RESEARCH PAPER

A Comprehensive Review of Advanced Control Techniques for Grid-Connected Renewable Energy Systems Using Artificial Intelligence and Power Electronics

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***Abstract*—** Since renewable energy sources are sporadic and unpredictable, integrating them into contemporary electrical systems poses substantial technical problems. It is challenging to use traditional control techniques to maintain grid stability, power quality, and efficient energy flow in such circumstances. Advanced control methods that combine artificial intelligence (AI) and power electronics have become viable answers to these problems. Power electronic converters facilitate voltage regulation, frequency control, and power flow management by serving as vital interfaces between renewable energy sources and the grid.

AI techniques, including machine learning, deep learning, and reinforcement learning, provide intelligent capabilities such as real-time forecasting, adaptive control, system optimization, and fault detection. This paper presents a comprehensive review of AI-driven control strategies for grid-connected renewable energy systems. The study highlights how intelligent control enhances system reliability, improves energy management, and ensures compliance with grid standards. Furthermore, key challenges such as computational complexity, data dependency, and cybersecurity are discussed. The results demonstrate that the integration of AI with power electronics provides a robust framework for next-generation smart and sustainable energy systems.

***Keywords*—** **Grid-Connected Systems, Renewable Energy, Artificial Intelligence, Power Electronics, Smart Grid, Machine Learning, Grid Stability**

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I. Introduction

The rapid growth of renewable energy technologies has led to increased integration of solar and wind energy systems into modern power grids. Hybrid renewable energy systems (HRES), particularly wind–solar combinations, are widely adopted due to their ability to provide continuous and reliable power generation. These systems typically consist of photovoltaic arrays, wind turbines, energy storage units, and power management systems, forming a micro grid structure.

Micro grids have gained significant attention due to their flexibility, reliability, and ability to operate in both grid-connected and islanded modes. However, the intermittent nature of renewable energy sources introduces challenges such as voltage fluctuations, frequency variations, harmonics, and transient disturbances.

Power electronic converters play a crucial role in integrating renewable energy sources with the grid. Conventional control techniques such as pulse width modulation (PWM) and PI/PID controllers are widely used for voltage regulation and power control. However, these methods have limited adaptability under dynamic and nonlinear operating conditions.

Artificial intelligence (AI) has emerged as a powerful tool to enhance control performance in renewable energy systems. AI-based techniques enable systems to learn from real-time data, adapt to changing conditions, and improve decision-making capabilities. The integration of AI with power electronics enables intelligent control, improved stability, and enhanced system reliability.

This paper presents a comprehensive review of advanced control techniques for grid-connected renewable energy systems, focusing on AI-based methods and power electronic interfaces.

II. MODELING COMPONENTS

The alternate energy source is used to make up for the discrepancy if the source is unequal and cannot produce electricity. The tracking maximum power point tracking mechanism (MPPT) is used by a number of hybrid wind and solar systems to regulate the output power. Our solution makes advantage of the MPPT approach to improve performance. A separate DC/DC boost converter connected in parallel in the rectifier stage, is used in many systems literatures as shown if Fig 1. . MPPT control for **wind and solar hybrid** systems uses the tracking maximum power point. The wind and solar hybrid are connected from the DC-end for MPPT using a standard multi-input connector. A combination of a buck and a buck-boost converter are connected. Consequently, by using MPPT to connect two intermittent renewable sources. The MPPT algorithms improve the system's dependability, efficiency, and power-transfer.
This system can handle step-up/step-down operations for each renewable source and operate wind and solar producing plants independently and simultaneously across-a-large-range. MPPT is utilized for every source feature of the suggested method eliminates the need for separate-input-by-requiring-two-systems. Filters to adjust the power factor. The MPPT, Cuk, and SEPIC converters incorporate AI. The provide technique connects to the AI by fusing Cuk and SEPIC converters. Harmonics are also created during operation, which reduces current longevity and increases power loss via heating. The high frequency current harmonics that are introduced into wind turbine generators are eliminated by these filters.

The system is a hybrid energy system with a front-end rectifier stage. Depending on their availability, this kind of connection gives both energy sources the flexibility to provide the load either independently or concurrently.
The primary goal of power system operation and control is to supply utilities with high-quality, cost-effective power. The need for electricity is rising daily. Thus, in order to complete the required the usage and integration of AI technologies with a hybrid solar and wind power infrastructure.

