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Modeling and Simulation of Energy Storage Performance of Renewable Energy Storage System

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

In recent times, there has been a notable increase in attention towards the reduction of greenhouse gas emissions and the enhancement of energy security. Over the past decade, there has been a significant increase in the incorporation of intermittent renewable energy sources (RESs), such as photovoltaic (PV) and wind energy, into the existing power system. However, the integration of this system hinders the reliable and steady running of the grid due to many operational and control challenges. Several challenges exist, including generation uncertainty, voltage and angular stability, power quality issues, reactive power support, and fault ride-through capabilities. The electricity produced by renewable energy sources (RESs) exhibits fluctuations due to meteorological phenomena beyond human control, such as wind speed and sunlight intensity. Energy storage systems (ESSs) play a crucial role in mitigating volatility by effectively storing excess electricity generated and facilitating its availability when needed. This study utilises the MATLAB/Simulink programme to develop an optimised configuration model for the wind hybrid power storage system.

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1. INTRODUCTION

The utilisation of renewable energy sources has led to a substantial decrease in reliance on hydrocarbons for power generation and transportation. According to Hargreaves and Jones [1], the integration of renewable energy generation into the power grid can be achieved through two distinct operating modes: grid-connected mode and islanded mode. Renewable energy sources play a substantial role, accounting for around 14.8% of the overall energy demand in industrial sectors, particularly in industries that necessitate low-temperature processes. Nevertheless, it is imperative to recognise that the integration of renewable energy sources in sectors characterised by significant energy consumption, such as cement, steel, and chemicals, remains limited, constituting merely a fraction of their overall energy requirements. At now, a variety of energy sources, such as electricity, solar energy, wind energy, and nuclear energy, are employed to meet the power requirements of load systems in various locations globally. It is important to highlight that the utilisation of alternative energy sources in fulfilling the global energy requirements is currently below 1% [2].

The operational efficiency of the electrical grid is negatively affected by the variability of green energy sources, particularly in terms of grid stability, reliability, and power quality [3,4]. The main obstacle to the widespread integration of green energy sources into the current system is the unpredictable and uncertain nature of power generation. Energy storage systems (ESS) are essential in addressing grid fluctuations by separating electricity supply from demand. Additionally, the integration of ESS improves the power quality of the electrical grid by providing ancillary services [5]. As the integration of renewable energy sources into the power grid is projected to increase, the demand for energy storage is expected to rise accordingly.

Hossain et al. [6] assert that energy storage systems (ESS) hold significant importance as technological solutions across diverse industries, spanning both established and new applications. These applications encompass a wide array of domains, including personal grooming, electric vehicles, the incorporation of green energy sources, and various other fields. Energy storage systems (ESS) are of paramount importance in enhancing the dependability of the electrical grid. Alternative forms of energy offer a dependable and consistent energy supply, while also offering a diverse array of beneficial functions such as load balancing, load levelling, energy augmentation, quality enhancement, and the reduction of power fluctuations. The integration of renewable energy sources, such as wind power, is often accompanied with the implementation of large-scale energy storage systems (ESSs) in order to improve the dependability of electricity generation. Poullikkas [7] conducted a comprehensive analysis of several energy storage technologies used for the integration of plentiful renewable energy sources into the power grid. The integration of Energy Storage Systems (ESS) with renewable energy sources greatly enhances the possibilities for attaining carbon neutrality within the energy industry. The incorporation of high-quality and sustainable energy storage systems (ESS) is poised to exert a substantial influence in mitigating the adverse environmental consequences associated with conventional energy sources.

