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## Power Management for HRES using Model Predictive Control and Energy Storage Systems: A Comprehensive Analysis



**Abstract:** - Renewable energy sources are pivotal in Industry 4.0, driving sustainable growth and reducing carbon footprints. They enhance energy efficiency and resilience, aligning with corporate sustainability goals. Incorporating diverse renewable energy sources into Hybrid Renewable Energy Systems (HRES) offers substantial potential for sustainably meeting rising energy demands. These systems enhance reliability and efficiency, aligning perfectly with corporate sustainability objectives. Embracing HRES positions companies at the forefront of innovation and environmental responsibility.

In the quest for sustainable energy solutions, the integration of Model Predictive Control (MPC) in Wind Energy Conversion Systems (WECS) and effective power management for Battery Energy Storage Systems (BESS) emerges as an advanced approach. The MPC addresses the limitations of conventional controllers by optimizing loading conditions and DC link voltage stability and minimizing power fluctuations. The advanced power management algorithm for BESS facilitates dynamic energy storage and distribution, enhancing system stability and reliability. The power generated from WECS-based MPC control reduces the power fluctuations when the battery is in charging mode.

The proposed work deals with the simulation analysis of MPC-based WECS and power management for WECS & BESS hybrid standalone power system to fed DC load and charging of BESS. Through simulation studies, the effectiveness of control strategies and MPC control operate satisfactorily with change in climatic conditions.

**Keywords:** HRES, WECS, BESS, MPC, Power Management.

### I. INTRODUCTION

The escalating global demand for sustainable and resilient energy solutions has propelled WECS and BESS to the forefront of contemporary power generation methodologies. With mounting environmental apprehensions and a noticeable shift towards renewable energy sources, the imperative to seamlessly integrate and efficiently manage these resources within current power infrastructure has become paramount. This paper embarks on a thorough exploration of the intricate application of MPC as a sophisticated control paradigm, meticulously tailored to enhance the operational intricacies of both standalone WECS and integrated WECS-BESS configurations.

The pursuit of sustainable energy solutions has underscored the significance of integrating renewable energy sources like wind power into existing grids. Nevertheless, the inherently intermittent nature of wind poses substantial challenges for seamless integration. To address this, the adoption of standalone WECS and BESS emerges as a pragmatic approach. This paper is focusing on harnessing the capabilities of MPC as an advanced control strategy to optimize the performance of standalone WECS and BESS configurations operating independently.

WECS face a myriad of challenges stemming from the inherent unpredictability and fluctuating nature of wind resources, which serve as the primary source for harnessing dynamic kinetic energy. Given these complexities, the application of MPC is indispensable, leveraging its well-established predictive capabilities and robust optimization framework. By proactively anticipating changes and making timely adjustments within a predefined prediction horizon, MPC effectively enhances power extraction efficiency and facilitates the seamless integration of wind-generated electricity into the existing grid infrastructure.

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Operating autonomously in standalone mode, WECS are tasked with efficiently converting wind energy into electrical power, necessitating the implementation of precise control strategies to maximize overall system efficiency. However, conventional control methods, such as the widely used Proportional-Integral (PI) control, often encounter significant challenges in managing the inherent variability and unpredictability associated with the switching frequencies inherent in wind energy conversion systems. In contrast, MPC, with its advanced predictive capabilities, enables the WECS to anticipate and adapt dynamically to shifts in wind patterns, thereby optimizing energy capture and ensuring system stability even amidst changing environmental conditions.

This sophisticated control paradigm not only enables WECS to react swiftly to evolving wind conditions but also empowers them to maintain operational stability while maximizing energy yield. Through MPC's proactive approach, WECS can adjust control parameters in real time, thereby enhancing system performance and contributing to the overall reliability of renewable energy systems. As the global demand for sustainable energy solutions continues to rise, the integration of MPC within WECS represents a crucial step towards achieving greater efficiency and reliability in renewable energy generation.

In essence, the surveyed literature offers a comprehensive array of control strategies and methodologies, all aimed at enhancing the performance, stability, and reliability of microgrid systems. These contributions collectively advance the integration of renewable energy sources, energy storage systems, and electric vehicles, heralding a promising future for sustainable energy utilization. Abdelaziz et al. [1] proposed a multistage centralized control scheme for islanded microgrids with plug-in electric vehicles (PEVs), aiming to optimize renewable energy sources and PEV utilization while ensuring grid stability. Kou et al. [2] introduced a stochastic coordination approach using MPC to manage PEVs and wind turbines, effectively handling uncertainties in renewable energy generation and demand. Senapati et al. [3] presented an enhanced power management control strategy for renewable energy-based DC microgrids with energy storage integration, emphasizing improved grid stability and reliability. Bellinaso et al. [4] proposed a cascade control scheme with an adaptive voltage controller for photovoltaic boost converters, enhancing photovoltaic system performance in microgrid environments. Khan and Khalid [5] focused on refining the transient response of hybrid energy storage systems for voltage stability in DC microgrids using an autonomous control strategy. Evald et al. [6] contributed a least-squares-based adaptive proportional-integral (PI) controller for grid-tied DC-AC converters, enhancing control accuracy and robustness. Mudi et al. [7] offered an improved auto-tuning scheme for PI controllers, enhancing control performance across various microgrid scenarios. Chishti et al. [8] proposed a robust normalized mixed-norm adaptive control scheme to augment power quality in wind-solar PV-BESS microgrids. Liu et al. [9] developed a model predictive current control strategy for hybrid energy storage systems, considering the state of charge (SOC) of supercapacitors to enhance system efficiency and stability. Cheng et al. [10] advocated for an MPC approach in DC-DC boost converters, featuring a reduced prediction horizon and constant switching frequency to optimize converter performance. Li et al. [11] shifted focus towards stability-oriented design, advocating for MPC in DC/DC boost converters to ensure robust operation across varying conditions. Shabbir et al. [12] and [13] proposed MPC-based voltage and frequency regulation strategies for distributed generation in isolated microgrids, effectively tackling challenges associated with grid stability and reliability. Abdelghany et al. [25] developed a model predictive control strategy to optimize hydrogen-based energy storage operations in wind farms, enhancing system efficiency and grid integration by effectively balancing energy production and storage capacities. Additionally, Abdelghany et al. [26] introduced a hierarchical model predictive control system for managing both islanded and grid-connected microgrids with wind generation and hydrogen storage, improving reliability and sustainability by coordinating multiple energy sources and ensuring stable energy supply under varying conditions. Syed et al. [27] proposed an intelligent model predictive control strategy for stable power dispatch in hybrid solar-wind systems with hydrogen electrolyzers and battery storage, aiming to maximize stability and efficiency by dynamically adjusting power flows and storage operations based on predictive algorithms. Thaler et al. [28] developed a hybrid model predictive control for renewable microgrids with seasonal hydrogen storage, focusing on improving energy management flexibility and efficiency by integrating short-term and long-term storage solutions to meet varying energy demands. Ali et al. [29] discussed a model predictive control approach in a consensus-based energy management system for DC microgrids, highlighting improved coordination and energy distribution by using predictive models to align the operations of distributed energy resources, thereby enhancing overall system performance. Martinez Alonso et al. [30] proposed a multi-state optimal power dispatch model for off-grid hybrid energy systems using power-to-power technologies, illustrated

through a case study in Spain, showcasing the model's ability to enhance energy reliability and efficiency in remote areas by optimally dispatching energy resources. Alonso et al. [31] conducted a techno-economic assessment of hybrid energy storage systems combining hydrogen and batteries, evaluating cost and performance benefits in a Belgian case study to determine the most cost-effective and efficient energy storage solutions for varying energy demands and economic conditions. Bouaouaou et al. [32] presented a model predictive control framework for grid-connected hybrid renewable energy systems, aiming to enhance integration and performance by using predictive algorithms to optimize the interaction between different renewable energy sources and the grid, ensuring stable and efficient energy supply.

The main objectives of this paper are to explore the efficacy of MPC and advanced power management techniques within a HRES. The contributions of this research lie in elucidating:

- To address the effectiveness of the MPC algorithm for optimizing the dynamic response and operational efficiency for WECS for standalone operation.
- To test the MPC algorithm for change in climatic conditions and load permutations.
- To showcase the impact of advanced power management algorithm for the coordination of electrical power generation from WECS inclusion with energy storage, and power sharing between WECS and BESS for standalone applications.
- To develop and simulate a hierarchical control architecture for BESS power management, incorporating outer voltage and inner current control, and to integrate battery management algorithm to optimize battery state-of-charge, and power capability for standalone operation.
- To analyse the HRES's ability to withstand change environmental conditions and load fluctuations in standalone mode of operation using MPC.

By addressing these objectives and contributions, this paper aims to advance the understanding of MPC and power management techniques in optimizing renewable energy systems, thus paving the way for more sustainable and efficient energy solutions. Following the establishment of the pressing need for sustainable energy solutions and the identification of associated challenges, this paper proceeds to explore the technical intricacies of system configuration and control strategies. Section 2 elucidates the framework supporting the proposed methodology, commencing with a thorough examination of system architecture and the derivation of the MPC framework. Expanding upon this foundation, the subsequent discussion delves into the intricacies of the power management algorithm, which plays a pivotal role in managing the dynamic interaction among WECS, BESS, and load demand. follow.

## II. SYSTEM CONFIGURATION

Fig. 1 illustrates the layout of the HRES, showcasing the integration of the WECS and the BESS within the power management framework. This setup ensures consistent power generation from the WECS and efficiently manages the charging and discharging cycles of the BESS. Advanced control techniques are deployed to achieve this coordination, with the WECS's Maximum Power Point Tracking (MPPT) governed by MPC within a standalone DC microgrid. The system configuration features a 25 kW WECS and a 50 kWh BESS, which collectively work to maintain a stable DC link voltage of 220V, critical for meeting the 25 kW DC load demands.

