New control strategy for maximizing power extraction in the grid-connected CHP-PV-wind hybrid system

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ABSTRACT

This work represents a significant contribution to the advancement of modern electrical systems by combining advanced control strategies with robust protection solutions to address the challenges of the energy transition. It focuses on the integration of renewable energy within electrical grids, with particular attention to wind energy, cogeneration (CHP), and photovoltaic energy. The main contributions include the development of innovative methods to enhance system stability and improve energy quality. This is achieved notably through the use of advanced control algorithms, such as the synchronously rotating frame (SRF) transformation, applied to converters and voltage source converter-based high voltage direct current (VSC-HVDC) systems. These approaches enable precise voltage regulation, optimized power flow management, and significant reduction of harmonic distortion. The paper also explores novel techniques, such as control based on the ANFIS algorithm, to improve voltage regulation, current stability, and converter efficiency. Finally, an effective protection solution against voltage faults is proposed, ensuring the stable and reliable transfer of energy produced by offshore wind farms to onshore grids.

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1. INTRODUCTION

The global shift towards sustainable development has intensified the search for alternative, clean, and renewable energy sources to mitigate the environmental degradation and resource depletion caused by excessive fossil fuel consumption. In this context, renewable energy technologies such as solar photovoltaic (PV), wind power, and combined heat and power (CHP) systems have become essential pillars of modern energy strategies due to their ability to reduce greenhouse gas emissions and support long-term energy security. Furthermore, these technologies are increasingly promoted through national and international regulatory frameworks, which aim to accelerate the energy transition and strengthen the resilience of power systems in the face of climate change challenges [1].

Nevertheless, the incorporation of such variable energy sources into large-scale electrical networks entails complex technical challenges that must be carefully addressed. Their intermittent and stochastic nature complicates essential operational aspects, including real-time synchronization, voltage and frequency regulation, and overall grid stability. These difficulties become even more pronounced in advanced infrastructures such as voltage source converter-based high voltage direct current (VSC-HVDC) systems, where any fluctuation in renewable generation can lead to significant disturbances in power quality and dynamic performance. As a result, ensuring the reliable integration of renewable energy into modern power grids requires sophisticated control strategies and robust system design [2].

Recent research has introduced multiple strategies to enhance the integration of renewable energy systems into power grids [3]. Advanced control techniques, including vector control and direct power control, are increasingly employed due to their effectiveness in real-time management of active and reactive power [4]. To further improve power quality and mitigate total harmonic distortion (THD), multilevel converters have been extensively investigated, especially in photovoltaic and wind energy grid-connected applications. Moreover, intelligent control approaches such as fuzzy logic, neural networks, and hybrid adaptive models have demonstrated strong potential in addressing the inherent uncertainties and nonlinear dynamics of renewable energy sources.

In the area of maximum power point tracking (MPPT), traditional techniques such as perturb and observe (P&O) and incremental conductance (IncCond) frequently prove inadequate under rapidly fluctuating environmental conditions [5]. To address this, more recent efforts have turned to artificial intelligence-based techniques, including ANFIS and machine learning models, which provide faster convergence and better adaptation. In parallel, synchronization techniques such as the synchronously rotating frame (SRF) transformation have been utilized to decouple and control power components in dynamic conditions, offering improved system stability [6]. Despite these advances, there remain significant challenges in the seamless coordination and integration of hybrid renewable energy systems, particularly when interfacing with modern HVDC grids and offshore infrastructures. Issues such as fault resilience, synchronization accuracy, power quality management, and the optimization of energy extraction continue to drive ongoing research in this domain.

Previous studies have extensively addressed the technical challenges related to the integration of renewable energy sources into electrical grids. The intermittent and stochastic behavior of wind and solar energy significantly affects power system stability and synchronization [7], [8]. Various control techniques, including vector control, direct torque control, and droop-based methods, have been developed to regulate power flow and maintain voltage/frequency stability under dynamic conditions [9].

Multilevel converters have been extensively investigated due to their ability to enhance power quality and minimize total harmonic distortion (THD), rendering them suitable for medium- and high-voltage applications in grid-connected renewable energy systems [10]. In the domain of energy harvesting, conventional MPPT algorithms, such as perturb and observe (P&O) and incremental conductance, are commonly employed; however, their performance deteriorates under rapidly changing environmental conditions. To address these limitations, intelligent approaches—including fuzzy logic, artificial neural networks (ANN), and hybrid models such as ANFIS—have demonstrated high effectiveness, providing fast convergence and robust adaptability to the nonlinear dynamics of complex systems [11], [12].

The deployment of high voltage direct current (HVDC) systems, particularly for offshore wind integration, has been recognized as a viable solution for long-distance energy transmission with minimal losses. However, studies have reported persistent challenges regarding system protection, synchronization, and control under fault conditions [13], [14]. Although progress has been made in individual domains, such as control strategies, MPPT algorithms, or HVDC technology, few studies offer a holistic approach that simultaneously addresses synchronization, fault tolerance, power quality, and real-time energy optimization in hybrid renewable energy systems.

