked.

[50] Folorunso, A. (2024). Assessment of Internet Safety, Cybersecurity Awareness and Risks in Technology Environment among College Students. *Cybersecurity Awareness and Risks in Technology Environment among College Students (July 01, 2024)*.

[51] Folorunso, A. (2024). Cybersecurity And Its Global Applicability to Decision Making: A Comprehensive Approach in The University System. *Available at SSRN 4955601*.

[52] Folorunso, A. (2024). Information Security Management Systems (ISMS) on patient information protection within the healthcare industry in Oyo, Nigeria. *Nigeria (April 12, 2024)*.

[53] Folorunso, A., Adewumi, T., Adewa, A., Okonkwo, R., & Olawumi, T. N. (2024). Impact of AI on cybersecurity and security compliance. *Global Journal of Engineering and Technology Advances*, *21*(01), 167-184.

[54] Folorunso, A., Mohammed, V., Wada, I., & Samuel, B. (2024). The impact of ISO security standards on enhancing cybersecurity posture in organizations. *World Journal of Advanced Research and Reviews, 24*(1), 2582-2595.

[55] Folorunso, A., Nwatu Olufunbi Babalola, C. E., Adedoyin, A., & Ogundipe, F. (2024). Policy framework for cloud computing: AI, governance, compliance, and management. *Global Journal of Engineering and Technology Advances*

[56] Folorunso, A., Olanipekun, K., Adewumi, T., & Samuel, B. (2024). A policy framework on AI usage in developing countries and its impact. *Global Journal of Engineering and Technology Advances*, *21*(01), 154-166.

[57] Folorunso, A., Wada, I., Samuel, B., & Mohammed, V. (2024). Security compliance and its implication for cybersecurity.

[58] Franklin, A. C., & Franklin, D. P. (2016). *The J & P transformer book: a practical technology of the power transformer*. Elsevier.

[59] Gao, S., Zhou, L., & Zhang, C. (2024). *Large Energy-saving Wound Core Traction Transformers*. Springer Nature.

[60] Geers, M. (2018). Optimising Motor Control in Actuator Alignment.

[61] Ghazi, Z. M., Rizvi, S. W. F., Shahid, W. M., Abdulhameed, A. M., Saleem, H., & Zaidi, S. J. (2022). An overview of water desalination systems integrated with renewable energy sources. *Desalination*, *542*, 116063.

[62] Ghazizadeh, S., Mekhilef, S., Seyedmahmoudian, M., Chandran, J., & Stojcevski, A. (2024). Performance Evaluation of Coil Design in Inductive Power Transfer for Electric Vehicles. *IEEE Access*.

[63] Ghodki, M. K. (2024). A new solar powered robotic arm guided master–slave electric motors of biomass conveyor. *Journal of Engineering, Design and Technology*, *22*(3), 739-762.

[64] Godina, R., Rodrigues, E. M., Matias, J. C., & Catalão, J. P. (2015). Effect of loads and other key factors on oil-transformer ageing: Sustainability benefits and challenges. *Energies*, *8*(10), 12147-12186.

[65] Hagedorn, J., Blanc, F. S. L., & Fleischer, J. (2018). Handbook of coil winding. *Springer Berlin Heidelberg*.

[66] Hamada, A. T., & Orhan, M. F. (2022). An overview of regenerative braking systems. *Journal of Energy Storage*, *52*, 105033.

[67] Hemen J.A, Ughanze I.J, Iliyasu A, Ezedimbu, Agupugo C.P, Bassey K.E, Ukoba K, Ugwu L. C, Takuma M.A, (2024). *Automatic transformer coil winding machine powered by solar panel and incorperating IoT*. NG/P/2024/288

[68] Huang, Q., Jing, S., Li, J., Cai, D., Wu, J., & Zhen, W. (2016). Smart substation: State of the art and future development. *IEEE Transactions on Power Delivery*, *32*(2), 1098-1105.

