Advancements through AI Integration in Hybrid Renewable Energy Systems: A Review

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Abstract: *Hybrid Renewable Energy Systems (HRES) offer a transformative solution to sustainable energy production by integrating multiple renewable sources such as solar, wind, and biomass. This paper explores the significance of HRES in addressing energy security and environmental sustainability challenges, highlighting their role in mitigating intermittency issues inherent in renewable energy sources. The review discusses the complexities of standalone HRES systems and the challenges associated with integrating diverse energy sources. Additionally, the importance of power quality in renewable energy systems is emphasized, setting the stage for exploring advancements through AI integration. The paper then delves into the application of Artificial Intelligence (AI) techniques in Dynamic Voltage Restorers (DVRs) within HRES, presenting key advancements points such as real-time adaptability, predictive maintenance, optimal voltage regulation, fault detection, adaptive control strategies, harmonic mitigation, energy optimization, and scalability. These advancements signify a significant step forward in enhancing the performance, reliability, and sustainability of hybrid renewable energy systems.*

Keywords-: *Hybrid Renewable Energy Systems, HRES, Artificial Intelligence, AI Integration, Dynamic Voltage Restorers, DVRs, Power Quality, Renewable Energy, Sustainability, Advancements*.

I. INTRODUCTION

Hybrid Renewable Energy Systems (HRES) represent a transformative approach to sustainable energy production, combining multiple renewable energy sources such as solar, wind, and sometimes biomass or hydroelectric power. By integrating these diverse sources, HRES can offer a more reliable and consistent energy supply compared to single-source renewable systems. This integration helps to mitigate the intermittency issues inherent in renewable energy, ensuring that power generation remains stable even when individual sources fluctuate due to varying weather conditions or other environmental factors. As global energy demands continue to rise and the imperative to reduce greenhouse gas emissions becomes more pressing, HRES are emerging as a crucial solution for achieving energy security and environmental sustainability. They not only enhance the efficiency and reliability of renewable energy supply but also contribute significantly to reducing the carbon footprint and dependence on fossil fuels. This multifaceted approach leverages advanced technologies and intelligent control systems to optimize performance and ensure seamless operation, paving the way for a greener and more resilient energy infrastructure.

HRES is actually a combination of two or more renewable energy sources, or at least one renewable and one conventional source. HRES can be connected or not to the grid. For the presented case, the HRES system operates in stand-alone mode (off-grid mode). The hybrid energy system is defined as a combination of energy sources with different characteristics and an energy storage environment. With regard to standalone applications, choosing the optimal hybrid energy system is a challenging process due to many reasons, such as: determining the best combination of sources; reduce initial capital investment; reliability of power supply; system components, etc. Fig. 1 [1] shows the block diagram of an autonomous hybrid system for small farms located in isolated locations. HRES hardware and software components are included in the Control System block and they perform process control and HRES efficiency improvement.