The grid operation is constrained by several critical factors, including fault tolerance, energy dispatch efficiency, protection coordination, voltage regulation, harmonic suppression, and overall transmission system stability [15], [16]. These operational constraints become increasingly difficult to manage as modern power networks integrate diverse and complex energy resources, each introducing unique dynamic behaviors. Moreover, faults occurring in AC/DC transmission lines, converter malfunctions, or sensor failures can trigger system-wide disturbances that significantly degrade both performance and reliability. Therefore, maintaining secure and stable grid operation requires advanced monitoring and control strategies capable of anticipating and mitigating such disturbances in real time.

This study focuses on the effective integration of hybrid energy systems into electrical grids, with the aim of enhancing stability, reducing energy losses, and maintaining high power quality. To achieve this, the paper proposes advanced control techniques and power electronics solutions, emphasizing multilevel converters, synchronization strategies, and the optimization of micro grids and offshore wind integration via HVDC technologies. The key contributions of this research include the development of robust control algorithms based on synchronously rotating frame (SRF) transformations, aimed at enhancing grid stability in hybrid systems. In addition, a novel MPPT algorithm combining ANFIS and Kalman filters has been implemented to maximize energy extraction while minimizing harmonic distortion. Finally, the study provides a comprehensive analysis of offshore wind farm integration using HVDC transmission, with a focus on ensuring stable and efficient energy delivery to onshore networks.

2. METHOD

The methodology section provides a detailed description of the control strategies and power electronics approaches developed to address the challenges associated with integrating hybrid renewable energy systems into electrical grids. It outlines the theoretical models, mathematical formulations, and algorithmic principles that form the foundation of the proposed control architecture. In addition, the methodology incorporates advanced simulation tools to validate system behavior under various operating scenarios, ensuring the robustness, stability, and overall effectiveness of the developed techniques.

2.1. Advanced algorithms (SRF)

This research employs the synchronously rotating frame (SRF) transformation to achieve precise synchronization of hybrid renewable energy systems with the electrical grid. The SRF approach enables the decoupling of active and reactive power components, allowing independent control of each and thereby improving the overall system stability. Furthermore, this transformation simplifies the control structure of power converters, making it particularly effective for mitigating dynamic disturbances and enhancing the performance of grid-connected renewable systems.

This research leverages the SRF transformation as a core component of the control strategy for hybrid renewable energy systems [17]. The SRF method plays a crucial role in ensuring precise synchronization between renewable energy sources such as wind, photovoltaic (PV), and combined heat and power (CHP) systems and the main electrical grid. The SRF technique enables the dynamic decoupling of active (P) and reactive (Q) power components. This decoupling simplifies the control of power flows, allowing the controller to independently regulate each component with higher accuracy [18]. As a result, the system can rapidly adapt to fluctuations in generation and load, which is especially critical in renewable energy systems characterized by intermittent and unpredictable output. Furthermore, the SRF transformation enhances the robustness of the system under various grid conditions, including voltage sags, frequency deviations, and transient disturbances [19].

By integrating the SRF-based control approach with multilevel power converters, the system achieves superior voltage and current waveform quality, reduced harmonic distortion, and faster dynamic response. These improvements contribute significantly to maintaining grid stability, minimizing synchronization errors, and supporting seamless integration of distributed energy resources into high-voltage networks. Overall, the SRF transformation is a foundational tool in this study, providing both theoretical and practical benefits for optimizing the performance of hybrid renewable energy systems in real-time grid-connected scenarios.

2.2. MPPT optimization (ANFIS + Filtre de Kalman)

A novel MPPT algorithm, integrating adaptive neuro-fuzzy inference systems (ANFIS) and Kalman filters, has been developed. This approach dynamically adapts to rapidly fluctuating environmental conditions, aiming to maximize energy extraction from wind and photovoltaic sources while minimizing harmonic distortion. By combining the adaptive capabilities of ANFIS with the predictive accuracy of Kalman filtering, the proposed MPPT algorithm enhances the performance and reliability of energy harvesting from variable renewable sources.

The proposed hybrid algorithm is designed to dynamically track the maximum power point (MPP) of wind and photovoltaic (PV) systems under rapidly changing environmental conditions, such as fluctuations in solar irradiance, temperature, and wind speed. The ANFIS component offers a self-adaptive control mechanism that integrates the learning capabilities of neural networks with the reasoning of fuzzy logic [20]. This allows the system to model highly nonlinear behaviors of renewable sources without requiring an explicit mathematical model. It adapts in real time to variations in operating conditions and system dynamics, making it highly suitable for renewable energy applications [21]. Complementing ANFIS, the Kalman filter is employed to enhance the accuracy and stability of the MPPT process. It acts as a predictive estimator that filters out measurement noise and disturbances, allowing for smooth and reliable tracking of the true power output. By continuously updating the system state based on both current and predicted measurements, the filter minimizes estimation errors and improves the system's response time.

The integration of these two techniques results in a robust MPPT algorithm that not only maximizes the energy harvested from wind and PV sources but also significantly reduces harmonic distortion and power fluctuations at the output. This leads to improved power quality, enhanced system efficiency, and greater compatibility with grid standards. Overall, the proposed ANFIS-Kalman MPPT algorithm represents a powerful tool for real-time energy optimization in hybrid renewable energy systems, addressing both performance and reliability challenges in dynamic operating environments.

