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APPLICATION OF CONTROL SYSTEMS IN RENEWABLE ENERGY IN NIGERIA: A REVIEW

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ABSTRACT

The use of control systems in renewable energy across the states of Nigeria is the focus of this research. It shows how supervisory, predictive, and adaptive control systems are crucial for maximising efficiency and dependability. Examining renewable energy ecosystems on a global and regional scale, the literature review highlights the distinct obstacles and possibilities present in each. Investigating technological advancements—such as improved monitoring, AI, and blockchain—and showcasing their revolutionary effects is the focus here. Some of the future possibilities discussed in the article include quantum computing, decentralised systems, and stricter cybersecurity regulations. Policymakers, researchers, and industry stakeholders can use the findings to better understand the complex relationship between control systems and renewable energy. This knowledge will help them navigate the ever-changing world of sustainable energy solutions.

KEYWORDS: Renewable Energy; Control Systems; Technological Innovations; Regional Variances.

1. INTRODUCTION

Renewable energy sources, including solar, wind, hydro, and biomass, have become crucial alternatives to conventional fossil fuels due to their sustainability and potential to mitigate climate change. Nigeria, with abundant renewable energy resources, has increasingly turned to these alternatives to address the energy deficit and reduce reliance on fossil fuels (Olawale & Mofoluwake, 2019). However, the successful integration of renewable energy into the national grid presents significant technical challenges, especially regarding efficiency and reliability. This is where control systems, designed to optimize and manage energy generation, storage, and distribution, are essential (Wang et al., 2020).

Control systems play a critical role in enhancing the performance of renewable energy systems by addressing issues such as energy intermittency and fluctuations in output due to weather conditions (Sulaimon & Adebayo, 2021). These systems help ensure stability, reliability, and maximum efficiency in renewable energy generation, crucial for a country like Nigeria, where power outages and irregularities are commonplace. Advanced control algorithms and strategies are needed to regulate energy flow, manage voltage stability, and synchronize renewable energy sources with the national grid (Ede & Nwulu, 2019).

Despite the potential of renewable energy in Nigeria, the lack of infrastructure, inadequate technical skills, and insufficient policy frameworks present barriers to the effective deployment of control systems. This gap in technical capacity has hindered the full integration of renewable sources into Nigeria's power grid (Ojo & Abiodun, 2021). By focusing on the role of control systems in optimizing renewable energy systems, this study aims to highlight solutions for Nigeria to overcome these challenges and achieve a more efficient and sustainable energy future.

2. LITERATURE REVIEW

Being an ever-growing phenomenon, renewable energies take hold within the global energy mix, and is then providing renewed importance to research on the interfacing or integration of control systems in such infrastructure. Control systems have now become paramount with the increased complexity in controls relating to dynamics of diverse energy sources as scientists and engineers strive to increase the efficiency and reliability of renewable energy systems.

Supervisory control, predictive control, and adaptive control techniques form the multifaceted function of control systems in renewable energy (Bordons, Garcia-Torres, & Ridao, 2020). Because at the supervisory control, the higher-level management menus coordinate the various parts of a renewable energy system to work in harmony. Due to the forecasting approaches that predictive control algorithms use, proactive modifications can be implemented upon the changes in the incoming renewable energy sources (Garcia-Torres et al., 2021). Adaptive control methods, in contrast, improve the robustness of a renewable energy system by dynamically reacting to such variations and uncertainties. A contextual analysis of the global renewable energy scene is needed for a comprehensive understanding of the applications of control systems in renewable energy. Looking into the present state and future trends in the global renewable energy adoption shall give us a chance to discuss the effectiveness of control systems. When we consider some cases such as the US, Africa, and Canada, it is clear that each region has its share of challenges and opportunities.

In Canada, with its distributed set of energy sources-in an environment abundant in renewable resources such as hydropower and covering such a vast geographical space-away-side-range control systems should be considered (Brinkman et al., 2021; Jones, 2017). U.S. control techniques for wind, solar, and renewable energy sources must be customised according to its broad mix of resources and its well-established energy infrastructure (Ellabban et al., 2014; Jones, 2017). On the other hand, the control systems can be a change scenario for the continent of Africa, guaranteeing sustained and reliable energy access throughout its varied levels of energy demands and infrastructure developments (Broto, Baptista, Kirshner, Smith, & Alves, 2018; Welsch et al., 2013).