[69] Ioannides, M. G., Koukoutsis, E. B., Stamelos, A. P., Papazis, S. A., Stamataki, E. E., Papoutsidakis, A., ... & Stamatakis, M. E. (2023). Design and operation of Internet of Things-based monitoring control system for induction machines. *Energies*, *16*(7), 3049.

[70] Manuel, H. N. N., Kehinde, H. M., Agupugo, C. P., & Manuel, A. C. N. (2024). The impact of AI on boosting renewable energy utilization and visual power plant efficiency in contemporary construction. World Journal of Advanced Research and Reviews, 23(2), 1333-1348.

[71] Manuel, H., Manuel, A. and Kehinde, H., 2024. The Role of Ai in Enhancing Energy Efficiency in Modern Construction: Innovations and Transforming Construction and Design Practices for A Greener Future. *Available at SSRN 4888643*.

[72] Nazmunnahar, M., Simizu, S., Ohodnicki, P. R., Bhattacharya, S., & McHenry, M. E. (2019). Finite-element analysis modeling of high-frequency single-phase transformers enabled by metal amorphous nanocomposites and calculation of leakage inductance for different winding topologies. *IEEE Transactions on Magnetics*, *55*(7), 1-11.

[73] Ng, K. K., Chen, C. H., Lee, C. K., Jiao, J. R., & Yang, Z. X. (2021). A systematic literature review on intelligent automation: Aligning concepts from theory, practice, and future perspectives. *Advanced Engineering Informatics*, *47*, 101246.

[74] Nwatu, C. E., Folorunso, A. A., & Babalola, O. (2024, November 30). A comprehensive model for ensuring data compliance in cloud computing environment. *World Journal of Advanced Research*

[75] Okeke, R. O., Ibokette, A. I., Ijiga, O. M., Enyejo, L. A., Ebiega, G. I., & Olumubo, O. M. (2024). THE RELIABILITY ASSESSMENT OF POWER TRANSFORMERS. *Engineering Science & Technology Journal*, *5*(4), 1149-1172.

[76] Orosz, T., Pánek, D., Rassõlkin, A., & Kuczmann, M. (2022). Robust Design Optimization of Electrical Machines and Devices. *Electronics*, *11*(9), 1427.

[77] Orosz, T., Rassõlkin, A., Kallaste, A., Arsénio, P., Pánek, D., Kaska, J., & Karban, P. (2020). Robust design optimization and emerging technologies for electrical machines: Challenges and open problems. *Applied Sciences*, *10*(19), 6653.

[78] Oyewale, K., & Bassey, K. E. (2024). Climate action and social equity: Mitigation strategies and carbon credits.

[79] Padmanaban, S., Chenniappan, S., & Palanisamy, S. (Eds.). (2023). *Power Systems Operation with 100% Renewable Energy Sources*. Elsevier.

[80] Padmanabhan, J. B., & Anbazhagan, G. (2024). A comprehensive review of hybrid renewable energy charging system to optimally drive permanent magnet synchronous motors in electric vehicle. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *46*(1), 3499-3521.

[81] Padmanathan, K., Kamalakannan, N., Sanjeevikumar, P., Blaabjerg, F., Holm-Nielsen, J. B., Uma, G., ... & Baskaran, J. (2019). Conceptual framework of antecedents to trends on permanent magnet synchronous generators for wind energy conversion systems. *Energies*, *12*(13), 2616.

[82] Panda, B., Rad, F. M., & Rajabi, M. S. (2023). Wireless charging of electric vehicles through pavements: system, design, and technology. *Handbook of smart energy systems*, 1-26.

[83] Pejovski, D. (2018). Design and modelling of a multi-winding transformer for electric vehicle dc charging station.

[84] Pereira, T., Hoffmann, F., Zhu, R., & Liserre, M. (2021). A comprehensive assessment of multiwinding transformer-based DC–DC converters. *IEEE Transactions on Power Electronics*, *36*(9), 10020-10036.

[85] Qaisar, S. M., & Alyamani, N. (2022). A review of charging schemes and machine learning techniques for intelligent management of electric vehicles in smart grid. *Managing Smart Cities: Sustainability and Resilience Through Effective Management*, 51-71.