This study investigates a hybrid renewable energy system integrating photovoltaics, wind power (MADA, PMSG), and a cogeneration unit (CHP) connected to a low-voltage grid. Simulations in

MATLAB/Simulink are conducted to validate system behavior and test the integration of a two-level VSC-HVDC system, followed by a three-level NPC converter. System stability and performance are analyzed.

A wind farm is then connected to a three-level VSC-HVDC system via a submarine DC cable, using PMSG machines. Advanced MPPT techniques are applied to maximize power extraction and control converters in real time. A new topology is developed to optimize performance, reduce losses, ensure stability, and minimize harmonics. The study also explores hybrid networks, analyzing the impact of equipment and loads on power quality. A dynamic model of the high-voltage photovoltaic system is proposed for integration into the offshore VSC-HVDC network.

2.3. Design of hybrid systems connected to the electrical grid

The design and feasibility of photovoltaic systems, wind turbines, and cogeneration units connected to the distribution grid rely on accurate modeling of the turbine, the permanent magnet synchronous generator (PMSG), and their associated control strategies. As illustrated in Figure 1, the overall architecture of the hybrid renewable system highlights the interactions between energy conversion stages, control loops, and grid-interface components, which are essential for understanding system behavior. The integration of these energy sources into the electrical grid becomes increasingly complex due to their stochastic and intermittent nature, which can introduce fluctuations and dynamic uncertainties. Additionally, the widespread use of power converters may degrade energy quality, leading to issues such as harmonic distortion and voltage instability [22]–[24]. Therefore, to optimize the exploitation of these renewable sources and ensure their smooth and secure integration into the electrical network, it is necessary to design a robust and optimal global system that can effectively manage all these challenges [25]–[27].

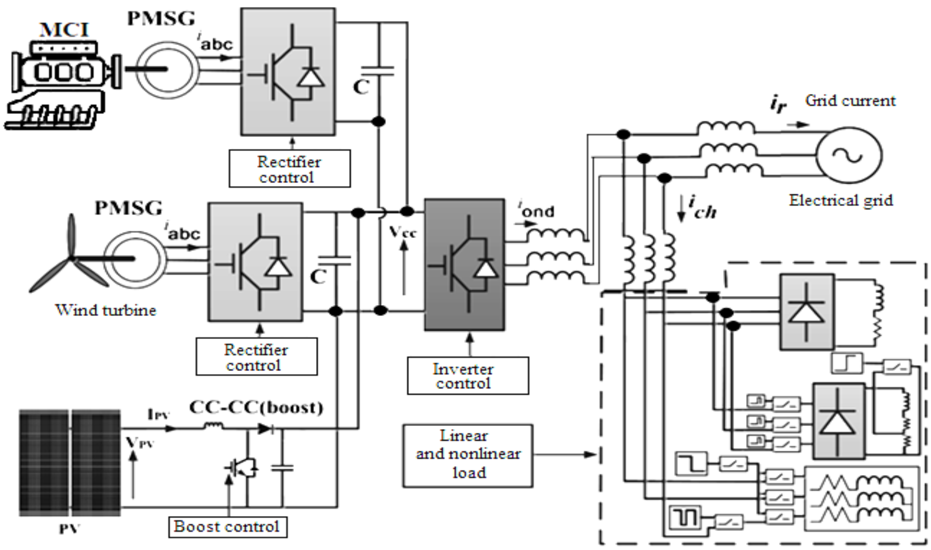


Figure 1. Hybrid renewable energy systems

2.4. Photovoltaic module and field

The module is evaluated based on the chosen configuration (series/parallel). Generally, the model uses a simple analytical formulation of the photovoltaic field's characteristics, allowing for a quick assessment of the energy performance of different configurations. This helps in selecting the most efficient configuration under given sunlight and temperature conditions. According to Chibuko *et al.* [28]. The equivalent electrical circuit diagram of a PV cell model is shown in Figure 2.

The current I_{ph} generated by the system corresponds to the short-circuit current I_{cc}. The resistances R_s (series resistance) and R_{sh} (parallel resistance) model the ohmic losses of the material and the leakage currents, respectively. The solar cell model [29] can be represented by the following equations:

$$I_{ph} = I_d + I_{sh} + I_{pv} \quad ; \quad I_{pv} = I_{ph} - I_d - \frac{V_D}{R_{sh}} \tag{1}$$

With R_{sh} characterizes the recombination losses of carriers due to structural defects in the material, R_s characterizes the Joule losses, and V_D is the voltage across the diode.

$$I_d = I_0(e^{V_D/V_t} - 1) \quad (2)$$

With I_0 being the reverse saturation current of the diode, and V_t is the thermal voltage

$$V_D = R_s.I_{pv} + V_{pv} \quad (3)$$

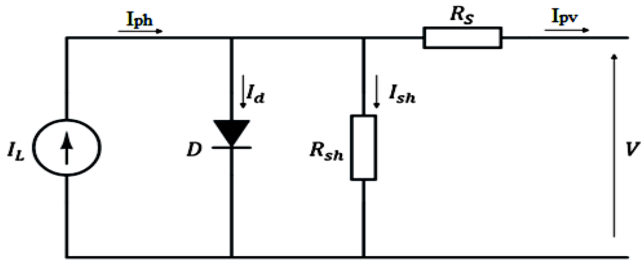


Figure 2. The equivalent electrical circuit diagram of a PV cell model

2.5. Modeling and control of the boost converter

The parallel Boost converter is a static DC/DC converter designed to increase the DC voltage level of an electrical system by stepping up the input voltage. As illustrated in Figure 3, the parallel configuration enhances current-sharing capability and improves the overall reliability and efficiency of the conversion stage, especially in renewable energy applications. This voltage step-up process is achieved through the energy storage and release mechanism of the inductor, which enables the output voltage to exceed the input supply. The operation of the Boost converter relies on key components including the inductor, the diode, and a controlled insulated gate bipolar transistor (IGBT) whose coordinated switching ensures continuous energy transfer and stable output regulation.