This arrangement not only optimizes the utilization of renewable energy harnessed from the WECS but also enhances the efficiency of energy storage in the BESS, thereby ensuring a reliable and stable power supply.

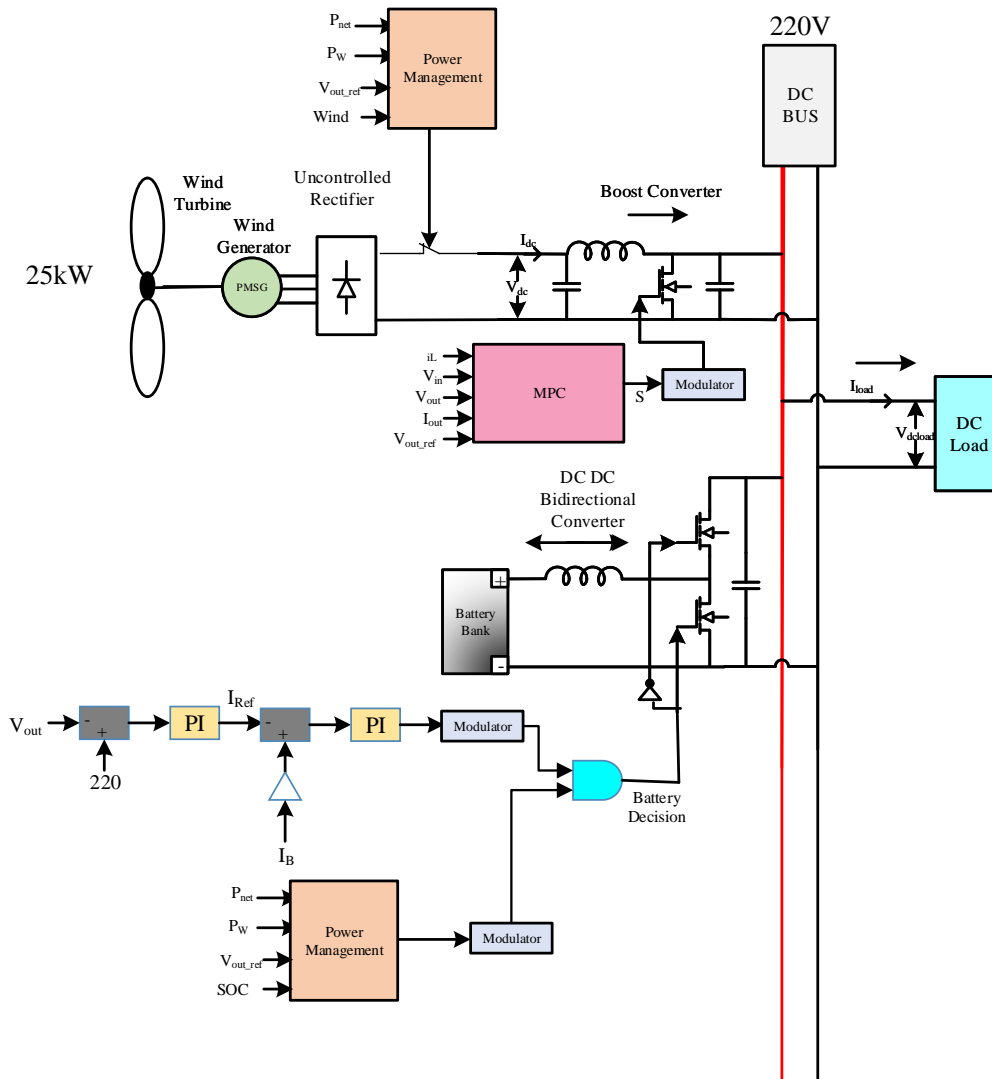


Fig.1 Layout of HRES with WECS and BESS.

### A Wind Energy Conversion System

Wind power systems utilize the kinetic energy of moving air to generate electricity, providing a sustainable and renewable energy source. Comprising primarily of wind turbines (WT), these systems employ blades to capture wind energy, spinning a rotor connected to a generator that produces electrical power through electromagnetic induction. The power output of a WT can be determined as follows:

$$PW_{T,t} = 0.5 \cdot \rho \cdot A \cdot v^3 \cdot C_p \tag{1}$$

Here,  $PW_T$  represents the power output,  $\rho$  denotes air density,  $A$  indicates the swept area of the rotor,  $v$  represents wind speed, and  $C_p$  is the coefficient of performance reflecting the efficiency of turbine energy conversion.

Wind power systems offer various advantages, including clean energy production, contribution to energy independence, and relatively low operational costs. However, they encounter challenges such as intermittent wind patterns and potential visual and noise impacts on landscapes and communities.

While WT power systems hold significant potential for energy production and offer environmental and economic benefits, they must address variability in wind conditions, visual and noise concerns, and issues related to maintenance and site selection. Thoughtful planning and technological advancements are crucial to optimizing wind energy production while addressing its limitations.

### B Battery Energy Storage Systems

BESS are emerging as indispensable components for standalone energy systems, offering a transformative solution for off-grid power generation and storage. By incorporating advanced battery technologies alongside sophisticated power conversion and control systems, BESSs revolutionize the dynamics of energy management and storage in standalone setups. These systems address the inherent intermittency of renewable energy sources by efficiently storing surplus energy during periods of high generation and releasing it when demand arises. Additionally, BESSs enable load shifting, optimizing energy consumption by transferring usage from peak to off-peak periods, thereby enhancing cost-effectiveness and reducing strain on the standalone energy system. Mathematically, the power flow in a standalone BESS ( $P_{batt}$ ) can be expressed as:

$$P_{batt} = P_{in} - P_{out} \tag{2}$$

Here  $P_{in}$  represents the power input during charging, while  $P_{out}$  denotes the power output during discharging. Furthermore, the state of charge (SoC) of the battery at any given time  $t$  can be calculated using the equation:

$$SoC(t) = \frac{Q(t)}{Q_{max}} \times 100 \% \tag{3}$$

Where  $Q(t)$  is the charge stored in the battery at time  $t$ , and  $Q_{max}$  is the maximum charge capacity of the battery. Additionally, the efficiency  $\eta$  of the battery system, representing the ratio of output power to input power, can be calculated as:

$$\eta = \frac{P_{out}}{P_{in}} \times 100 \%$$

As standalone energy systems continue to gain prominence in remote and off-grid locations, BESSs emerge as essential components in realizing sustainable, resilient, and self-sufficient energy solutions.

### C Model Predictive Control

The equivalent diagram of the boost converter at various switching periods is depicted in Fig. 2. This diagram illustrates the operation of the boost converter according to its operating principle. By analyzing this diagram, the following equation can be derived:

$$\frac{dV_{out}}{dt} = \frac{1-d}{C} i_L(k) - \frac{1}{RC} V_{out}(k) \tag{4}$$

$$\frac{di_L}{dt} = \frac{1}{L} V_{in} - \frac{1-d}{L} V_{out}(k) \tag{5}$$

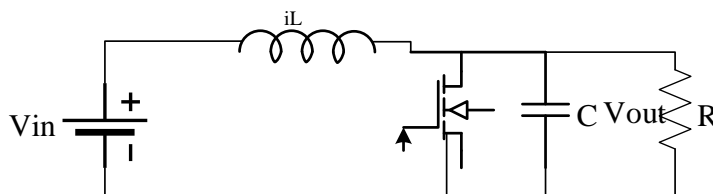
where  $d$  denotes the duty cycle. Assuming a high sampling frequency, we discretize these equations using the forward Euler approximation method, resulting in:

$$V_{out}(k + 1) = V_{out}(k) + \frac{1-d}{C} i_L(k)T_s - \frac{1}{RC} V_{out}(k)T_s \tag{6}$$

$$i_L(k + 1) = i_L(k) - \frac{1-d}{L} V_{out}(k)T_s + \frac{1}{L} V_{in}T_s \tag{7}$$

Here,  $T_s$  represents the sampling time.

Equations (6) and (7) allow us to predict the output voltage and inductor current at the next sampling instance. These predictions serve as the control objectives for MPC.



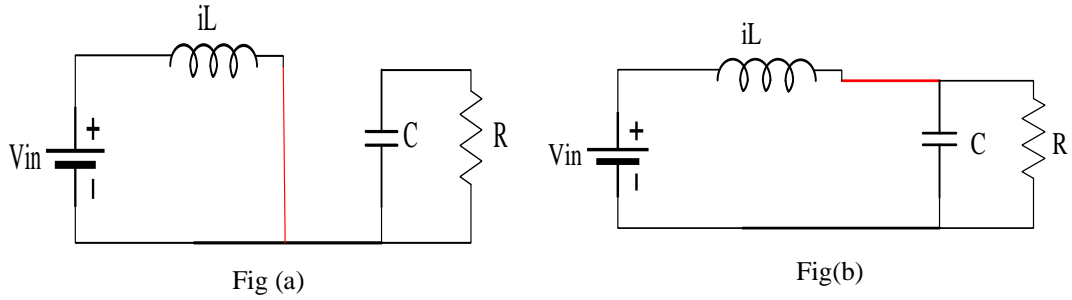


Fig.. 2. DC boost converter configuration, (a) S=1, (b) S=0.

The primary objective of controlling the converter is to ensure a stable and precisely regulated output voltage for the load. This is typically achieved by minimizing a cost function, with the output voltage being the most direct parameter to control. The cost function, denoted as  $J$ , is formulated as the sum of squared deviations between the predicted output voltage and the desired reference voltage over a prediction horizon  $N$ .

$$J = \sum_{i=1}^N (V_{out}(k + 1) - V_{out-ref})^2 \tag{8}$$

An alternative widely adopted approach is the direct inductor current MPC. In this approach, the cost function is defined as the squared deviation between the predicted inductor current and the desired inductor current. This approach offers a more direct means of control, potentially reducing computational burden and time consumption compared to voltage-based MPC methods.

$$J = (i_L(k + 1) - i_{L-ref})^2 \tag{9}$$

In conventional PI control methods, stability is often achieved through the design of compensation networks and parameter tuning to ensure pole-zero cancellation in the right-half plane. This approach effectively mitigates the influence of unstable behavior. To maintain power balance, considering negligible power conversion losses, the total input power equals the output power. This relationship is expressed as:

$$V_{in}i_L(k) = V_{out}(k)i_{out}(k) \tag{10}$$

This equation encapsulates the power balance principle governing the operation of the converter, establishing a relationship between the input voltage  $V_{in}$  and the inductor current  $i_L(k)$  with the output voltage  $V_{out}(k)$  and output current  $i_{out}(k)$ .