Adaptive, predictive, and supervisory control methods are crucial for renewable energy control systems. Khan et al. (2023) defined supervisory control as the method that optimises performance of a system by co-ordinating the working of its several components. Predictive control algorithms can make more efficient control actions by anticipating changes in renewable energy generation. While methods of adaptive control ensure that systems stand against altering conditions by counteracting uncertainty whenever they arise. Apart from the traditional control strategies, recent times saw an evolution in control systems for renewable energies thanks to AI, advanced monitoring systems, and machine learning (Sankarananth, Karthiga, Suganya, Sountharrajan, & Bavirisetti, 2023; Serale, Fiorentini, Capozzoli, Bernardini, & Bemporad, 2018). The modern monitoring systems provide data in real-time to help make informed decisions. In contrast, AI and ML algorithms can provide renewable energy with control mechanisms that learn by themselves and adapt (Cheng & Yu, 2019). The incorporation of control systems into renewable energy projects heavily depends on the regulatory environment. To chart out opportunities and threats associated with the implementation of control systems, it becomes necessary to know the policies and regulations governing renewable energy in North America. The rate at which these new control technologies are adopted in the regions depends on the openness of the policymakers to them.

3. Types of Control Systems in Renewable Energy

Intermittency and unpredictability due pose many difficulties for the integration of renewable energy sources into the power grid and hence require fairly complex control systems. In any renewable energy source, the control systems are essential for reliability and efficiency. Here we look at some of the control systems commonly used in renewable energy.

This all-encompassing management layer acquires data on the renewable energy system as a whole. From this level of supervision, optimal performance is obtained through real-time monitoring, coordination, and optimisation of multiple components. This level of control, hence, allows for the adjustment to new circumstances and the balancing act between energy supply and demand. According to Cabacho, Samad, Garcia-Sanz, and Hiskens (2011) and Uddin, Chidolue, Azeez, and Iqbal (2022), supervisory control is a must for large-scale renewable energy projects that elegantly marry various sources, such as wind and solar.

1. Predictive Control: These control methods for renewable energy production utilize forecasting tools to predict probable future changes in output. These control systems optimize the performance of renewable energy systems by considering weather forecasts, energy demand forecasts, and other related data with respect to the present. Since the prediction is related to future considerations, it acts in an anticipatory fashion. With this anticipatory mechanism, we are able to integrate renewable energy more efficiently, using our resources more, and causing less interruptions. With predictive control, the power grid would be less affected by uncertainties if one were able to accurately predict the production of renewable energy (Yaramasu & Wu, 2016).
2. Adaptive controls are one of the systems allowing the renewable energy system to react to changes on the fly and unknowns. Having renewable energy generation experiencing swings with respect to weather or equipment malfunction, adaptive control ensures that modifications are made in real-time to keep things stable. O. Chidolue and Iqbal (2023) evaluated that these systems promote the robustness of renewable energy installations by continuously monitoring their performances and then making fast changes through some feedback mechanisms. Because renewable energy sources are inherently unpredictable, adaptive control is required to solve this issue (Fabri & Kadirkamanathan, 2001).
3. Multiple-level Control Structures: Control functions in a renewable energy system are organised in multilevel arrangements through hierarchical control structures. Controls at the supervision, decentralised, and local level commonly exist. Bearing in mind the supervisory control, global planning is envisaged. Under decentralised control, subsystems are coordinated, and at local control, specific components' operations are concerned. According to Well, Rezgui, Hippolyte, Jayan, and Li (2017) suggest that hierarchical control is adaptable for managing complex renewable energy systems and so

prevents scalability. Another feature of renewable energy systems comprises decentralised control, where decision-making authority is delegated amongst different subsystems or components. The entire system's subsystems function hand-in-hand with one another, yet each subsystem operates on its own and makes decisions using locally collected data. This method of decentralised control comes in handy when components can alternatively run on their own pace and, in the meantime, generate decisions at local levels with data available in real-time. Collins (2012) asserted that this particular approach enhances the reliability and adaptability of renewable energy systems.

To enable the operation to be optimized, and future behavior anticipated, advanced control strategies, including Model Predictive Control, employ dynamic models of renewable energy systems. By competing system constraints, MPC enables decisions that lead to optimal performance on predicted horizons. Such controls-Seem to work well when the renewable energy systems can be modelled with absolute accuracy (Maasoumy, Razmara, Shahbakhti, & Vincentelli, 2014; Mariano-Hernández, Hernández-Callejo, Zorita-Lamadrid, Duque-Pérez, & García, 2021).

Different renewable energy control systems work hand in-hand in the smooth integration of renewable energy sources with the power grid. It is very important to consider installation size, renewable resource characteristics, and energy system objectives while selecting a control strategy. Renewable energy generation stands very efficient at the moment, for it shall only get better with the advent of newer control systems.