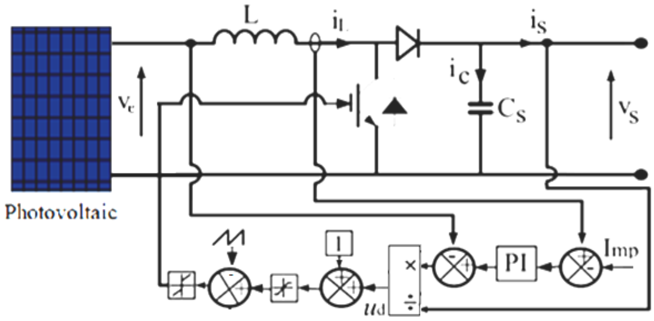


Figure 3. Diagram of the Boost converter control

The first operating mode of the boost converter occurs when the switch is closed and the diode is blocked during the interval $0 < t < \alpha T$. The voltage across the inductor is expressed as (4):

$$V_{pv} = L\frac{di_L}{dt};\ V_s = -V_c \quad ; \quad \frac{V_s}{R} = -C\frac{dV_s}{dt} \quad (4)$$

The state representation of the first operating mode is written as (5):

$$\dot{X}(t) = A1.X(t) + B1.V_{pv};\ \begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_s}{dt} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_s \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{pv} \quad (5)$$

The second operating mode of the boost converter is explained as follows: For $\alpha T < t < T$, the switch is open, and the diode is conducting. The voltage across the inductor is given by (6):

$$\frac{di_L}{dt} = \frac{V_{pv}}{L} - \frac{V_S}{L} \tag{6}$$

The state representation of the second operating mode is written as (7):

$$\dot{X}(t) = A2.X(t) + B2.V_{pv}; \begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_S}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_S \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{pv} \tag{7}$$

To relate the two operating modes, the average model is used:

$$A = A1.d + A2.(1-d) \ with\ B = B1.d + B2.(1-d) \tag{8}$$

$$A = \begin{bmatrix} 0 & -\frac{(1-d)}{L} \\ \frac{(1-d)}{C} & -\frac{1}{RC} \end{bmatrix} \ and B = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} \tag{9}$$

The state-space model of the Boost converter is as (10):

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_S}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{(1-d)}{L} \\ \frac{(1-d)}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_S \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{pv} \tag{10}$$

The control law is presented as (11):

$$L\frac{di_L}{dt} = V_{pv} - (1-d)V_S = u \ \ and\ \ d = 1 + \frac{u - V_{pv}}{V_S} \tag{11}$$

The control law is presented as follows, with "u" being the output of the *PI* controller. To control the boost converter, a PI regulator is adopted, which regulates the error between the reference current (i_L^*) and the inductor current (i_L). The transfer function of the PI regulator is given by the following [30]:

$$G_{PI}(s) = K_P + \frac{K_i}{s} \tag{12}$$

where K_P is the proportional gain, K_i is the integral gain, and *s* is the Laplace transform variable.

2.6. Modeling a cogeneration unit (CHP)

A CHP generator is composed of an internal combustion engine equipped with a speed governor, which drives the alternator, together with a regulation of voltage that ensures the stability of the entire unit [31]. In the literature, the modeling of cogeneration units generally considers mechanical, electromechanical, and electrical phenomena, while the parameters are often derived from thermochemical aspects linked to the thermodynamic cycle of the heat engine [32]. The instantaneous electrical power delivered by the generator can be expressed as (13):

$$P_g = \frac{3}{2}\left[\left(i_d.\frac{d\varphi_d}{dt} + i_q.\frac{d\varphi_q}{dt} + 2i_o.\frac{d\varphi_o}{dt}\right) + \left(\varphi_d.i_q - \varphi_q.i_d\right)\omega_e - \left(i_d^2 + i_d^2 + 2i_o^2\right)R_a\right] \tag{13}$$

[Variation in armature magnetic energy] [Electromagnetic power] [Joules loss]

2.7. Offshore wind system

The wind turbine employed in our research is coupled with a 2MW permanent magnet synchronous generator (PMSG). The stator of the PMSG is connected to the grid through a power electronics system (back-to-back two-level converter), as depicted in Figure 4. The control system of the setup includes an algorithm designed to extract the maximum power (MPPT). Both converters are regulated to ensure a constant DC voltage and to reliably transfer the maximum power to the grid.

The mechanical power of the turbine shaft is calculated using the expression given by [33] and [34]. The mechanical power (P_{mec}) is represented by the following form:

$$P_{mec} = \frac{1}{2}\rho S V^3 \text{ with } S = \pi R^2 \tag{14}$$

where C_p is the power coefficient and S is the swept area of the blades.