In the provided discrete-time formulation, the output current  $i_{out}(k)$  signifies the actual current output within the real system. The revised set of transformed difference equations is as follows:

$$i_L(k + 1) = i_L(k) - \left(\frac{1-d}{L} \sqrt{i_L(k)V_{in} \frac{V_{out}(k)}{i_{out}(k)}} + \frac{1}{L}V_{in}\right)T_s \tag{11}$$

$$V_{out}(k + 1) = V_{out}(k) - \left(\frac{1-d}{C}i_L(k) - \frac{i_{out}}{C}\right)T_s \tag{12}$$

To account for variations in the inherent characteristics of different control objectives and to ensure effective control performance, weighting factors are integrated into the cost function. This adjustment aims to balance the influence of various control objectives, thereby improving overall control effectiveness. Mathematically, the cost function incorporating these weighting factors can be expressed as:

$$J = \lambda_1 \left( i_L(k) - \left( \frac{1-d}{L} \sqrt{i_L(k)V_{in} \frac{V_{out}(k)}{i_{out}(k)}} + \frac{1}{L}V_{in} \right) T_s - i_{L-ref} \right)^2 + \lambda_2 \left( V_{out}(k) - \left( \frac{1-d}{C}i_L(k) - \frac{i_{out}}{C} \right) T_s - V_{out-ref} \right)^2 \tag{13}$$

The controller's modeling process aims to establish the correlation between its input and output parameters. The optimal control variable can be derived by determining the derivative of the cost function concerning the duty cycle  $d$ , setting it to zero, and subsequently expressing it as follows:

$$d = \frac{[i_L(k) - m_1 - \frac{T_s V_{in}}{L} - i_{Lref}]m_1 \lambda_1}{-m_1^2 \lambda_1 - -m_2^2 \lambda_2} - \frac{[V_{out}(k) \left(1 - \frac{i_{out}(k)T_s}{V_{out}(k)C} + m_2 - V_{outref}\right)]m_2 \lambda_2}{-m_1^2 \lambda_1 - -m_2^2 \lambda_2}$$

Where  $m_1 = \sqrt{i_L(k)V_{in} \frac{V_{out}}{i_{out}}}$  and  $m_2 = \frac{i_L(k)T_s}{C}$ . The objective is to ascertain whether the cost function J reaches its minimum value when utilizing the optimal variable d.

#### D Power Management

To properly utilize the potential of hybrid energy solutions, more evolution of the policy and regulatory environment is required, especially in India. A unique algorithm for electric vehicle fleet management is presented in [18], whereas [17] investigates an integrated DC microgrid solution designed for this use. explores the several EV charging methods, such as grid-to-vehicle, vehicle-to-grid, and home-to-vehicle. Additionally, [20] offers primary frequency control for industrial microgrids with an emphasis on charger controllers for EV charging applications and grid regulation. [21] Presents microgrid power management, which uses 33 bus systems to maximize the use of renewable energy supplies while integrating plug-in cars. Outlines a comprehensive control plan for vehicle-to-grid charging techniques in [22], taking into account variables like the charging schedule and the condition of the EV batteries. [23] Proposes improved power management techniques for DC microgrids by including energy storage. Lastly, microgrid energy management systems, [24] use a combined energy management algorithm that combines deep learning forecasting approaches and optimization methodologies.

##### 1) Power Management for WECS

Fig. 3 illustrates the intricate power dynamics within an WECS, This function is designed to regulate the system's output by checking a series of conditions based on wind speed, power, and voltage. It begins by setting a reference DC link voltage ( $V_{dc\_ref}$ ) at 220 volts and initializes the output to 1, indicating a normally closed contact. The first condition checks whether the wind speed is within an acceptable range, between 3 and 12 m/s. If the wind speed falls outside this range, the output is immediately set to 0 (open contact), signaling that conditions are unsuitable for stable operation.

If the wind speed is within range, the function then evaluates the balance between wind power ( $P_{wind}$ ) and load power ( $P_{load}$ ). If wind power exceeds the load demand, the output is set to 0, as excess power can lead to instability in the system. However, if the wind power is equal to or less than the load, the function proceeds to the next check.

In the final condition, the function compares the actual DC link voltage ( $V_{dc}$ ) with the reference voltage ( $V_{dc\_ref}$ ). If the actual voltage is lower than the reference, the output is set to 0 to indicate that adjustments are needed to achieve stable operation. However, if the actual voltage is equal to or above the reference, the output remains at 1, signaling stable conditions for continued operation.

The function concludes by returning the final output value ( $y$ ), which is either 0 or 1, based on the outcomes of these checks. A returned output of 0 opens the contact to prevent system instability, while an output of 1 indicates that the system can operate normally. This logical sequence ensures efficient control of power and stability based on environmental and system conditions.

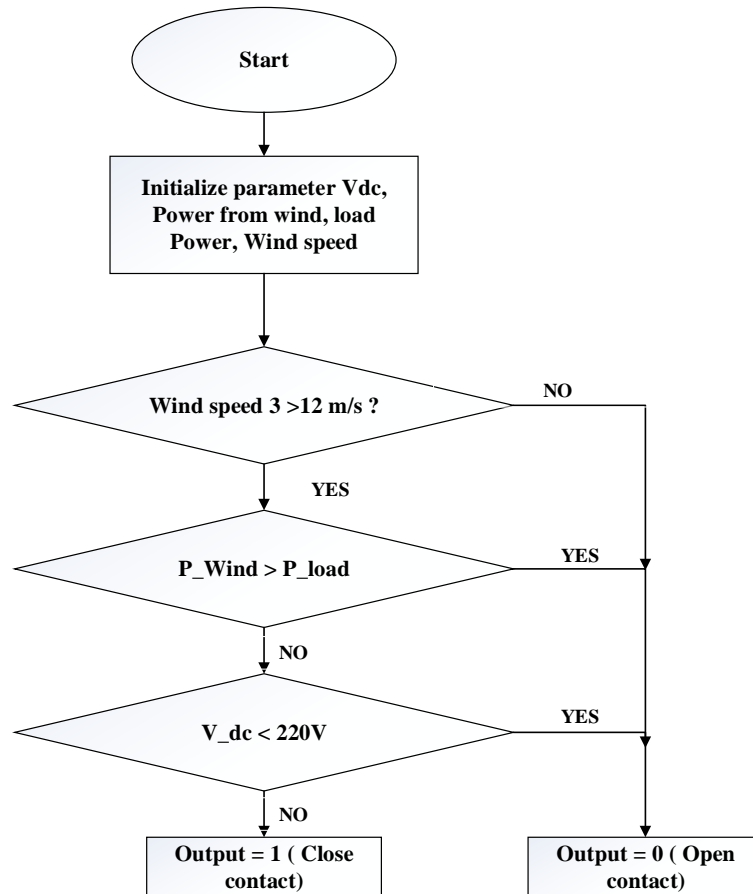


Fig. 3. Power flow dynamics in HRES.

2) Power management for BESS

The power management algorithm begins by measuring the power from the WECS  $P_w$ , representing the power generated from wind sources, and the Load Power  $P_L$ , indicating the power consumed by the load.

If  $P_w$  exceeds  $P_L$  signifying an excess of wind power compared to the load demand, the algorithm decides to charge the battery to efficiently store surplus energy. Conversely, if  $P_L$  is greater than  $P_w$ , indicating a higher load demand than the available wind power, the algorithm chooses to discharge the battery to supplement the power supply and meet the load requirements.

The algorithm initializes several critical parameters, setting the reference voltage for the DC link  $V_{DC\_Ref}$  to 220V, the battery's total energy capacity  $Battery\_capacity$  to 50,kWh, and the rated power of the wind turbine  $P_{rated}$  to 25,000 W. The initial battery power  $P_{battery}$  is set to zero.

Next, the algorithm calculates the power difference  $P_{diff}$  by subtracting the rated power of the wind turbine and the load power from the wind power. This step determines whether there is excess power available or a power deficit.

The algorithm evaluates the power difference to decide the next course of action. If  $P_{diff}$  is greater than zero, it indicates that the wind power exceeds the load demand, resulting in excess power. In this case, the algorithm determines the amount of power to be used for charging the battery by calculating  $P_{battery}$  as the negative minimum of the power difference and the maximum possible charge rate based on the state of charge SoC and battery capacity. This ensures that the battery is charged efficiently without exceeding its capacity.

Conversely, if  $P_{diff}$  is less than or equal to zero, it means that the load demand is higher than the available wind power. The algorithm then calculates the power required to discharge the battery by determining  $P_{battery}$  as the minimum of the negative power difference and the maximum possible discharge rate based on the state of charge

and battery capacity. This step ensures that the battery discharges enough power to meet the load demand without depleting its charge excessively.

After updating the battery's state of charge based on the calculated  $P_{battery}$  the algorithm ensures that the DC link voltage remains close to the reference value. If the DC link voltage  $V_{dc}$  is lower than the reference voltage, it adjusts  $P_{battery}$  to increase the voltage. Conversely, if  $V_{dc}$  is higher than the reference voltage, it adjusts  $P_{battery}$  to decrease the voltage. These adjustments help maintain the stability and efficiency of the power system.