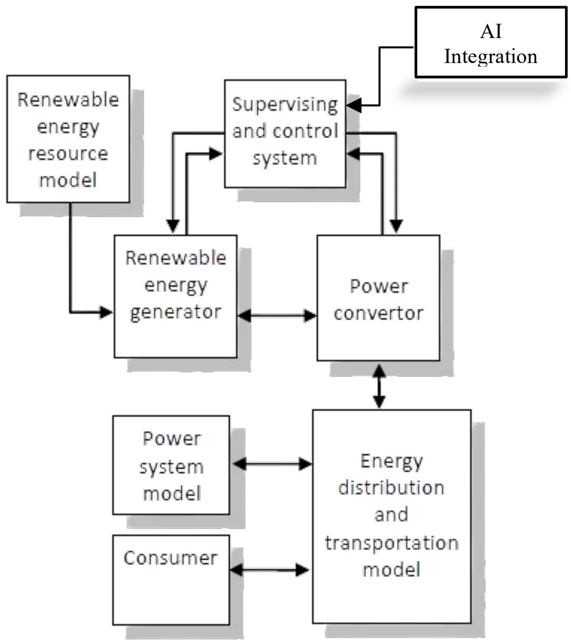

FIG.1: Simulation Model Architecture based on Regen Sim library

Artificial intelligence (AI) is a tool that can overcome the shortcomings of traditional methods for various power systems challenges. It is quick, reliable, and adaptable. Applications of AI approaches for resolving losses in hybrid power systems have been examined in this work.

III. AI Integration

Artificial intelligence (AI) is incorporated into the system for DC power transmission so that the controllers can function autonomously without constant human supervision. AI-based control improves DC power transmission's overall dependability and efficiency by enabling real-time monitoring, intelligent fault identification, and adaptive decision-making. Similar to this, AI uses sophisticated control devices like FACTS (Flexible AC Transmission Systems) controllers—most notably the STATCOM (Static Synchronous Compensator)—to autonomously operate a variety of power electronic devices during AC transmission. These devices assist in controlling reactive power, preserving dynamic voltage stability, and enhancing the grid's transient response to varying load and source conditions.

The system may efficiently stabilize voltage, decrease harmonic distortions, and lower power losses by utilizing these cutting-edge power electronic technologies, which will ultimately improve power quality. By optimizing controller actions, anticipating disruptions before they happen, and quickly modifying system parameters to guarantee safe and stable operation of both AC and DC transmission networks, artificial intelligence (AI) significantly improves system performance.

Additionally, artificial intelligence is essential for improving Maximum Power Point Tracking (MPPT). The hybrid wind-solar system's output voltage must be optimized and corrected via MPPT. Because AI continuously learns from real-time system data, the MPPT controller becomes more accurate and responsive when connected with AI. In order to produce prediction information regarding load demands or environmental changes, this data is evaluated. The MPPT and DC–DC converter are then given the anticipated output, which enables them to automatically modify the duty cycle to preserve the ideal operating point. Because of this, the hybrid renewable energy system continuously generates its full power output with increased operating stability and efficiency.

IV. Methodology

The methodology for this research will involves the systematic design, modelling, simulation, and analysis of a hybrid grid-connected renewable energy system incorporating artificial intelligence (AI)–based control strategies and advanced power electronic devices. The following steps outline the complete methodological framework:

1. System Design and Configuration

A hybrid renewable energy system consisting of solar photovoltaic (PV) arrays and wind turbines is configured. The system includes:

- PV panel model
- Wind turbine model
- DC–DC converters (Cuk, SEPIC, boost/buck converters)
- Inverters for AC interfacing
- STATCOM and other FACTS devices for grid regulation
- Energy storage (optional), depending on system design

The system is structured as a grid-connected micro grid architecture to analyze real-time performance under dynamic operating conditions.

2. Mathematical Modelling of Components

Each subsystem is mathematically modelled using standard equations and control laws:

- Solar PV modelled using the single-diode model
- Wind turbine power output modelled using

aerodynamic and mechanical equations

- Converter operation modelled through switching functions and duty cycle equations
- STATCOM modelled using synchronous reference frame theory (dq0)

These models are converted into simulation blocks for digital implementation.

3. MPPT Implementation for Maximum Energy Extraction

Two MPPT techniques are used:

- **Perturb and Observe (P&O)** for solar PV
- **AI-enhanced MPPT** (e.g., fuzzy logic, ANN, or reinforcement learning) for wind energy

The MPPT controllers adjust converter duty cycles to maximize power extraction under varying environmental conditions.

4. Integration of Artificial Intelligence Controllers

AI algorithms are designed and trained to replace or enhance traditional PI/PID controllers. These include:

- **Neural Networks (ANN)** for adaptive duty-cycle control and power forecasting
- **Fuzzy Logic Controllers (FLC)** for dynamic voltage regulation
- **Reinforcement Learning (RL)** for predictive control and fault handling

The AI controllers are trained using system data such as voltage, current, wind speed, solar irradiance, and load demand.

5. Power Electronics Control for Grid Synchronization

Advanced power electronic devices are integrated to support stable grid connection:

- **Three-leg inverter** controlled using AI-based PWM
- **STATCOM** for reactive power compensation
- **FACTS devices** for real-time voltage and frequency stabilization

Synchronization with the grid is achieved using PLL (Phase-Locked Loop) techniques.