4. Technological Innovations in Renewable Energy Control Systems

Renewable energy control systems have evolved through improving efficiency, reliability, and adaptability. This section discusses important technical developments that are featured on the renewable energy control landscape.

Among the most important components of modern technology for renewable-energy management is the advanced monitoring system. These advanced monitoring systems use a variety of sensors and communications technologies to collect data, in real time, about different variables such as energy output, grid operation, environmental conditions, etc. By the help of advanced monitoring systems, operators can maximise energy generation and respond rapidly to unexpected breakdowns of equipment or sudden variations in the availability of renewable resources in addition to being able to make educated decisions (Gharavi & Ghafurian, 2011).

To maximise the efficiency of renewable-energy-based systems, two revolutionary technologies have lately surfaced into our view: AI and ML. ML algorithms try to find patterns in data, forecast energy production, and suggest control strategies. Because they can learn from past data and situational changes and make decisions autonomously, AI control systems can enhance efficiency. These technologies have been regarded as developments enabling the real-time optimisation of system creduction, as well as for the handling of the inherent variability of renewable energy sources (Őerban & Lytras, 2020; Cheng & Yu, 2019).

1. Edge computing: this allows for faster decision making by processing data closer to its place of origin, thus reducing latency from transmission. Edge computing allows renewable energy control systems to be distributed far and wide depending upon data processing, enabling independent control elements or devices to reply locally to data analysis. Feng et al. (2021) and Sittón-Candanedo, Alonso, García, Muñoz, and Rodríguez-González (2019) state that this allows control systems to be more responsive and react in real time to changes in renewable energy generation or grid conditions.
2. Virtual Power Plants (VPPs): These innovative concepts coordinate and optimise energy generation from various decentralised energy resources using complex control systems. Energy storage systems, wind turbines, solar energy systems, and a centralised control system are combined together. With by maximising the use of different energy sources, VPPs ensure the grid remains stable and responsive. According to López Sáez de Argandoña (2020) VPPs earn their importance especially under circumstances where there abound renewable distributed energy sources having multiple interconnections.
3. Blockchain: Being a novel decentralised ledger technology, it is just beginning to permeate renewable energy control systems. In a distributed energy system, smart contracts running on the blockchain open up the possibility of destructive energy trade between users and generators. By giving rise to new economic models for renewable energy producers and enabling peer-to-peer energy trading, this invention could lead to enhanced efficiency of renewable energy markets (Yang et al., 2021).
4. Digital Twins: This enables the operation and assessment of real-world assets (such as renewable energy systems) through their digital embodiments. With digital twins, renewable energy control-system operators virtually see how the system performs before

making any physical changes, hence helping with optimisation. According to Agostinelli, Cumo, Guidi, and Tomazzoli (2021) and Rasheed, San, and Kvamsdal (2020), this has led to greater reliability and performance through predictive maintenance, system optimisation, and scenario analysis.

The field of cyber-physical systems (CPS) relates to the fusion of communication algorithms with physical processes in a way that such systems can interact with and respond to the physical or real-world entities. When it comes to renewable energy, CPS ensures enhanced interaction and coordination between control systems and physical components. However, thanks to this integration, renewable energy systems can be stabilized under adverse environmental scenarios due to the presence of adaptive control and resilient control mechanisms (Darwish & Hassanien, 2018).

The changes in technology and development are alone responsible for changing the face of the renewable energy control systems landscape. Making these renewable energy infrastructures smart, adaptive, and efficient through the advanced application of monitoring, machine learning, edge computing, virtual power plants, blockchain, digital twins, and cyber-physical systems would be well deserved. The ongoing research and developments in these technology domains promise future improvements to the energy landscape, thereby moving us on the pathway toward a sustainable and resilient energy future.

5. Future Prospects in Renewable Energy Control Systems

Compared with pressing global energy needs, changing regulatory environments, and the obligation to promising new technologies, the brightest future is in renewable energy control engineering. The major avenues and opportunities are beginning to take shape and will likely influence future avenues of renewable energy control engineering.

Quantum computing thus has a massive potential in revolutionising the control systems of renewable energy. With the great power it carries, quantum processors can help in furnishing new paradigms in optimisation techniques, data analysis, and intricate simulations, enabling more accurate control strategies (Hassanzadeh, 2020). This technology can thus improve the efficiency and performance of computational problems encountered by renewable energy systems on a large scale. Renewable energy control systems are expected to incorporate artificial intelligence far more each day. Ongoing development of AI algorithms will pave the way for advanced predictive analytics, adaptive control methods, and autonomous decision-making capabilities. According to Duan, Edwards, and Dwivedi (2019) and Paudel et al. (2022), this increased form of intelligence will optimise energy output, stabilise grids, and generally make renewable energy systems more resilient.