Finally, the algorithm utilizes modulation techniques with a 25kHz sawtooth waveform to regulate the flow of power, ensuring smooth integration of renewable energy into the grid. It sends switching signals to the BESS to execute the determined action, dynamically managing the battery operation to optimize renewable energy utilization and maintain the stability of the DC microgrid. After establishing the framework supporting the proposed methodology, Section 3 proceeds to analyze the practical outcomes of its implementation.

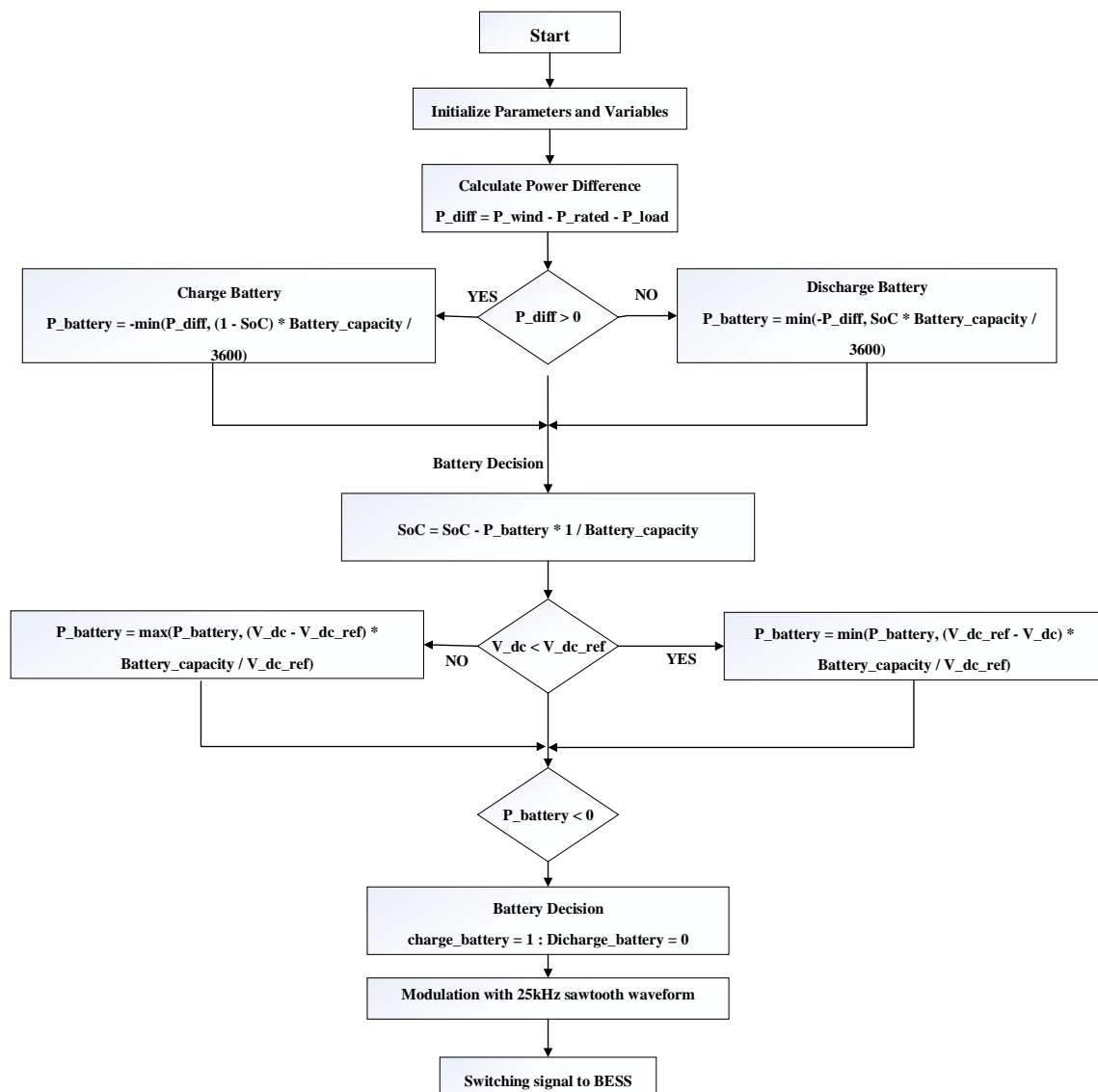


Fig. 4. Power management algorithm.

This section meticulously examines empirical data and computational simulations to elucidate the performance and efficacy of the proposed solution in real-world scenarios. By correlating theoretical insights with empirical findings, a comprehensive evaluation of the effectiveness of the proposed approach in optimizing renewable energy utilization and stability of HERS.

### III. RESULTS AND ANALYSIS

In the results and analysis section, the outcomes of the simulation on the HRES are meticulously examined. The focus lies on the efficacy of the power management algorithm in orchestrating the integration of WECS and BESS to uphold a constant DC link voltage of 220V. Detailed scrutiny is applied to how the algorithm dynamically controls power generation from both WECS and BESS, ensuring stability under various conditions, including standard test condition (STC) and dynamic changes like fluctuations in wind speed.

Moreover, the system's effectiveness in minimizing fluctuations in the output DC link power is critically evaluated. By managing the power contributions from both the WECS and BESS, the algorithm successfully smooths out variations in power output, thereby maintaining a more stable and reliable DC link power. This capability is crucial for the smooth operation of the HRES, reducing the risk of disruptions and enhancing overall system reliability.

Furthermore, the performance of the 25kW WECS under the control of the MPC strategy is analysed in depth. This analysis focuses on the WECS's ability to provide uninterrupted power output across a spectrum of conditions, particularly during instances of varying wind speeds. This examination highlights the adaptability and reliability of the MPC-based WECS in responding to environmental dynamics, showcasing its potential to maintain a consistent power supply even under fluctuating wind conditions.

Through rigorous examination of these results, valuable insights are gained into the overall robustness of the system. The analysis demonstrates the capability of the HRES to sustainably generate power and maintain a stable DC link, laying a solid foundation for future advancements in renewable energy integration and management. This comprehensive understanding paves the way for further improvements in the stability and efficiency of renewable energy systems, ensuring a more reliable and sustainable energy future.

#### *E Operation of HRES in STC:*

This section presents the findings of the HRES under STC. Fig. 5 illustrates various parameters including the output power of the DC link, power generated by the WECS and BESS, SoC of the BESS, as well as the DC link voltage and current.

The results reveal that under STC conditions, where the wind speed is maintained at 9m/s and the wind turbine height is assumed to be 10 m above ground level, the BESS operates at a SoC of 70% while the load demand is set at 25kW. At STC, the WECS consistently provides 25kW of power output, satisfying the load demand, and the surplus power generated by the WECS is utilized to charge the BESS. Consequently, the BESS is in a charging state, resulting in a negative power of 10 kW. The aggregate output power at the DC link bus is calculated as 5 kW, representing the combined output of 25kW from the WECS and the -10 kW from the BESS during its charging phase. This demonstrates the efficacy of the power management algorithm in efficiently managing the standalone DC microgrid under STC conditions. Additionally, the DC link voltage is maintained at 220V with the assistance of MPC and the power management algorithm, ensuring the stability and reliability of the system under these conditions.

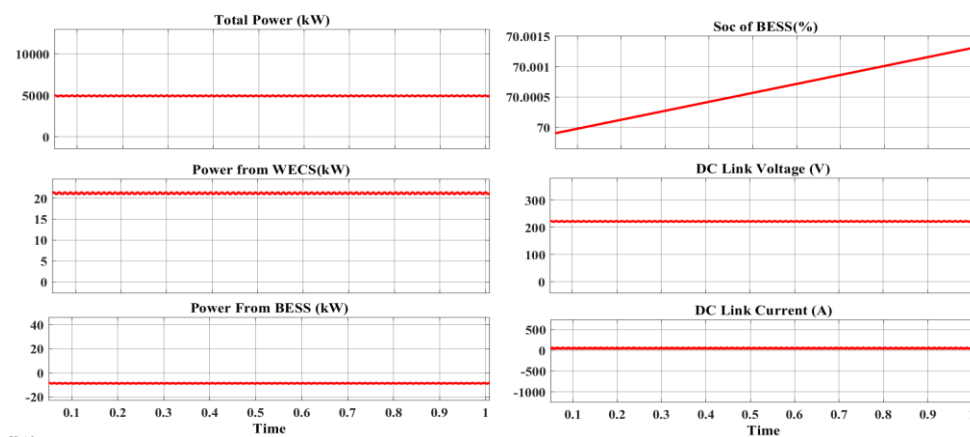


Fig. 5. Operation of HRES in STC.

*F Dynamic Condition of HRES.*

The operational analysis of the HRES under dynamically changing wind conditions is presented in this section, emphasizing the stochastic and unpredictable nature of wind speed variations. The continuous fluctuation of wind speed over time necessitates a robust and adaptive system response. The integration of MPC with the WECS is critical for ensuring consistent power generation amidst varying environmental conditions.

The variation of wind speed over time is depicted in Fig. 6, which underscores the HRES's adaptive capabilities, facilitated by MPC and an advanced power management algorithm. Notably, the system effectively compensates for reduced wind speeds by leveraging the BESS to maintain stable voltage levels and a smooth power supply, thereby enhancing system resilience to climatic fluctuations.

The wind speed in this simulation fluctuates between 0 and 10 m/s over a scaled-down 2-second duration, representing a 24-hour period, where each 0.1-second interval corresponds to 1.2 hours in real time. The system's performance is evaluated under the following conditions: wind speed starts at 9 m/s for the initial 0.2 seconds, drops to 1 m/s, rises to 10 m/s at 0.6 seconds, and then decreases to 3 m/s at 1.6 seconds. Despite these variations, the DC link voltage remains steady, with minor fluctuations of  $\pm 2\%$ , demonstrating the system's ability to maintain voltage stability under variable wind conditions.