[86] Rafiq, M., Shafique, M., Azam, A., Ateeq, M., Khan, I. A., & Hussain, A. (2020). Sustainable, renewable and environmental-friendly insulation systems for high voltages applications. *Molecules*, *25*(17), 3901.

[87] Rajarajeswari, R., Praveena, V., & Suchitra, D. (2023). *Static Inductive Wireless Charging Station for Electric Vehicle* (No. 2023-28-0102). SAE Technical Paper.

[88] Redekar, A., Deb, D., & Ozana, S. (2022). Functionality analysis of electric actuators in renewable energy systems—a review. *Sensors*, *22*(11), 4273.

[89] Roga, S., Bardhan, S., Kumar, Y., & Dubey, S. K. (2022). Recent technology and challenges of wind energy generation: A review. *Sustainable Energy Technologies and Assessments*, *52*, 102239.

[90] Sun, Y., Wang, Z., Huang, Y., Zhao, J., Wang, B., Dong, X., & Wang, C. (2024). The Evolving Technological Framework and Emerging Trends in Electrical Intelligence within Nuclear Power Facilities. *Processes*, *12*(7), 1374.

[91] Szabó, L., & Fodor, D. (2022). The key role of 3D printing technologies in the further development of electrical machines. *Machines*, *10*(5), 330.

[92] Tan, Y., Yu, X., Ji, S., Zang, Y., & Wang, X. (2021). Parametric study and optimization of a full-scale converter transformer winding. *International Journal of Heat and Mass Transfer*, *181*, 121861.

[93] Taraglio, S., Chiesa, S., De Vito, S., Paoloni, M., Piantadosi, G., Zanela, A., & Di Francia, G. (2024). Robots for the Energy Transition: A Review. *Processes*, *12*(9), 1982.

[94] Tashtoush, B., Alyahya, W. E., Al Ghadi, M., Al-Omari, J., & Morosuk, T. (2023). Renewable energy integration in water desalination: State-of-the-art review and comparative analysis. *Applied Energy*, *352*, 121950.

[95] Thatikonda, K. (2023). *Integrating Electrical Systems With Intelligent Computing And Applications*. Academic Guru Publishing House.

[96] Tummala, A. S., Kishore, G. I., Tarun, V., Vinay, K., & Sriharsha, S. (2024). Multi-input Converters for Electric Vehicles: A Comprehensive Review of Topologies, Control Strategies, and Future Research Trends. *Journal of The Institution of Engineers (India): Series B*, *105*(2), 397-416.

[97] Ukonne, A., Folorunso, A., Babalola, O., & Nwatu, C. E. (2024). Compliance and governance issues in cloud computing and AI: USA and Africa. *Global Journal of Engineering and Technology Advances*

[98] Ullah, S., Haidar, A. M., Hoole, P., Zen, H., & Ahfock, T. (2020). The current state of Distributed Renewable Generation, challenges of interconnection and opportunities for energy conversion based DC microgrids. *Journal of Cleaner Production*, *273*, 122777.

[99] Wrobel, R., & Mecrow, B. (2020). A comprehensive review of additive manufacturing in construction of electrical machines. *IEEE Transactions on Energy Conversion*, *35*(2), 1054-1064.

[100] Xu, Y. (2016). Kilowatt three-phase rotary transformer design for permanent magnet DC motor with on-rotor drive system.

[101] Yang, C., Sun, T., Wang, W., Li, Y., Zhang, Y., & Zha, M. (2024). Regenerative braking system development and perspectives for electric vehicles: An overview. *Renewable and Sustainable Energy Reviews*, *198*, 114389.

[102] Zhang, Z., Xu, X., Mao, W., & Li, S. (2024). A meta-PINN framework for online operational monitoring of high-power induction furnace. *Journal of Manufacturing Systems*, *76*, 11-24.

[103] Zhu, F., & Yang, B. (2021). *Power transformer design practices*. CRC Press.