Grid resilience and adaptability will be the main considerations in the development of any next generation renewable energy management system. A smart grid associated with the advanced control systems would essentially ensure the integration of renewable energy sources, storage systems, and demand-side management (Panda et al., 2022; Said, 2022). A holistic approach to strengthening the energy infrastructure, enabling energy trading, and maintaining grid stability is given emphasis. Using renewable energy sources and advanced control systems, it is expected that distributed energy systems will become more prevalent. Through blockchain-enabled peer-to-peer energy trading, end consumers will be able to directly interact in the energy market; hence creating a decentralized and democratized energy system. Such transformation threatens the very nature of traditional energy models by promoting energy self-sufficiency and grassroots sustainability (Burke & Stephens, 2018; Howell et al., 2017).

The underlying concept of the "Energy Internet" is to develop an extremely intelligent, highly-interconnected energy system. Various energy assets will be able to exchange information and negotiate control amongst themselves in interconnected renewable energy systems through the employment of complicated control algorithms. This integration will serve to optimise energy flows, enhance real-time decision-making, and render the energy ecosystem more flexible and efficient (Hussain, Narayanan, Nardelli, & Yang, 2020; Joseph & Balachandra, 2020; Y. Wu, Wu, Guerrero, & Vasquez, 2020). As control systems undergo an ever-greater digital dependency and interconnection, greater attention will be paid to cybersecurity measures. Strong cybersecurity frameworks will be a must in any future renewable energy control system to counteract threats and facilitate the safe and reliable operation of essential energy infrastructure.

Policy backing and standardisation will largely determine the future of renewable energy control systems. It is expected that regulatory agencies and governments keep a thrust into the policies that advocate for advanced control systems. Thus it becomes possible for the renewable energy sector to collaborate better under standardisation efforts that support compatibility and interoperability. In view of the advancements in renewable energy control systems and with a strong intent towards a circular economy approach, sustainable development targets will get much wider uplift. This requires the integration of renewable energy systems into regenerative economic models with very extreme focus on eliminating waste and the maximum utilisation of all possible resources. Control systems are set to become a centrepiece that co-ordinate with and bring extraordinary sustainability benefits to these complex systems.

6. CONCLUSION

The rapid development of control systems for renewable energy has been seen as a rapidly changing field, characterised by new technologies, an ever-changing regulatory landscape, and the passion to fix the energy problems of the world. A few general observations arise from our discussion so far concerning some key findings and insights from the review. Control systems must be collinearly embedded into the infrastructure to use renewable energy in their full potential. The range of control solutions is broad, from optimisation at system-wide levels by supervisory control, prevention of change by predictive algorithms, to fading away through adaptive mechanisms. Each of these brings a level of efficiency to renewable sources of energy and thus helps with the sources being reliable and stable.

Specificities in a geographic environment indicate the need to adapt control systems to the peculiar difficulties and opportunities facing given locations. Adaptations would have to be drawn for each locality coming up against challenges: one from Canada, another from the US energy landscape, and so on all the way to Africa. Our preparedness to analyze various regional disparities is the driving force behind the concerted attempt to build exact control systems that navigate the complexities of each energy ecosystem. The potential for control systems in renewable energy depends on technological progress. Advancements are thus causing a paradigm shift in how renewable energy resource management is conceived: advanced monitoring systems, machine learning, AI, and blockchain technology. These technologies facilitate the establishment of decentralized, adaptive, and intelligent energy networks while also improving the efficacy of energy systems. Therefore, there is a positive outlook for control systems for renewable energy. Development in quantum computing, AI, and decentralized power systems is paving the way for a more complex, resilient, and interconnected energy infrastructure. To tackle the intricacies of the growing energy sector, a big-picture approach should hence be envisaged, as seen through the lenses of cybersecurity, policy support, and sustainability.

Collaborators from the research community, legislators, and industry stakeholders are critically important to working together as humans embark on this new road towards URN. This work steps up from the existing library on control systems for renewable energies and hence can be of great use in policymaking, decision-making, and technical updates. At the end of all these pathways lies a stronger and sustainable environment for energy, and this to great extent depends on the strategic interfacing of control systems with renewable energy-a technological requirement and an opportunity. It is for sure that the world's joint effort to set in motion these technologies will stand as the guiding factor in brightening the way of mankind into a future wherein renewable energy sources are optimally harnessed, thus making this world cleaner and sustainable.

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