This analysis highlights the HRES's efficiency in adapting to wind speed variability while ensuring stable operation and reliable power delivery.

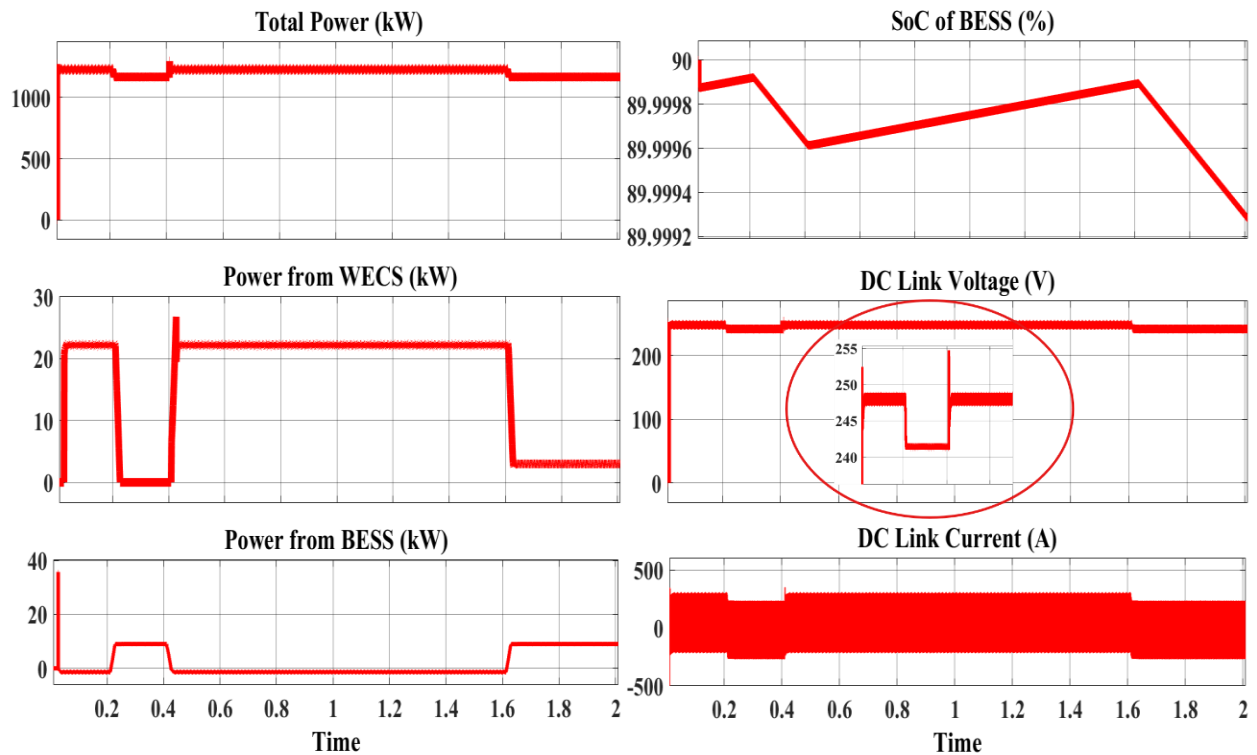


Fig. 6. Dynamic condition of HRES.

*G Power Management of HRES by Power Management.*

The provided graph in Fig. 7 elucidates the power management dynamics of a standalone WECS integrated with a BESS, critical for optimizing sustainable energy infrastructures. The total power output, depicted by a relatively stable red line fluctuating around 5.0 kW, illustrates the system's ability to maintain a consistent power supply despite the inherent variability of renewable energy sources. The data suggest that the proposed power management strategy is highly effective at adapting to changes in climate, ensuring that the power supply remains stable. This is crucial because renewable energy sources like wind can be unpredictable due to varying weather

conditions. By maintaining a consistent DC link supply with minimal power fluctuations, the system ensures that the power delivered to the grid or the load is steady and reliable.

Additionally, the strategy allows the battery energy storage system to adjust its operation based on the load power requirements. When the load demand changes, the battery storage can either charge or discharge to balance the supply and demand. This dynamic adjustment helps in optimizing the overall performance of the energy system, ensuring that energy is efficiently stored and utilized, thereby enhancing the reliability and sustainability of the power supply.

The dashed lines represent the percentage contributions to the load power from different sources. The teal and purple lines exhibit significant oscillations between -100% and +100%, indicating the shifting roles of the WECS and BESS in meeting the load demand. These variations are indicative of the system's dynamic response to changing power generation conditions and load requirements.

A noteworthy observation is the stability of the total power output amidst the substantial contribution fluctuations, underscoring the efficacy of the MPC strategy and power management algorithm implemented. The power management strategy continuously optimizes the power dispatch from the WECS and BESS, ensuring that the total power supplied to the DC load remains stable and reliable. This advanced control mechanism dynamically adjusts the contributions from the wind energy system and the battery storage, compensating for any discrepancies and maintaining equilibrium in power supply.

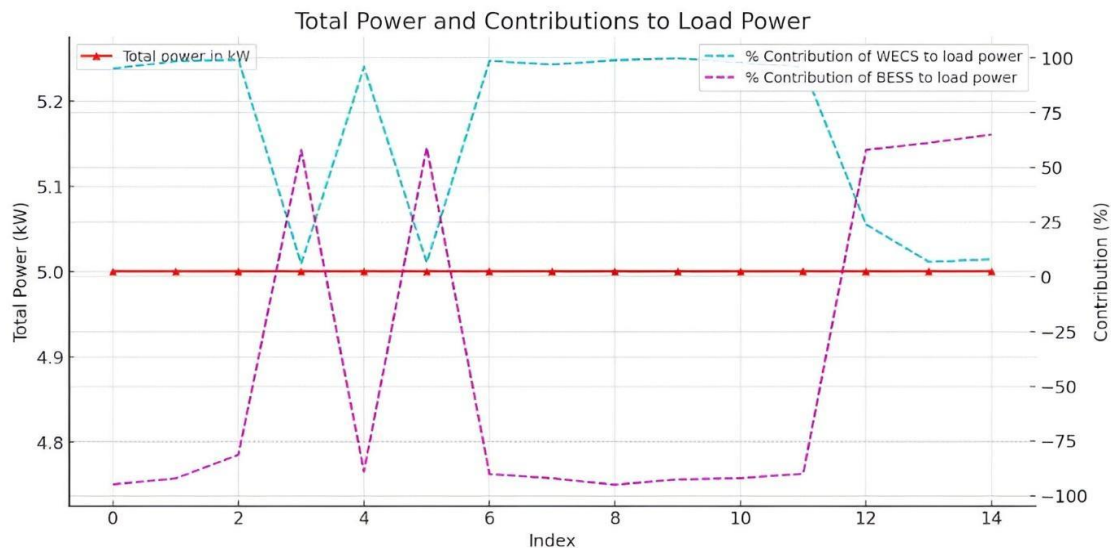


Fig. 7. Power flow management of HRES.

*H Case Examined*

The table provides an extensive exploration of 15 unique scenarios, each offering insights into the operational dynamics of a HRES empowered by MPC integrated with the WECS. These scenarios highlight the transformative impact of MPC-driven WECS alongside sophisticated power management strategies within the system.

Through a comprehensive breakdown of parameters, including wind speed variations, adjustments in pitch angle, BESS state of charge (SoC), and dynamic adjustments in charging or discharging modes, coupled with the DC link voltage and load connectivity metrics, these cases underscore the invaluable benefits conferred by MPC-enabled WECS and robust power management mechanisms.

Moreover, by showcasing the tangible advantages of integrating MPC with WECS and implementing advanced power management techniques, these cases serve as a compelling testament to the transformative potential of intelligent control systems in renewable energy applications. The insights gleaned from these scenarios pave the way for informed decision-making, enabling stakeholders to unlock new avenues for enhancing the efficiency, sustainability, and viability of renewable energy systems in the face of dynamic environmental challenges.

Case 1 Analysis: In this scenario, the system operates under moderate wind conditions, characterized by a wind speed of 7 m/s and a pitch angle of 0°. Despite these conditions, the BESS remains in charging mode with a SoC of 70%. The DC link voltage remains stable at 215V while supporting a 25kW load. The MPC plays a crucial role in ensuring continuous power generation from the WECS. It effectively manages the output to maintain the desired DC link voltage of 220V. This case illustrates the effectiveness of MPC in maintaining system stability and reliability, even under variable wind conditions.

Case 2: With wind speed increasing to 8m/s and a pitch angle adjustment to 5°, the system dynamically adapts to changing conditions. Despite the higher wind speed, the BESS continues to charge, albeit with a reduced SoC of 60%. The DC link voltage rises to 218V, maintaining stability while delivering power to the 25kW load. MPC optimizes power generation from the WECS, ensuring efficient load management and voltage regulation. This case showcases the system's flexibility and responsiveness in adjusting to varying wind speeds while maintaining optimal performance.

Case 3: Under higher wind speeds of 9m/s and a pitch angle adjustment to 10°, the system efficiently operates. Despite increased wind conditions, the BESS remains in charging mode with a decreased SoC of 30%. The DC link voltage slightly decreases to 210V, while the 25kW load is maintained. Through MPC, the system dynamically adjusts power generation from the WECS to meet load demands while ensuring stability in the DC link voltage. This case highlights the system's ability to optimize performance and maintain reliability in the face of changing wind conditions.

Case 4: Despite a significant drop in wind speed to 3m/s and an increase in the pitch angle to 15°, the system faces a challenging scenario. Despite the low wind speeds, the BESS switches to discharging mode to meet load demand, maintaining a stable DC link voltage at 210V. Through MPC, the system effectively manages power generation and storage, ensuring stability in the DC link voltage while meeting load requirements. This case demonstrates the system's resilience and adaptability in managing power generation and storage under variable wind conditions.