The power coefficient depends on two values: the tip-speed ratio λ and the blade pitch angle β relative to the wind. By adjusting this angle, the wind turbine is able to capture maximum power [35].

$$C_P(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3.\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + \lambda C_6 \ ; \ \frac{1}{\lambda_i} = \frac{1}{\lambda+\beta C_7} - \frac{C_8}{1+\beta^2} \tag{15}$$

With $C_1, C_2 \dots . C_8$ were wind coefficients. To describe the operating speed of a wind turbine, the reduced tip speed of the turbine blades relative to the wind speed is used, and it is given by (16):

$$\lambda = \frac{R\Omega}{V} \tag{16}$$

where λ is the tip-speed ratio, Ω: Angular velocity of the blades (rad/s), R: Radius of the wind turbine blades (m), V: Wind speed (m/s).

The C_p coefficient of horizontal-axis wind turbines is always below the Betz limit (0.59). Three-blade wind turbines are the most commonly used because they represent a compromise between the cost of the wind generator and the vibrations caused by rotation. The power coefficient reaches high values and decreases gradually as the wind speed increases.

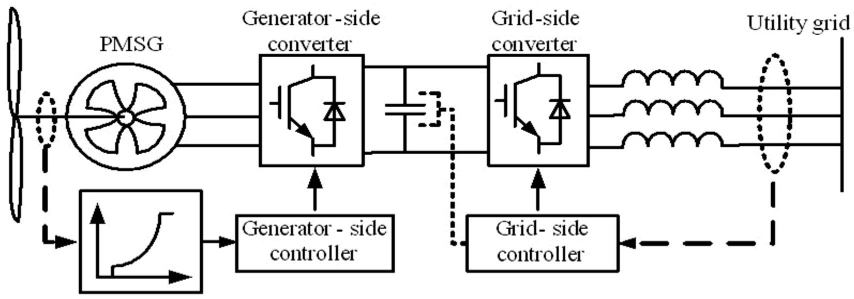


Figure 4. PMSG wind turbine connected to the grid

2.8. Modeling of the PMSG generator

The synchronous machine model is used to study dynamic behavior and implement control laws. The Park model is employed to describe the equations and operate in continuous quantities. Zhang *et al.* [36] presents the machine by considering the magnetic axis of phase "*a*" as the reference axis, along with the transformation axes *d* and *q*. According to the phases of the machine, the equations for the voltage and electromotive forces can be written based in the stationary reference frame and then using the Park transformation.

$$v_d = L_q\omega_r i_q - \frac{L_d di_d}{dt} - R_s i_d \ \ and \ \ v_q = \lambda_m\omega_r - L_d\omega_r i_d - \frac{L_q di_q}{dt} - R_s i_q \tag{17}$$

Knowing that the electromotive force is given by (18):

$$E_d = L_q\omega_r i_q \ \ and \ \ E_q = \lambda_m\omega_r - L_d\omega_r i_d \tag{18}$$

2.9. Controlstrategy for maximizing power extraction

In this study, a simple yet robust control strategy is proposed to enhance the quality of renewable energy injected into the grid. The approach aims to maximize the power transferred from wind, CHP, and photovoltaic solar sources. To this end, a combination of maximum power point tracking (MPPT) and active power control algorithms is implemented on a two-level inverter, which interfaces the PV-PMSG energy sources with the grid. The effectiveness of the proposed models is evaluated and validated through simulations carried out in MATLAB/Simulink.

2.10. Fuzzy inference system based on adaptive neural networks

Multilayer neural networks (NN) are universal approximators capable of modeling nonlinear functions with high accuracy. As shown in Figure 5, the structure of neuro-fuzzy systems integrates the learning capability of neural networks with the interpretability of fuzzy inference mechanisms, providing a more flexible framework for complex system modeling. These hybrid systems offer significant advantages: they are often designed using human expert knowledge and benefit from strong descriptive power through the use of linguistic variables. Consequently, the integration of fuzzy logic and neural computation naturally led to the development of the neuro-fuzzy approach [37]. Within this context, the ANFIS introduced by Jang implements a Takagi–Sugeno fuzzy inference model organized into five computational layers, where each layer plays a specific role in parameter learning and rule evaluation [38].

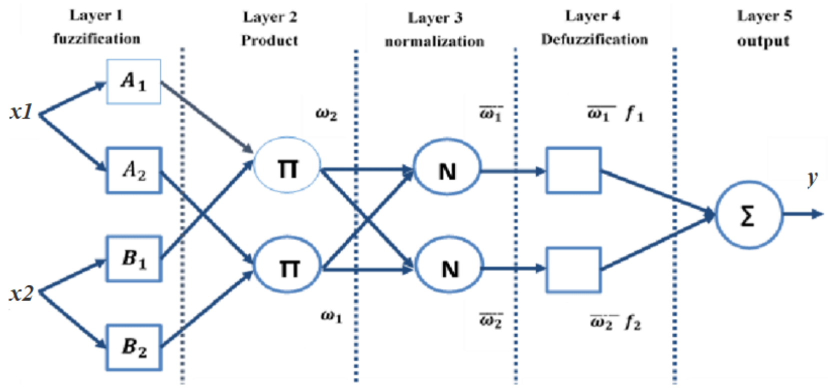


Figure 5. Equivalent architecture of ANFIS for two rules

The output Q_{ki} of node *i* in layer *k* (referred to as node (*i, k*)) depends on the signals from layer *k−1* and the parameters of node (*i, k*).

$$Q_{ki} = f(inputs\ from\ layer\ k-1, parameters\ of\ node\ (i,k)) \tag{19}$$

where *nk−1* is the number of nodes in layer *k−1*, and *a,b,c,…* are the parameters of node (*i, k*). For a circular node, these parameters do not exist.