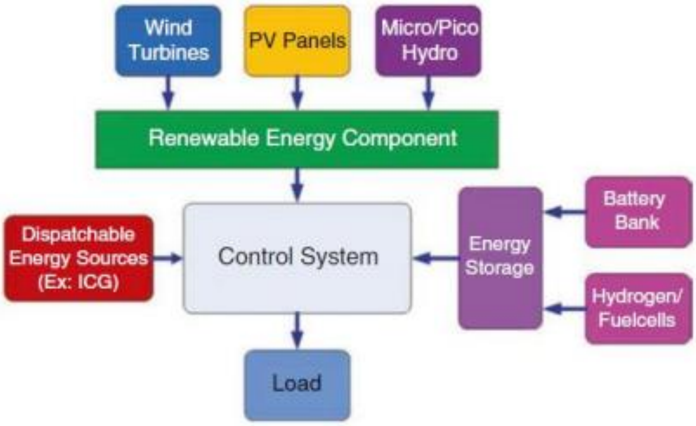

Figure 1 Diagram bloc of a stand-alone hybrid energy system

The use in situ of HRES systems for isolated locations is a new step towards decentralized electrification. The systems can be grouped into single-phase or three-phase MNs, which feed local consumers and/or small farms. The interconnection of these sources of electricity in parallel on a common network raises many problems, caused mainly by their different functioning mode, by the different installed electric power, as well as by other particular aspects of each system. Often, in a HRES type system, in addition to renewable energy sources, conventional fossil fuel generators, generally Diesel engine generators, are used intermittently. They are introduced into the system when the demand for electricity of the consumers exceeds the capacity of the renewable sources. Combinations of more than two renewable sources become complex hybrid systems requiring higher-order investments. Reducing the techno-economic indicator of such a hybrid energy system involves complex studies and detailed analyses before manufacturing. Fig. 2 shows the main systems of a hybrid HRES network: solar, wind, hydrokinetic, energy storage.

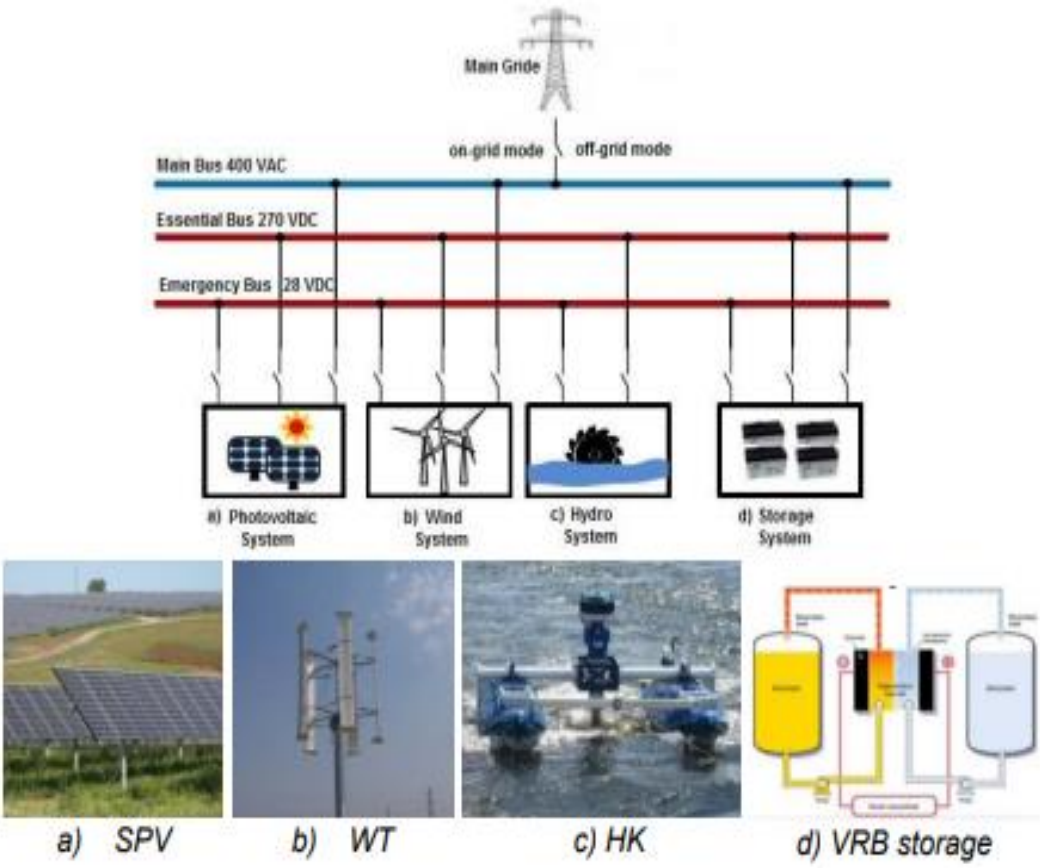

Figure 2 Micro-grid topology of hybrid renewable energy systems Source (MICROREN, 2015)

II. IMPORTANCE OF POWER QUALITY IN RENEWABLE ENERGY

The increasing demand for clean energy has led renewable energy sources (RES) to be a potential method to contribute in energy generation [1, 2]. Eradication of hazardous methods for energy generation is becoming a contemporary requirement around the globe [3]. Conventional ways of energy generation have caused major environmental impacts globally along with being highly wasteful and expensive. Renewable energy sources (RES) in this regard has appeared as a blessing being cost-effective and environment friendly at the same time [4, 5].