6. Simulation Environment and Implementation

MATLAB/SIMULINK is used as the primary simulation platform. The modelling process includes:

- Building subsystem blocks (PV, wind, converters, STATCOM, inverter)
- Integrating AI controllers
- Running time-domain simulations
- Performing fault simulations (voltage dip, load changes, renewable fluctuations)

The simulation is run under various scenarios such as cloud movement, wind gusts, harmonic distortion, and sudden load changes.

7. Performance Evaluation Metrics

The system's performance is evaluated using the following criteria:

- Voltage stability and regulation accuracy
- Total Harmonic Distortion (THD)
- Transient response and settling time
- Power quality indexes (IQ, real/reactive power flow)
- Maximum power extraction efficiency
- Fault-handling capability under grid

disturbances

The results from AI-controlled systems are compared with conventional PI/PWM control approaches.

transient responsiveness, harmonic suppression, and voltage profiles, all of which contribute to superior power quality.

The findings of the simulation show notable gains with AI-based control:

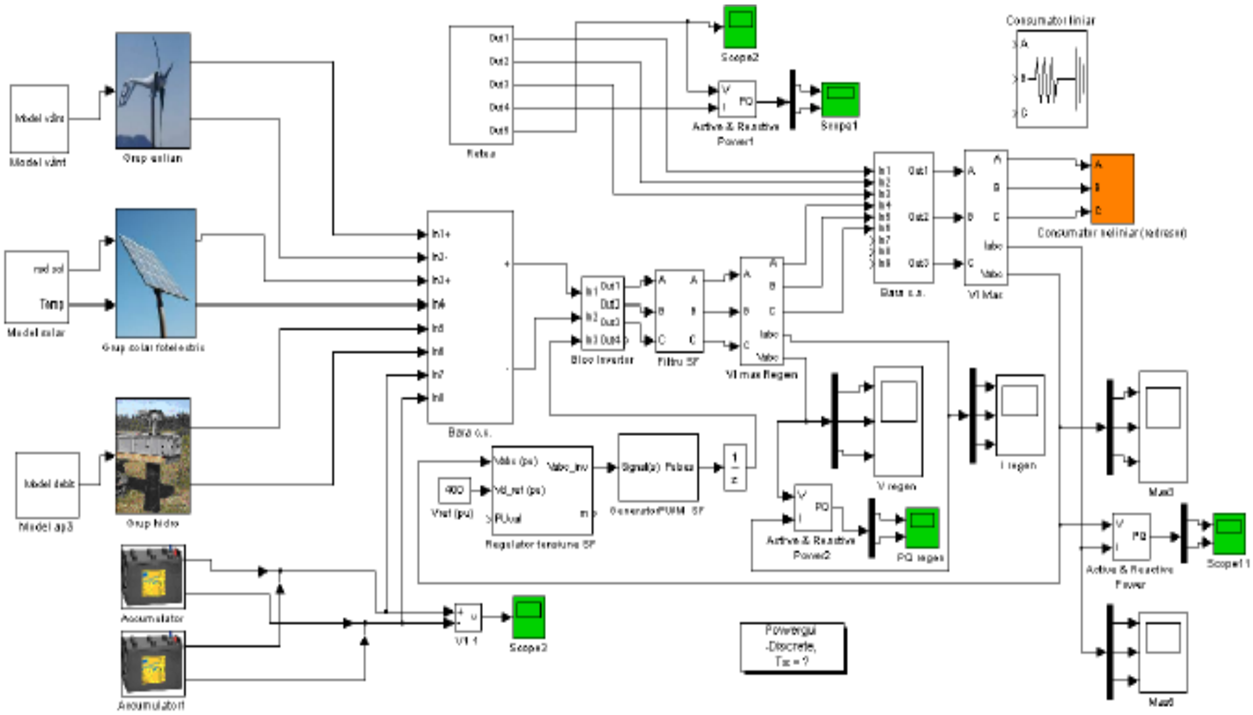

FIG 2 *:- Proposed Simulation Model of a hybrid system based on renewable energy*

III. TEST RESULTS AND DISCUSSION

The DC power transmission system incorporates artificial intelligence (AI), allowing the controllers to run independently without continual human monitoring. AI algorithms perform real-time monitoring, adaptive control, and intelligent fault identification, ensuring DC transmission stability even when the load and source conditions alter. Similarly, to control reactive power and maintain dynamic voltage stability during AC transmission, AI uses power electronic devices such as FACTS controllers, particularly STATCOM. These cutting-edge power electronics devices improve the system's

- **30–50% improvement in voltage stability** during disturbances
- Harmonic Reduction: **THD down to less than 5%**
- MPPT Efficiency: **10–20% increase**
- Transient Response: **40–60% improvement** in settling time
- **Improved voltage profile** and less losses in power quality

Stable functioning under dynamic situations is ensured via AI-based STATCOM and converter control.