2.11. Unit power factor

For achieving a unit power factor through reactive power compensation, the controller generates the direct-axis component of the load currents while maintaining the DC bus voltage at a constant level. The PI controller ensures the supply of the active power required to compensate for the losses in the DC bus of the VSC. The following expression represents the state at a given iteration:

$$i_d^*(k) = i_d^*(k-1) + k_{id}\varepsilon(k) + k_{pd}(\varepsilon(k) - \varepsilon(k-1)) \tag{20}$$

where $v_{cc}(k) = \varepsilon(k)$ is the error between the DC voltage $v_{cc}(k)$ and its reference $v_{cc}^*(k)$, and k_{id} and k_{pd} are the integral and proportional gains, respectively. The amplitude of the reference AC current is given:

$$i_d^* = i_{d\_Vcc}^* + i_{Ldh} \tag{21}$$

2.12. DC voltage control with anti-windup PI controller

The circuit voltage is regulated using the anti-windup PI controller. This is an intelligent controller with improved response. The purpose of using this controller is to set the value of v_{cc} to its reference value v_{cc}^* and to avoid exceeding the current limit by using the saturation block in case of system disturbances. The error ($v_{ccer} = \varepsilon$) is the difference between the reference (v_{cc}^*) and the measured voltage (v_{cc}) of the VSC.

$$\varepsilon(k) = v_{ccer}(k) = v_{cc}^*(k) - v_{cc}(k);\ \frac{dy}{dt} = k_i\big(\varepsilon - k_l(i - i_{max})\big);\quad i = y + \varepsilon k_p \tag{22}$$

The solution to this differential equation is presented below:

$$y(t) = \frac{\varepsilon(1-k_pk_l)+k_li_{max}}{k_l} + \frac{y_0k_l-\varepsilon(1-k_pk_l)-k_li_{max}}{k_l}.e^{-k_ik_lt} \tag{23}$$

3. RESULTS AND DISCUSSION

The performance of the hybrid PV–WIND-CHP generation system, as well as the effectiveness of the proposed control algorithms, has been thoroughly evaluated using the MATLAB/Simulink simulation platform. The model integrates both a permanent magnet synchronous generator (PMSG) driven by a wind turbine and a photovoltaic (PV) generator, each characterized by variable power output depending on environmental conditions. In addition, the system operates under various types of electrical loads, including balanced, unbalanced, and time-varying loads. Despite the inherent variability of both energy sources and loads, the system demonstrates efficient energy flow management, ensuring stable and reliable power delivery. This stability is maintained by advanced control algorithms that dynamically adapt the operation of converters and maximize the utilization of renewable energy resources.

3.1. Dynamic response and stability under irradiance variation

Figures 6 and 7 illustrate the dynamic response of the photovoltaic generator under varying irradiance conditions, with each subfigure highlighting a specific aspect of the system behavior. Figure 6(a) shows the irradiance profile applied to the PV generator, while Figure 6(b) presents the corresponding PV power output, demonstrating its ability to accurately track irradiance variations. Similarly, Figure 7(a) depicts the evolution of PV voltage during rapid irradiance transitions, and Figure 7(b) shows that the voltage exhibits only minor transient fluctuations, which are rapidly damped by the proposed control strategy. This fast and accurate response highlights the effectiveness and robustness of the integrated control algorithm when compared to existing approaches. In the work of Feddaoui *et al.* [39], for example, voltage stability is achieved for a hybrid PV–Wind system using fuzzy control, but at the expense of a significantly longer stabilization time. Other studies, such as those by Namrata *et al.* [40], report similar dynamic behavior but rely on more complex control architectures involving predictive and fuzzy controllers, increasing computational burden and sensitivity to modeling errors. In contrast, our unified optimized control approach provides a superior balance between simplicity, performance, and robustness, ensuring efficient management of energy transitions among different renewable sources.

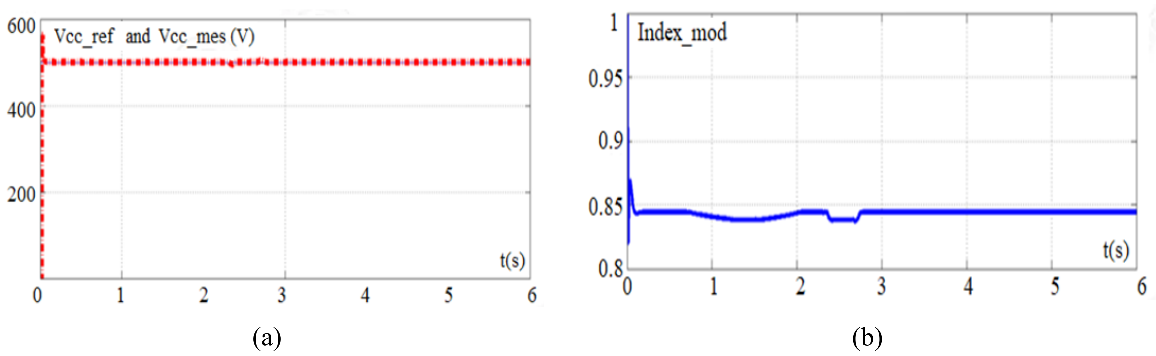


Figure 6. Dynamic response of the PV generator under varying irradiance conditions: (a) PV voltage response (reference and measured values) and (b) modulation index corresponding to the power output