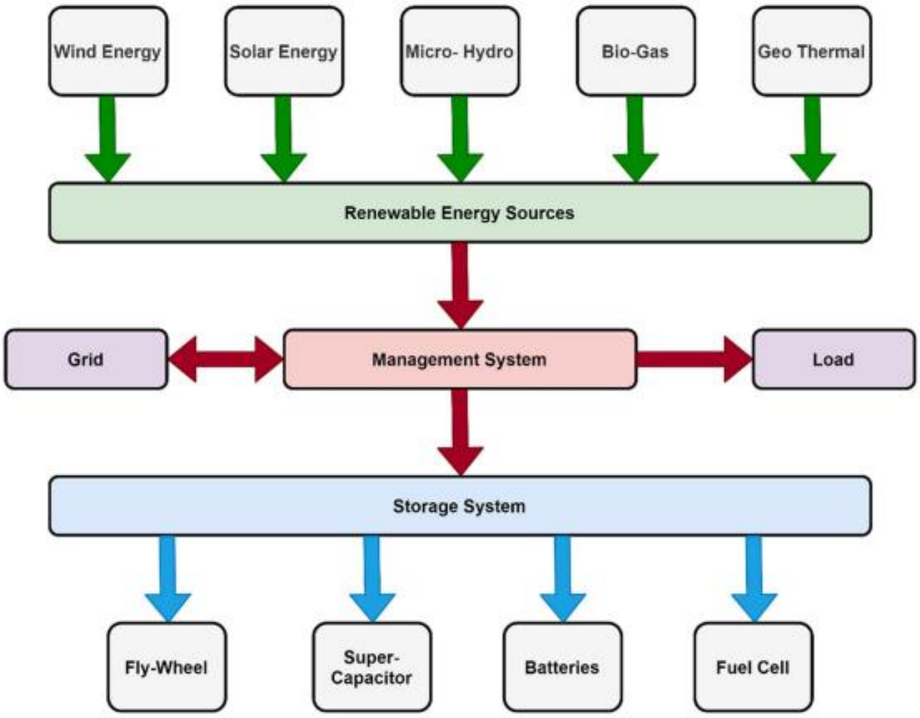

Figure 3 The possible combination of HRES systems

Renewable energy sources (RES) individually lack to perform as an independent power generation system since they are intermittent in nature. Therefore, the integration of two or more RES's is a possible solution to this issue. The integration of multiple renewable energy generation sources are known as hybrid renewable energy systems (HRES). Generally, they are utilized to construct an independent power generation system that increases the efficacy of the RES. Hence, HRES systems have become highly popular and they are implemented universally for high-quality power generation. Fig. 3 depicts the range of all possible HRES combinations along with the management system. Furthermore, the possible range of storage systems for power back-up during intermittent conditions is also depicted in Fig. 3. Power converters are primarily utilized to regulate the input voltage as per the application requirement. Power converters play a predominant role in power engineering and drives since decades. Vast applications of converters can be found in industrial applications and RES systems. Power converters have been adapted to replace the conventional voltage divider circuits that include rheostat and power conversion circuits. These conventional methods tend to have low output voltage and efficiency.

III. LITERATURE REVIEW

Molla et al. (2020) [10] researched renewable energy sources, noting their abundance and environmental benefits. However, the intermittent nature of sources like wind and solar PV can lead to fluctuations of the power. To mitigate these fluctuations and protect the sensitive loads, dynamic voltage restorers (DVRs) are commonly employed. This study focused on using a battery and "super magnetic energy storage (SMES)"-based DVR for compensating voltage sag conditions in a grid-connected hybrid PV-wind power system, using a pre-sag compensation method.