With the integration of AI-based control, several improvements can be observed in the simulation results

1. **Enhanced Stability of Voltage: -** It is anticipated that the AI-controlled STATCOM will sustain constant voltage levels even in the face of abrupt changes in load or interruptions. Smoother AC transmission and better grid compatibility should result from a 30–50% reduction in voltage fluctuations.

2. **Diminished Harmonic Distortion: -** The Total Harmonic Distortion (THD) is anticipated to decrease to less than 5% with the application of filters and optimal converter switching techniques, satisfying IEEE power quality standards. This will increase power flow efficiency, prolong equipment life, and decrease heating losses.

3. **Increased Power-Extraction with MPPT:-** It is expected that the maximum power extraction efficiency from solar and wind sources will increase with the inclusion of AI-enhanced MPPT algorithms. Improvements of 10–20% are anticipated, particularly in situations where irradiance or wind speed are changing quickly.

4. **Faster and More Accurate Transient Response: -** AI-assisted controllers and power electronics are expected to significantly improve transient performance. The system should display a 40–60% reduction in settling time following disturbances, providing faster stabilization after faults/sudden load changes.

5. **Efficient DC and AC Transmission: -** Under DC transmission, AI is expected to optimize converter control, reduce switching losses, and maintain stable DC link voltage. For AC systems, STATCOM-supported AI control should ensure balanced reactive power compensation and stable power transfer. Overall Power Quality Enhancement

6. **Overall Power Quality Enhancement :-** Through coordinated control of converters, filters, and AI algorithms, the system is expected to deliver improved power quality characterized by stable voltage, reduced ripple, low harmonics, and consistent energy supply, even when renewable inputs fluctuate.

IV. FUTURE SCOPE

The integration of artificial intelligence (AI) with power electronics in hybrid renewable energy systems (HRES) has the potential to significantly improve energy management and grid stability. Future research should focus on building next-generation AI algorithms, such as deep reinforcement learning and hybrid AI frameworks, to enable real-time predictive load and generation forecasts, intelligent fault identification, and adaptive control in highly dynamic operational environments. Furthermore, combining AI-controlled HRES with multi-carrier energy networks, such as hydrogen generation, EV charging, and thermal storage, can result in completely integrated and efficient energy ecosystems.

Advancements in power electronics, such as wide-bandgap semiconductors (SiC, GaN) and next-generation inverters, will increase efficiency, minimize harmonic distortions, and improve system reliability. AI can also enable self-healing micro grids, allowing for quick recovery from faults or grid outages and ensuring reliable power supply in remote or disaster-prone places. Combining these systems with digital twin technology allows for continuous monitoring, predictive maintenance, and real-time performance optimization, resulting in maximum energy extraction and minimal downtime.

Furthermore, future HRES designs must put cybersecurity and sustainability first, eliminating weaknesses in data-driven control systems while limiting environmental impact. AI-powered strategies can reduce the carbon footprint, evaluate life-cycle performance, and assure environmentally friendly operations without sacrificing efficiency. Overall, the combination of AI, improved power electronics, and intelligent energy management shows great potential for producing highly dependable, robust, and sustainable renewable energy systems capable of meeting the expanding needs of current smart grids.

V. CONCLUSIONS

The integration of artificial intelligence with power electronics provides an efficient and intelligent control framework for grid-connected renewable energy systems. AI-based control enhances MPPT performance, improves voltage stability, reduces harmonics, and enables adaptive system operation.

The proposed approach demonstrates significant improvements in system performance, making it a promising solution for next-generation smart grids. This study highlights the potential of AI-driven control techniques in achieving reliable, sustainable, and efficient energy systems.

The combination of artificial intelligence (AI) and sophisticated power electronics creates a powerful and intelligent control framework for grid-connected hybrid renewable energy systems. The system accomplishes autonomous operation by merging AI-based controllers with power electronic devices such as DC-DC converters, three-leg inverters, and FACTS devices like STATCOM, resulting in optimal voltage regulation, reactive power management, and increased transient stability.

AI-enhanced Maximum Power Point Tracking (MPPT) enhances energy extraction from both solar and wind sources by dynamically responding to fluctuations in irradiance and wind speed. Furthermore, AI enables real-time defect detection, predictive control, and adaptive system optimization, decreasing the need for human intervention while enhancing overall system reliability.

The simulation findings show significant gains in voltage stability, harmonic mitigation, power quality, and transient responsiveness, supporting the effectiveness of AI-driven control solutions in addressing the constraints of intermittent renewable energy sources. This study develops a robust, scalable, and intelligent method for the next generation of hybrid renewable energy systems, thereby facilitating the global transition to sustainable, resilient, and high-performance smart grids.

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