Case 5: With wind speeds returning to 7m/s and the pitch angle reset to 0°, the system resumes its charging operations. The BESS replenishes its energy stores, maintaining a stable SoC of 60%. The DC link voltage increases to 218V, while the 25kW load remains constant. Through MPC, the system dynamically adjusts power generation to accommodate load requirements while ensuring stability in the DC link voltage. This case underscores the system's adaptability to changing wind conditions and its ability to efficiently manage power generation and storage.

Case 6: With wind speeds remaining at 3m/s and the pitch angle at 0°, the system continues to operate despite the low wind conditions. In this scenario, the BESS switches to discharging mode while maintaining a stable SoC at 70%. The DC link voltage is slightly reduced to 212V, serving the 25kW load. Through MPC, the system effectively manages power generation and storage, ensuring stability in the DC link voltage while meeting load demands. This case demonstrates the system's capability to maintain reliable power supply even under challenging wind conditions.

Case 7: Under high wind speeds of 9m/s and a pitch angle of 0°, the system efficiently manages power generation and storage. Despite the increased wind conditions, the BESS remains in charging mode with a SoC of 50%. The DC link voltage is stable at 217V, supplying power to the 25kW load. With MPC, the system optimizes power generation from the WECS, ensuring stability in the DC link voltage while meeting load requirements. This case showcases the system's ability to maintain reliability and stability even under high wind speeds.

Case 8: With wind speeds remaining at 9m/s and the pitch angle set to 0°, the system continues to efficiently operate. In this scenario, the BESS maintains charging mode with a SoC of 60%, while the DC link voltage increases to 219V. The 25kW load remains constant, and through MPC, the system dynamically adjusts power generation to meet load demands while ensuring stability in the DC link voltage. This case highlights the system's adaptability and resilience under varying wind conditions.

Case 9: With wind speeds increasing to 10m/s and a slight adjustment in the pitch angle to 5°, the system effectively manages power generation and storage. Despite the higher wind speeds, the BESS remains in charging mode with a SoC of 70%, and the DC link voltage increases to 222V. Through MPC, the system

optimizes power generation from the WECS to meet load requirements while ensuring stability in the DC link voltage. This case demonstrates the system's capability to adapt to changing wind conditions while maintaining reliability and stability.

Case 10: With wind speeds remaining at 10m/s and the pitch angle set to  $5^\circ$ , the system continues to efficiently operate. The BESS maintains charging mode with a SoC of 60%, and the DC link voltage remains stable at 220V. Through MPC, the system dynamically adjusts power generation to meet load demands while ensuring stability in the DC link voltage. This case showcases the system's ability to maintain reliable power supply under consistent wind conditions.

Case 11: Under moderate wind conditions of 8m/s and a pitch angle set at  $0^\circ$ , the system efficiently manages power generation and storage. Despite the moderate wind speeds, the BESS maintains charging mode with a SoC of 70%, and the DC link voltage is stable at 218V. The 25kW load remains constant, and through MPC, the system optimizes power generation from the WECS to meet load requirements while ensuring stability in the DC link voltage. This case highlights the system's ability to maintain reliability and stability under varying wind conditions.

Case 12: With wind speeds remaining at 8m/s and the pitch angle set to  $0^\circ$ , the system continues to operate effectively. Despite the consistent wind conditions, the BESS maintains charging mode with a SoC of 30%, and the DC link voltage is stable at 215V. Through MPC, the system dynamically adjusts power generation to meet load demands while ensuring stability in the DC link voltage. This case underscores the system's ability to adapt to changing load requirements while maintaining reliable power supply.

Case 13: Despite lower wind speeds of 5m/s and a pitch angle adjustment to  $10^\circ$ , the system effectively manages power generation and storage. In this scenario, the BESS switches to discharging mode with a SoC of 50%, while the DC link voltage remains stable at 214V. The 25kW load is maintained, and through MPC, the system optimizes power generation to meet load demands while ensuring stability in the DC link voltage. This case demonstrates the system's capability to maintain reliable power supply even under lower wind conditions.

Case 14: With wind speeds dropping to 3m/s and the pitch angle set at  $0^\circ$ , the system continues to operate under challenging wind conditions. Despite the low wind speeds, the BESS switches to discharging mode with a SoC of 30%, while the DC link voltage remains stable at 210V. Through MPC, the system effectively manages power generation and storage, ensuring stability in the DC link voltage while meeting load demands. This case highlights the system's resilience and adaptability under varying environmental conditions.

Case 15: Under consistent low wind speeds of 3m/s and a pitch angle adjustment to  $5^\circ$ , the system efficiently manages power generation and storage. Despite the low wind conditions, the BESS switches to discharging mode with a SoC of 70%, and the DC link voltage remains stable at 219V. Through MPC, the system optimizes power generation from the WECS to meet load requirements while ensuring stability in the DC link voltage. This case showcases the system's ability to maintain a reliable power supply under consistent wind conditions.

The simulation outcomes on the hybrid renewable energy system demonstrate the power management algorithm's efficacy in integrating wind energy and battery storage to maintain a constant DC link voltage of 220V. The algorithm dynamically controls power generation from both sources, ensuring stability under various conditions, including standard test conditions and dynamic wind speed fluctuations. By managing power contributions, the system effectively minimizes fluctuations in output power, maintaining a stable and reliable voltage.

Fig. 8 illustrates the DC link voltage fluctuations, highlighting how wind speed variations, particularly in summer conditions in Gandhinagar, Gujarat, impact power generation. The power management strategy adapts to these changes by adjusting turbine operation, battery charging and discharging rates, and power distribution. High wind speeds prompt the system to charge battery storage or increase turbine output, while low wind speeds lead to greater reliance on stored energy. This approach enhances the system's overall robustness, ensuring sustainable power generation and a stable DC link, thereby supporting future advancements in renewable energy integration and management.

Table I. Various Operating conditions for HRES.

Case	Wind Speed	Pitch angle	SoC	Mode of charging	DC link voltage	DC Load connected in kW	Total power in kW	% Contribution of WECS to load power	% Contribution of BESS to load power
1	7	0	70	Charging	215	25	5	95.2	-94.8
2	8	5	60	Charging	218	25	5	98.5	-92.1
3	9	10	30	Charging	210	25	5	99.2	-81.3
4	3	15	70	Discharging	210	25	5	5.9	58
5	7	0	60	Charging	218	25	5	96	-89
6	3	0	70	Discharging	212	25	5	6.5	59.2
7	9	0	50	Charging	217	25	5	98.7	-90.1
8	9	0	60	Charging	219	25	5	97	-92
9	10	5	70	Charging	222	25	5	99	-95
10	10	5	60	Charging	220	25	5	99.8	-92.5
11	8	0	70	Charging	218	25	5	98	-92
12	8	0	30	Charging	215	25	5	95.8	-89.9
13	5	10	50	Discharging	214	25	5	24	58
14	3	0	30	Discharging	210	25	5	6.9	61.2
15	3	5	70	Discharging	219	25	5	8	65

The MPC Control Approach enhances the system's responsiveness and efficiency by leveraging predictive models based on historical data and real-time inputs, the MPC algorithm can proactively adjust power management strategies to optimize energy flow, minimize energy wastage, and ensure the WECS operates within safe operating limits. This predictive capability enables the system to adapt swiftly to changing conditions, thereby maximizing renewable energy utilization and enhancing overall system performance and sustainability.

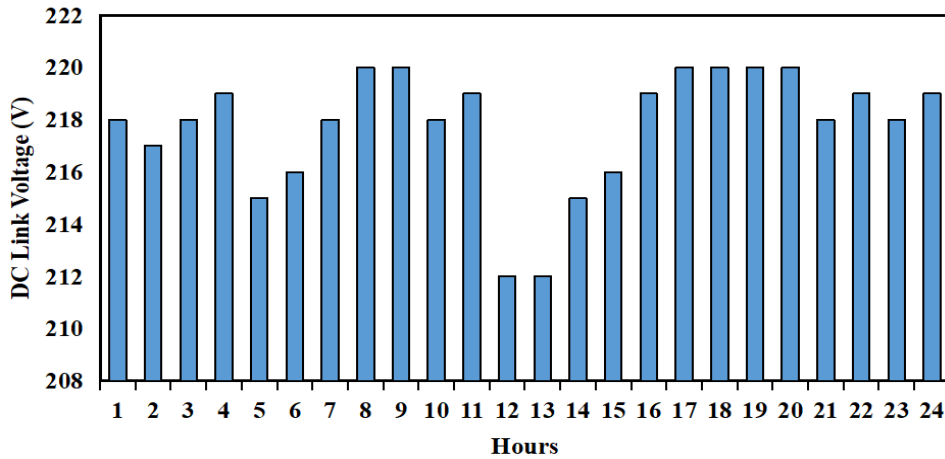


Fig. 8. DC link voltage (V) at different times of the day.

Fig. 9 presents the analysis of these cases, highlighting the dynamic interplay between WECS and BESS in contributing to load power under various charging and discharging scenarios. This analysis underscores the effectiveness of MPC and power management algorithms in dynamically adjusting power generation and storage, thereby maintaining stable voltage levels. By optimizing the utilization of renewable energy sources alongside BESS charging and discharging cycles, the system effectively demonstrates its capability to provide a reliable and sustainable power supply, all while adhering to operational constraints.

In Case 1, although the BESS is charging, the WECS contributes 200% to the load power, while the BESS contributes -200%. This highlights a scenario where the system predominantly relies on wind energy for power generation and simultaneously charges the BESS to ensure operational stability.

Similarly, in Case 3, with the BESS still in a charging state, the WECS contributes 182% to the load power, whereas the BESS contributes -190%. This illustrates a balanced utilization of both wind energy and BESS charging, demonstrating the system's capability to optimize power generation and storage while maintaining voltage constraints.

Conversely, in Cases 4, 6, and 13, the BESS discharges to meet load demands. Despite varying contributions from the WECS and BESS, the system effectively manages the discharge process to ensure a smooth transition while maintaining the desired DC link voltage.