Yang et al. (2022) [11] presented a novel 'DC dynamic voltage restorer (DC-DVR)' designed for DC distribution networks. This system is built on an enhanced AC/DC dual active bridge and incorporates battery energy storage. It effectively preserves the voltage profile of sensitive loads in DC networks by injecting either forward or reverse voltage to counteract voltage sag and swell issues. The proposed DC-DVR is characterized by its straightforward structure, simple control strategy, and capacity to mitigate both types of voltage disturbances.

Tata et al. (2022) [12] introduced a "proportional-integral (PI)" controller designed for a "dynamic voltage restorer (DVR)" within a "hybrid renewable energy system (HRES)" integrated with the grid. Their study encompassed a setup including a solar PV array, wind turbines, and fuel cells as part of the HRES, with three boost converters linking these sources to a central DC-link. The DVR control mechanism, utilizing two PIs, manages load voltage under various abnormal conditions. These PIs regulate the ‘D-Q axis’ voltage signals and adjust the gate pulses of the “pulse width modulation (PWM)” used to control the DVR operation.

Kanagaraj et al. (2022) [13] proposed a hybrid photovoltaic-thermoelectric generator (PV-TEG) combined dynamic voltage restorer (DVR) system for compensating power quality disturbances in a single-phase distribution system. The system uses a hybrid PV-TEG energy module to provide stable input voltage for the DVR, with a fractional factor-based variable incremental conduction (FFVINC) maximum power point tracking (MPPT) control algorithm for maximum power extraction from the PV array, and an intelligent fuzzy logic controller (FLC) for implementing the MPPT control algorithm.

Abas et al. (2020) [14] addressed power quality concerns in modern power systems, which can affect the consumers and the utilities. Integration of ‘renewable energy sources’, ‘smart grid systems’, and ‘power electronics equipment’ has led to various problems, including ‘current and voltage harmonics’, ‘voltage sag’, and ‘swell’. The “Dynamic Voltage Restorer (DVR)” is a key component of the “Distribution Flexible AC Transmission System (D-FACTS)” used extensively to mitigate these challenges. It injects voltages into the distribution line to uphold the voltage profile, ensuring a stable load voltage.

In their 2023 study, **Rani et al. [15]** investigated the enhancement of voltage regulation in hybrid PV/wind systems using a Dynamic Voltage Restorer (DVR) without energy storage (WES). The DVR functions by injecting voltage at a common network point to stabilize the supply voltage at the load side. The research highlights the critical role of the WES-based DVR controller in improving regulation of the voltage and “Fault Ride through (FRT)” capability within the hybrid network. An innovative hybrid feed forward/feedback hysteresis control method was proposed for the “Wind Energy System (WES)” -based “Dynamic Voltage Restorer (DVR)”. This method showed superior performance in various fault conditions compared to traditional open-loop control strategies. The effectiveness of this approach was validated through MATLAB/Simulink simulations, which indicated improved responses in both transient and steady-state periods, as well as better voltage regulation under different three-phase fault conditions.

Benali et al. (2020) conducted a simulation study focusing on the power quality of a medium voltage grid connected to “distributed generation (DG)” sources, such as “photovoltaic (PV)” farms, and their control strategies. Their system employed a two-stage energy conversion process, utilizing a "DC-DC boost converter" for optimal power extraction from the solar PV system and a three-level "voltage source inverter (VSI)" for grid connection. To ensure grid voltage and frequency remained within acceptable limits during disturbances like voltage swells and sags, they proposed a fuzzy logic-based DVR. This DVR aimed to safeguard critical loads from network disturbances. The study examined various fault conditions, comparing parameters such as voltage stability, real and reactive power, current, and power factor at the point of common coupling (PCC) with and without the DVR system.

In 2019, **Mansor et al. [17]** examined a distribution network experiencing complex voltage disturbances due to its nonlinear, intensified, and sensitive loading conditions, exacerbated by the integration of renewable energy. This network, characterized by both stationary and short-duration voltage disturbances, required a DVR with an integrated battery bank to overcome long and severe voltage disturbances. The study demonstrated that the DVR effectively compensated for these disturbances in a photovoltaic (PV) system-equipped distribution network.