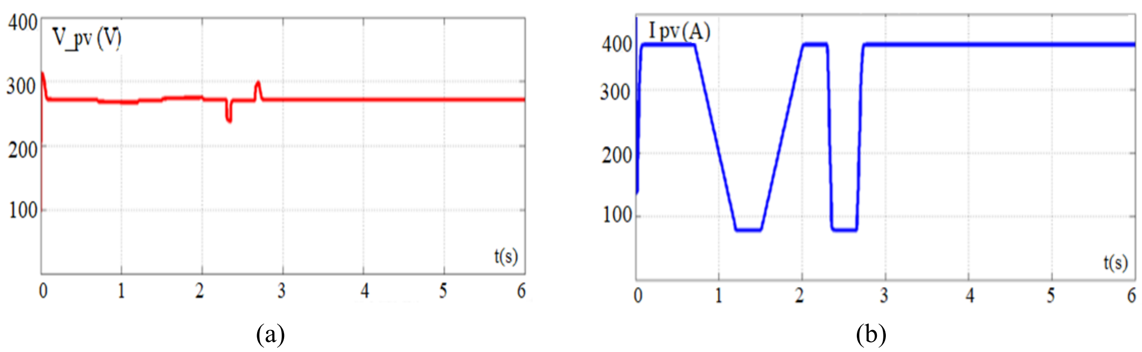


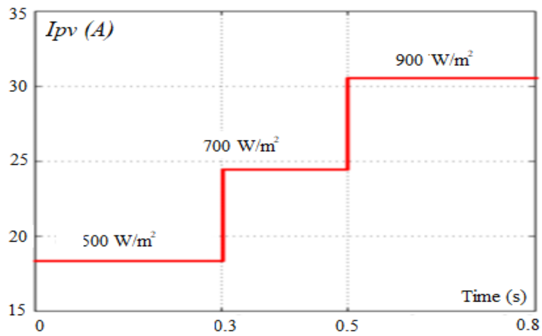
Figure 7. Dynamic response of the PV system under varying irradiance conditions: (a) voltage of the PV system and (b) current of the PV system

3.2. MPPT performance and voltage regulation

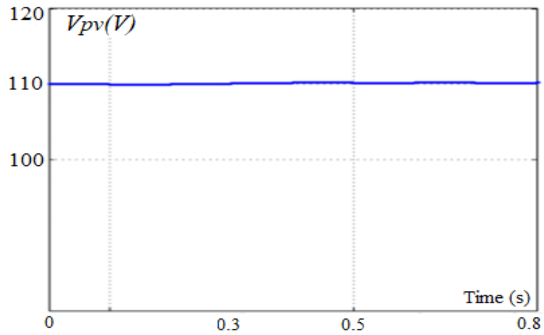
Figures 8(a) and 8(b) illustrate the dynamic response of the PV system under sudden irradiance changes. Specifically, Figure 8(a) shows the PV voltage behavior during a rapid transition toward 1000 W/m², while Figure 8(b) presents the corresponding output power. The system maintains voltage stability with only minor transient deviations, demonstrating the effectiveness of the integrated MPPT algorithm.

Figures 9(a) and 9(b) depict the system's performance under fluctuating solar irradiance over a longer period. Figure 9(a) shows the voltage regulation, and Figure 9(b) shows the extracted power following the MPPT strategy. These results highlight that the system can sustain stable operation and extract maximum power even under non-steady-state conditions.

This performance contrasts with classic PV–Wind hybrid models, such as those by Ramli *et al*. [41], which achieve satisfactory regulation but exhibit noticeable oscillations around the maximum power point. Similarly, Joisher *et al*. [42] propose hybrid MPPT strategies that improve tracking but increase complexity and implementation cost. Our approach achieves stable regulation with lower computational demands while ensuring maximum renewable energy utilization.

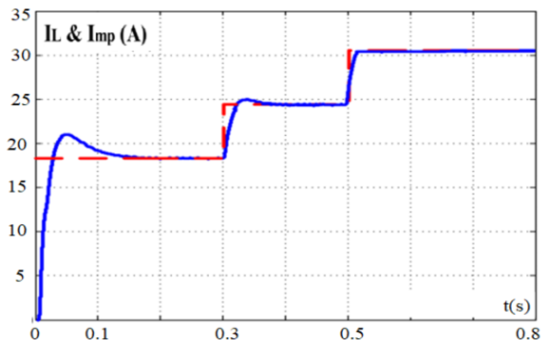


(a)