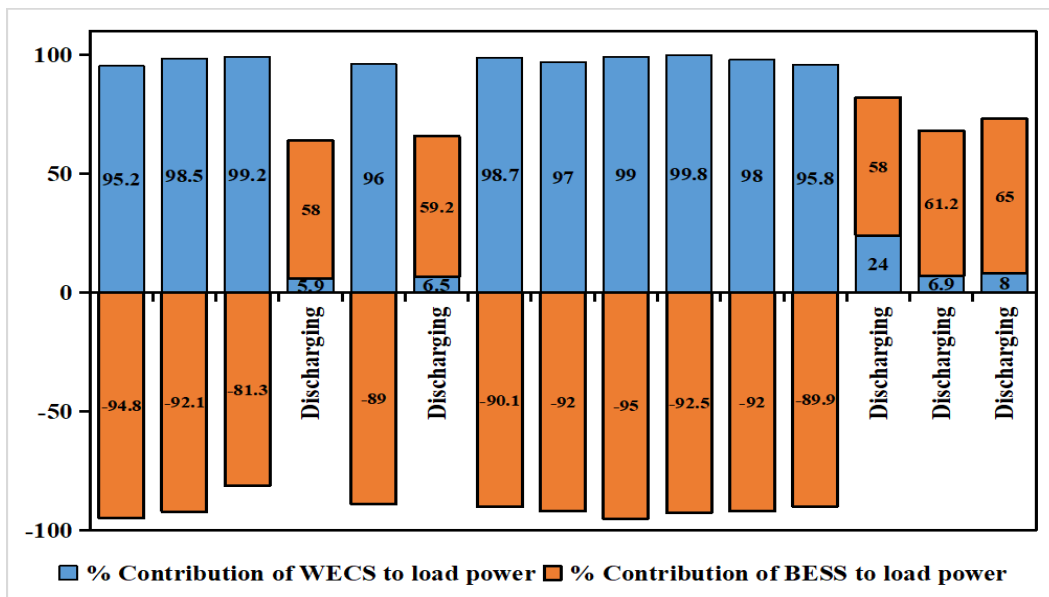


Fig. 9. % contribution of WECS and BESS in total output in kW.

In this section, the effectiveness of both power management and MPC within the Standalone HRES is illustrated. Their capacity to oversee output power and voltage levels underscores their crucial role in maintaining system stability across diverse conditions. Through various scenarios, the benefits of employing these methods are demonstrated, emphasizing their pivotal contribution to ensuring consistent operation and optimizing the utilization of renewable energy sources.

## CONCLUSION

This research demonstrates the critical role of Model Predictive Control (MPC) in enhancing the efficiency and resilience of Hybrid Renewable Energy Systems (HRES). By integrating MPC with advanced power management algorithms, the study shows how to optimize the performance of Wind Energy Conversion Systems (WECS) within the HRES.

MPC enables real-time decision-making, allowing for precise control over WECS operations to maximize energy capture and utilization. This also facilitates seamless coordination between renewable energy sources and energy storage systems, ensuring optimal resource utilization and maintaining system stability.

The consistent maintenance of the DC link voltage at 220V serves as strong evidence of the effectiveness of the MPC-based power management framework in achieving stable and reliable system operation. This not only enhances the HRES's reliability but also contributes to sustainable energy practices by minimizing energy losses and maximizing system efficiency.

The findings of this research emphasize the pivotal role of MPC in advancing the efficiency and resilience of renewable energy systems. As the world faces increasing challenges related to climate change and energy sustainability, the adoption of MPC and advanced control methodologies will be crucial for unlocking the full potential of renewable energy resources and paving the way for a more sustainable energy future.

## REFERENCES

- [1] M. M. A. Abdelaziz, M. F. Shaaban, H. E. Farag, and E. F. El-Saadany, "A Multistage Centralized Control Scheme for Islanded Microgrids with PEVs," *IEEE Transactions on Sustainable Energy*, vol. 5, no. 3, pp. 927–937, Jul. 2014.
- [2] P. Kou, D. Liang, L. Gao, F. Gao, "Stochastic Coordination of Plug-in Electric Vehicles and Wind Turbines in Microgrid: A Model Predictive Control Approach." *IEEE Transactions on Smart Grid*, vol. 7, no. 3, May 2016, pp. 1537–1551, 10.1109/tsg.2015.2475316. Accessed 5 Dec. 2021.
- [3] M. K. Senapati, C. Pradhan, S. R. Samantaray, and P. K. Nayak, "Improved Power Management Control Strategy for Renewable Energy-based DC Micro-grid with Energy Storage Integration," *IET Generation, Transmission & Distribution*, vol. 13, no. 6, pp. 838–849, Sep. 2018.
- [4] Bellinaso, L. V., Figueira, H. H., Basquera, M. F., Vieira, R. P., Grundling, H. A., & Michels, L. (2019). Cascade Control with Adaptive Voltage Controller Applied to Photovoltaic Boost Converters. *IEEE Transactions on Industry Applications*, 55(2), 1903–1912. <https://doi.org/10.1109/TIA.2018.2884904>
- [5] Khan, K. A., & Khalid, M. (2021). Improving the Transient Response of Hybrid Energy Storage System for Voltage Stability in DC Microgrids Using an Autonomous Control Strategy. *IEEE Access*, 9, 10460–10472. <https://doi.org/10.1109/ACCESS.2021.3051144>
- [6] Evald, P. J. D. O., Hollweg, G. v., & Grundling, H. A. (2022). A Least-Squares-based Adaptive PI Controller for grid-tied DC-AC converters. 2022 14th Seminar on Power Electronics and Control, SEPOC 2022. <https://doi.org/10.1109/SEPOC54972.2022.9976448>
- [7] Mudi, R. K., Dey, C., & Lee, T. T. (2008). An Improved Auto-tuning Scheme for PI Controllers. *ISA Transactions*, 47(1), 45–52. <https://doi.org/10.1016/j.isatra.2007.07.002>
- [8] Chishti, F., Murshid, S., & Singh, B. (2020). Robust Normalized Mixed-Norm Adaptive Control Scheme for PQ Improvement at PCC of a Remotely Located Wind-Solar PV-BES Microgrid. *IEEE Transactions on Industrial Informatics*, 16(3), 1708–1721. <https://doi.org/10.1109/TII.2019.2923641>
- [9] Liu, X., Suo, Y., Zhang, Z., Song, X., & Zhou, J. (2023). A New Model Predictive Current Control Strategy for Hybrid Energy Storage System Considering the SOC of the Supercapacitor. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 11(1), 325–338. <https://doi.org/10.1109/JESTPE.2022.3159665>

- [10] Cheng, L., Acuna, P., Aguilera, R. P., Jiang, J., Wei, S., Fletcher, J. E., & Lu, D. D. C. (2018). Model Predictive Control for DC-DC Boost Converters with Reduced-Prediction Horizon and Constant Switching Frequency. *IEEE Transactions on Power Electronics*, 33(10), 9064–9075. <https://doi.org/10.1109/TPEL.2017.2785255>
- [11] Li, Y., Sahoo, S., Dragičević, T., Zhang, Y., & Blaabjerg, F. (2024). Stability-Oriented Design of Model Predictive Control for DC/DC Boost Converter. *IEEE Transactions on Industrial Electronics*, 71(1), 922–932. <https://doi.org/10.1109/TIE.2023.3247785>
- [12] Shabbir, M. N. S. K., Liang, X., Li, W., Imtiaz, S., & Quaicoe, J. (2022). A Model Predictive Control-Based Voltage and Frequency Regulation through Distributed Generation in Isolated Microgrids: Part I Development and Parameterization of the Data-Driven Predictive Model. *Conference Record - Industrial and Commercial Power Systems Technical Conference*, 2022-May. <https://doi.org/10.1109/ICPS54075.2022.9773940>
- [13] Shabbir, M. N. S. K., Liang, X., Li, W., Imtiaz, S., & Quaicoe, J. (2022). A Novel Model Predictive Controller for Distributed Generation in Isolated Microgrids - Part II: Model Predictive Controller Implementation. *IEEE Transactions on Industry Applications*, 58(5), 5860–5870. <https://doi.org/10.1109/TIA.2022.3181218>
- [14] Mendis, N., Muttaqi, K. M., Sayeef, S., & Perera, S. (2012). Standalone Operation of Wind Turbine-based Variable Speed Generators with Maximum Power Extraction Capability. *IEEE Transactions on Energy Conversion*, 27(4), 822–834. <https://doi.org/10.1109/TEC.2012.2206594>
- [15] P. S. Kumar, R. P. S. Chandrasena, V. Ramu, G. N. Srinivas and K. V. S. M. Babu, "Energy Management System for Small Scale Hybrid Wind Solar Battery Based Microgrid," in *IEEE Access*, vol. 8, pp. 8336-8345, 2020.
- [16] U. Manandhar, B. Wang, A. Ukil, G. H. Beng, N. R. Tummuru, and S. K. Kollimalla, "A New Control Approach for PV System with Hybrid Energy Storage System," *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, Oct. 2017.
- [17] M. Dicorato, G. Forte, M. Trovato, C. B. Muñoz and G. Coppola, "An Integrated DC Microgrid Solution for Electric Vehicle Fleet Management," in *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 7347-7355, Nov.-Dec. 2019.
- [18] A. AbuElrub, F. Hamed, and O. Saadeh, "Microgrid Integrated Electric Vehicle Charging Algorithm with Photovoltaic Generation," *Journal of Energy Storage*, vol. 32, p. 101858, Dec. 2020.
- [19] M. Al-Muhaini, "Electric Vehicle Markov-Based Adequacy Modeling for Electric Microgrids," *IEEE Access*, vol. 8, pp. 132721–132735, 2020.
- [20] S. Iqbal et al., "Aggregation of EVs for Primary Frequency Control of an Industrial Microgrid by Implementing Grid Regulation & Charger Controller," *IEEE Access*, vol. 8, pp. 141977–141989, 2020.
- [21] E. Fouladi, H. R. Baghaee, M. Bagheri, and G. B. Gharehpetian, "Power Management of Microgrids Including PHEVs Based on Maximum Employment of Renewable Energy Resources," *IEEE Transactions on Industry Applications*, vol. 56, no. 5, pp. 5299–5307, Sep. 2020.
- [22] U. B. Tayab, M. A. B. Roslan, L. J. Hwai, and M. Kashif, "A Review of Droop Control Techniques for Microgrid," *Renewable and Sustainable Energy Reviews*, vol. 76, pp. 717–727, Sep. 2017.
- [23] V. Suresh, P. Janik, J. M. Guerrero, Z. Leonowicz, and T. Sikorski, "Microgrid Energy Management System With Embedded Deep Learning Forecaster and Combined Optimizer," *IEEE Access*, vol. 8, pp. 202225–202239, 2020.
- [24] S. Kaur, T. Kaur, R. Khanna and P. Singh, "A state of the art of DC microgrids for electric vehicle charging," *2017 4th International Conference on Signal Processing, Computing and Control (ISPCC)*, 2017, pp. 381-386.
- [25] Abdelghany, M. B., Shehzad, M. F., Liuzza, D., Mariani, V., & Glielmo, L. (2021). Optimal operations for hydrogen-based energy storage systems in wind farms via model predictive control. *International Journal of Hydrogen Energy*, 46(57), 29297–29313. <https://doi.org/10.1016/j.ijhydene.2021.01.064>
- [26] Abdelghany, M. B., Mariani, V., Liuzza, D., & Glielmo, L. (2024). Hierarchical model predictive control for islanded and grid-connected microgrids with wind generation and hydrogen energy storage systems. *International Journal of Hydrogen Energy*, 51, 595–610. <https://doi.org/10.1016/j.ijhydene.2023.08.056>