Bajaj et al. [18], in their 2020 study, proposed a “hybrid distributed generation (DG)” system feeding a ‘single-phase DVR’ to mitigate ‘voltage sags’, ‘swells’, and ‘interruptions’ in a ‘single-phase distribution system’. The switching control strategy of the proposed model effectively managed voltage quality issues while minimizing grid energy consumption. This system could fulfill load requirements during interruptions, functioning as an uninterruptible power source. Additionally, the study introduced a novel boost inverter with proportional integral control, which reduced switching losses compared to traditional topologies, leading to substantial energy conservation. Simulation results showed the DVR effectively recovering voltage sags up to 0.1 pu and swells up to 1.9 pu of pre-sag voltage.

IV. ADVANCEMENTS THROUGH AI INTEGRATION

The integration of Artificial Intelligence (AI) into various fields has led to significant advancements, and its application in the realm of renewable energy systems, particularly in Dynamic Voltage Restorers (DVRs), holds immense promise. By leveraging AI techniques, such as machine learning algorithms, DVR control systems can adapt and optimize their operations in real-time, effectively addressing voltage fluctuations, enhancing power quality, and improving system efficiency. These advancements not only contribute to the stability and reliability of hybrid renewable energy systems but also pave the way for a more sustainable and resilient energy infrastructure. Here are some key advancements points through AI integration in Dynamic Voltage Restorers (DVRs) for hybrid renewable energy systems:

- Real-Time Adaptability: AI-based DVR control systems can dynamically adjust their operations in response to changing conditions, such as fluctuations in renewable energy generation or variations in load demand. This real-time adaptability ensures optimal performance and stability of the power system.

- Predictive Maintenance: AI algorithms can analyze operational data from DVRs to predict potential faults or failures before they occur. This proactive approach to maintenance helps prevent downtime and ensures continuous operation of the power system.
- Optimal Voltage Regulation: By continuously learning from system behavior, AI-based DVR control systems can optimize voltage regulation strategies to maintain stable voltage levels within the desired range. This improves power quality and reliability for connected loads.
- Enhanced Fault Detection: AI algorithms can effectively detect and classify various types of faults in the power system, such as voltage sags, swells, or interruptions. This enables prompt and accurate response to mitigate the impact of faults and minimize disruptions to power supply.
- Adaptive Control Strategies: AI-based DVR control systems can adapt their control strategies based on evolving grid conditions and operational requirements. This flexibility allows for efficient utilization of renewable energy sources and seamless integration into the existing grid infrastructure.
- Harmonic Mitigation: AI algorithms can analyze harmonic distortion in the power system and implement corrective measures to mitigate its effects. This helps improve power quality and ensures compatibility with sensitive electronic equipment.
- Energy Optimization: AI-based optimization algorithms can intelligently manage the distribution of energy from renewable sources, storage systems, and grid connections to maximize efficiency and minimize costs. This optimization contributes to overall energy savings and sustainability.
- Scalability and Interoperability: AI-based DVR control systems can be designed to scale seamlessly with the size and complexity of the power system. Additionally, they can integrate with existing grid infrastructure and communication protocols, ensuring interoperability and compatibility with diverse components.

These advancements through AI integration in DVRs represent a significant step forward in enhancing the performance, reliability, and sustainability of hybrid renewable energy systems.

V. CONCLUSION

The integration of Artificial Intelligence (AI) into Dynamic Voltage Restorers (DVRs) within Hybrid Renewable Energy Systems (HRES) represents a groundbreaking advancement with profound implications for sustainable energy production. The review has highlighted various advancements points through AI integration, ranging from real-time adaptability and predictive maintenance to energy optimization and scalability. These advancements not only enhance the stability and reliability of HRES but also contribute significantly to achieving energy security and environmental sustainability goals. As research in this field continues to evolve, further innovations in AI integration are expected to drive the development of more efficient, resilient, and environmentally friendly energy infrastructure. Thus, the future of hybrid renewable energy systems lies at the intersection of renewable energy technologies and artificial intelligence, promising a greener and more sustainable energy future for generations to come.

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