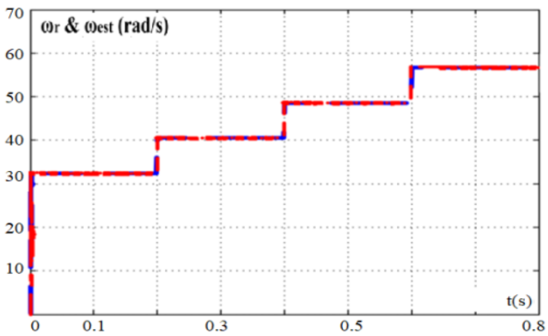


(b)

Figure 8. Simulation results of the PV system under sudden irradiance changes:
(a) photovoltaic current response and (b) PV voltage response under different irradiance levels



(a)



(b)

Figure 9. Performance of the PMSG-based PV–Wind system under fluctuating solar irradiance:
(a) DC–DC (boost) converter current and its reference and (b) estimated rotational speed of the PMSG generator and its reference

3.3. Compared to the state-of-the-art, our work stands out in several key aspects

The integration of a CHP unit in addition to PV and wind is rarely addressed in existing literature and ensures service continuity under extreme conditions.

3.4. Unified intelligent control

While many studies split their control strategies (MPPT for PV, wind control, grid regulation), our system features a centralized and harmonized control, reducing energy management conflicts and improving overall system efficiency. Experimental robustness: Unlike some studies based solely on idealized assumptions, our model includes variable, unbalanced, and realistic electrical loads, which significantly strengthens the practical validity of the proposed solution.

3.5. The DC bus and AC voltages remain constant

Figure 10 the hybrid system provides the necessary difference to the load on the grid. The unbalanced nonlinear load is disconnected, and the photovoltaic system delivers the maximum power (3400 W), while the wind turbine and CHP based on PMSG supplies 10.2 kW and 10 kW, respectively. The waveforms of the voltage and current from the different PV-wind-CHP sources have been analyzed, and it was found that their THD complies with IEEE 519 standards under variable load conditions, improving the power quality.

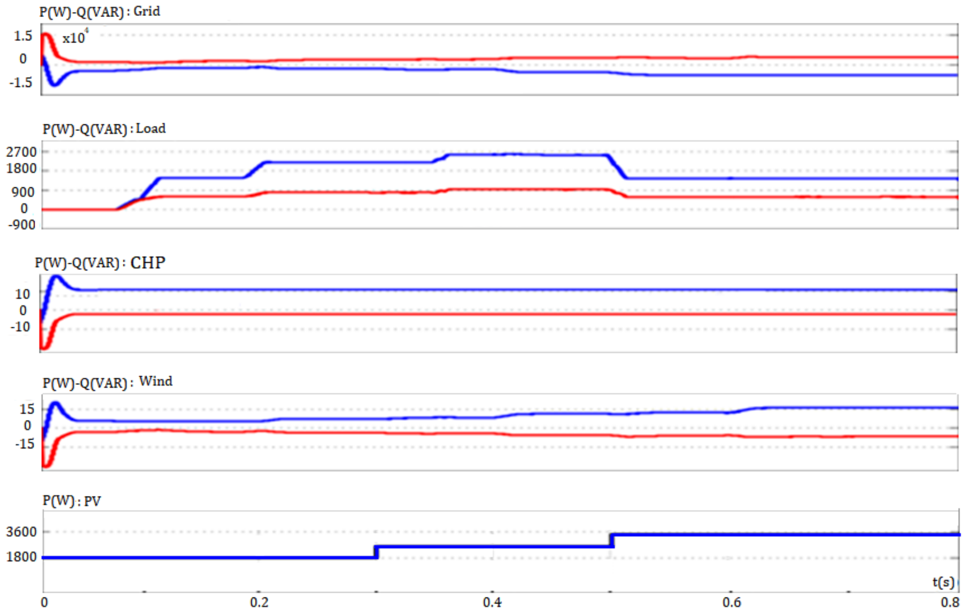


Figure 10. Active and reactive powers in balanced and unbalanced cases

4. CONCLUSION

The simulation and comprehensive analysis of a novel controller for a hybrid system combining wind energy and photovoltaic power generation connected to a three-phase grid are presented. The system's performance has been evaluated under various operating conditions, including load disturbances, wind speed fluctuations affecting the wind turbine, and solar irradiance variations influencing the photovoltaic array. The proposed synchronous reference frame (SRF) controller for the VSC is designed to mitigate harmonics, compensate reactive power, and enhance power quality at the point of common coupling (PCC). Furthermore, a DC–DC boost converter and an AC–DC converter is employed to extract the maximum power point (MPP) from the PV and WECS subsystems, respectively. The obtained results demonstrate a total harmonic distortion (THD) of less than 5%, in compliance with IEEE standards, with sinusoidal voltage and current waveforms at the PCC. The proposed controller exhibits fast and accurate reference tracking, thereby validating both the effectiveness of the SRF approach based on the anti-windup PI controller and the overall reliability of the hybrid energy system.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C	: **C**onceptualization	I	: **I**nvestigation	Vi	: **Vi**sualization
M	: **M**ethodology	R	: **R**esources	Su	: **Su**pervision
So	: **So**ftware	D	: **D**ata Curation	P	: **P**roject administration
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Fo	: **Fo**rmal analysis	E	: Writing - Review &**E**diting		

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