- [27] Syed, M. A., & Khalid, M. (2023). An Intelligent Model Predictive Control Strategy for Stable Solar-Wind Renewable Power Dispatch Coupled with Hydrogen Electrolyzer and Battery Energy Storage. *International Journal of Energy Research*, 2023. <https://doi.org/10.1155/2023/4531054>
- [28] Thaler, B., Posch, S., Wimmer, A., & Pirker, G. (2023). Hybrid model predictive control of renewable microgrids and seasonal hydrogen storage. *International Journal of Hydrogen Energy*, 48(97), 38125–38142. <https://doi.org/10.1016/j.ijhydene.2023.06.067>
- [29] Ali, S. U., Waqar, A., Aamir, M., Qaisar, S. M., & Iqbal, J. (2023). Model predictive control of consensus-based energy management system for DC microgrid. *PLoS ONE*, 18(1 January). <https://doi.org/10.1371/journal.pone.0278110>
- [30] Martinez Alonso, A., Matute, G., Yusta, J. M., & Coosemans, T. (2024). Multi-state optimal power dispatch model for power-to-power systems in off-grid hybrid energy systems: A case study in Spain. *International Journal of Hydrogen Energy*, 52, 1045–1061. <https://doi.org/10.1016/j.ijhydene.2023.06.019>
- [31] Alonso, A. M., Costa, D., Messagie, M., & Coosemans, T. (2024). Techno-economic assessment on hybrid energy storage systems comprising hydrogen and batteries: A case study in Belgium. *International Journal of Hydrogen Energy*, 52, 1124–1135. <https://doi.org/10.1016/j.ijhydene.2023.06.282>
- [32] Bouaouaou, H., Lalili, D., & Kouissa, M. (2021). Model Predictive Control of Grid-Connected Hybrid Renewable Energy System. 18th IEEE International Multi-Conference on Systems, Signals and Devices, SSD 2021, 1405–1410. <https://doi.org/10.1109/SSD52085.2021.9429376>
- [33] Murty, V. V. V. S. N., & Kumar, A. (2020). Optimal Energy Management and Techno-economic Analysis in Microgrid with Hybrid Renewable Energy Sources. *Journal of Modern Power Systems and Clean Energy*, 8(5), 929–940. <https://doi.org/10.35833/MPCE.2020.000273>.
- [34] F. Z. Kadda, S. Zouggar, M. E. Hafyani, and A. Rabhi, "Contribution to the optimization of the electrical energy production from a Hybrid Renewable Energy system," 2014 5th International Renewable Energy Congress (IREC), Mar. 2014.
- [35] Murty, V. V. V. S. N., & Kumar, A. (2020). Optimal Energy Management and Techno-economic Analysis in Microgrid with Hybrid Renewable Energy Sources. *Journal of Modern Power Systems and Clean Energy*, 8(5), 929–940. <https://doi.org/10.35833/MPCE.2020.000273>.
- [36] S. Rehman, H. U. R. Habib, S. Wang, M. S. Buker, L. M. Alhems, and H. Z. Al Garni, "Optimal Design and Model Predictive Control of Standalone HRES: A Real Case Study for Residential Demand Side Management," *IEEE Access*, vol. 8, pp. 29767–29814, 2020.
- [37] O. Erdinc and M. Uzunoglu, "Optimum Design of Hybrid Renewable Energy Systems: Overview of Different Approaches," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 3, pp. 1412–1425, Apr. 2012.
- [38] M. Kumar, "SPV Based DC Microgrid under Partial Shading Condition with Battery-Part 2: Energy Management System," 2018 8th IEEE India International Conference on Power Electronics (IICPE), 2018, pp. 1-6.
- [39] K. T. Ahmed, A. Merabet, R. Beguenane, H. Ibrahim and A. Allagui, "Real-time Platform for Controlling DC Microgrid Based Standalone Solar Energy Conversion System," 2016 International Conference on Industrial Informatics and Computer Systems (CIICS), 2016, pp. 1-5.
- [40] M. K. Deshmukh and S. S. Deshmukh, "Modeling of Hybrid Renewable Energy Systems," *Renewable and Sustainable Energy Reviews*, vol. 12, no. 1, pp. 235–249, Jan. 2008.
- [41] L. Li, Y. Ren, M. Alsumiri, J. Brindley and L. Jiang, "Maximum Power Point Tracking of Wind Turbine Based on Optimal Power Curve Detection Under Variable Wind Speed," *International Conference on Renewable Power Generation (RPG 2015)*, 2015, pp. 1-6.
- [42] Z. M. Dalala, Z. U. Zahid, W. Yu, Y. Cho and J. -S. Lai, "Design and Analysis of an MPPT Technique for Small-Scale Wind Energy Conversion Systems," in *IEEE Transactions on Energy Conversion*, vol. 28, no. 3, pp. 756-767, Sept. 2013.
- [43] Z. M. Dalala, Z. U. Zahid and J. Lai, "New Overall Control Strategy for Small-Scale WECS in MPPT and Stall Regions with Mode Transfer Control," in *IEEE Transactions on Energy Conversion*, vol. 28, no. 4, pp. 1082-1092, Dec. 2013.

- [44] Y. Xia, K. H. Ahmed and B. W. Williams, "A New Maximum Power Point Tracking Technique for Permanent Magnet Synchronous Generator Based Wind Energy Conversion System," in *IEEE Transactions on Power Electronics*, vol. 26, no. 12, pp. 3609-3620, Dec. 2011.
- [45] H. Ramadan, A.-R. Youssef, H. H. H. Mousa, and E. E. M. Mohamed, "An Efficient Variable-Step P&O Maximum Power Point Tracking Technique for Grid-Connected Wind Energy Conversion System," *SN Applied Sciences*, vol. 1, no. 12, Nov. 2019.
- [46] A. J. Mahdi, W. H. Tang, and Q. H. Wu, "Derivation of a Complete Transfer Function for a Wind Turbine Generator System by Experiments," 2011 *IEEE Power Engineering and Automation Conference*, Sep. 2011.
- [47] A. Sachan, A. K. Gupta, and P. Samuel, "A Review of MPPT Algorithms Employed in Wind Energy Conversion Systems," *Journal of Green Engineering*, vol. 6, no. 4, pp. 385–402, 2017.
- [48] Y. Krim, D. Abbes, S. Krim, and M. F. Mimouni, "Fuzzy Droop Control for Voltage Source Inverter Operating in Standalone and Grid Connected Modes," 2018 *15th International Multi-Conference on Systems, Signals & Devices (SSD)*, Mar. 2018.
- [49] M. U. Jan, A. Xin, M. A. Abdelbaky, H. U. Rehman and S. Iqbal, "Adaptive and Fuzzy PI Controllers Design for Frequency Regulation of Isolated Microgrid Integrated With Electric Vehicles," in *IEEE Access*, vol. 8, pp. 87621-87632, 2020.
- [50] B. Liu, F. Zhuo, Y. Zhu and H. Yi, "System Operation and Energy Management of a Renewable Energy-Based DC Micro-Grid for High Penetration Depth Application," in *IEEE Transactions on Smart Grid*, vol. 6, no. 3, pp. 1147-1155, May 2015.
- [51] H. S. V. S. K. Nunna, S. Battula, S. Doolla and D. Srinivasan, "Energy Management in Smart Distribution Systems With Vehicle-to-Grid Integrated Microgrids," in *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 4004-4016, Sept. 2018.
- [52] F. Miyagishima, S. Augustine, O. Lavrova, H. Nademi, S. Ranade and M. J. Reno, "Maximum Power Point Tracking and Voltage Control in a Solar-PV based DC Microgrid Using Simulink," 2021 *North American Power Symposium (NAPS)*, 2021, pp. 1-4.
- [53] R. Dharavath and I. Jacob Raglend, "Integration of Solar Photovoltaic with Battery Storage for Power Conditioning of Dynamic Loads," 2019 *Innovations in Power and Advanced Computing Technologies (i-PACT)*, 2019, pp. 1-6.