This study presents a comprehensive theoretical foundation for a hybrid wind energy storage system that incorporates the integration of batteries and capacitors. The power output of the hybrid energy storage system is initially improved through the integration of a fuzzy control system that combines Maximum Power Point Tracking (MPPT) and Hybrid Particle Swarm Optimisation (HPSO) approaches. The increased effectiveness of the wind system is further supported by the use of a MATLAB simulation model, which is then incorporated into real-world applications. The technology stated above demonstrates a significant level of adaptability in terms of energy distribution. The deployment of a grid-connected hybrid system enables the efficient use of wind and solar energy resources by including their storage capacities. Furthermore, the utilisation of the conductance fuzzy dual-mode control technique enhances the observation of the network distribution curve and output power curve [8,9]. There has been a significant reduction in the financial outlay involved with energy storage devices. This phenomenon not only leads to favourable environmental consequences but also contributes to economic benefits.

1.1The Need for Energy Storage

The disparity in energy consumption during peak and off-peak periods can be ascribed to a combination of various demand patterns and meteorological conditions. In light of the potential for energy production to exceed the aggregate demand, it may be imperative to procure additional energy reserves during periods characterised by low demand. The presence of discontinuity in renewable energy sources (RES) gives rise to a significant worry over the disparity between power supply and demand [10]. The integration of advanced renewable energy sources has significant consequences for the reliability of conventional systems. The grid system's stability could potentially be endangered when the proportion of intermittent renewable energy sources surpasses 20% of the total energy supply. Zhang et al. (2018) argue that the integration of large-scale energy storage systems (ESS) holds promise in mitigating the inherent limitations and inefficiencies frequently encountered in conventional power networks. Moreover, it has the potential to facilitate the smooth incorporation of renewable energy sources into the current energy framework. In general, Energy Storage Systems (ESS) possess the capacity to augment the stability and efficacy of the power grid, attain equilibrium between supply and demand, and alleviate power interruptions and environmental contaminants. Energy storage systems (ESSs) have the potential to be charged during periods typified by low net demand and discharged during periods of high demand. This attribute allows them to take advantage of discrepancies in energy prices, therefore improving the overall load factor. As a result, there is potential to decrease the dependence on generators, which are frequently associated with high costs, while concurrently promoting the widespread adoption of renewable energy sources. To substantiate this claim, it is crucial to utilise advanced forecasting and control methodologies, while assuring the seamless incorporation of demand-side flexibility. Zhu et al. (2020) presented a unique methodology that incorporates a capacitor hybrid energy storage system to improve the energy storage capacities of a wind-solar hybrid energy storage system connected to the grid. The implementation of this particular technique results in a significant enhancement in both the system's energy storage capacity and power output. The major objective of the study conducted by Wen et al. (2020) is to examine a hybrid energy storage system that combines hydrogen battery technology with a wind power grid, aiming to achieve seamless integration. A proposal has been put forth to deploy a hybrid energy storage system that integrates batteries and hydrogen storage as a potential remedy for the difficulties faced in connecting wind farms to the power grid. In their study, Li et al. (2015) utilised a unique model for battery life to examine the potential extension of battery life in a hybrid battery and SME (Superconducting Magnetic Energy) storage system. The aim of their investigation is to optimise the overall system performance and reduce system costs through the extension of battery life.

2. METHODOLOGY

The system architecture of the wind hybrid energy storage system is introduced in this section. Additionally, mathematical models for wind turbines, capacitors, inverter and converter output power are provided.

2.1 Structure of the System

Fig. 1 depicts the hybrid energy storage system employed in wind energy applications. The configuration comprises a hybrid energy storage system, a converter, DC and AC busbars, and a wind turbine (Zhang et al., 2014). As stated by Zekai (2013), the distributed generating system generates electrical energy which is subsequently sent by the DC bus to the converter, where it undergoes conversion into alternating current (AC). To ensure a steady and dependable supply of electrical power to both the load and the grid, the utilisation of a hybrid energy storage system is employed for efficient regulation of energy flow (Sandhu and Mahesh, 2016).

2.2 Wind Turbines

The study of the data has led to the determination that the dataset being examined can be appropriately modelled using the Weibull distribution (Yao & Ma, 2012). Therefore, the Weibull distribution is utilised to assess the probability density function of the wind speed data. The mathematical representation of the Weibull distribution is shown herein:

$$\phi_w = \left(\frac{k}{v}\right)\left(\frac{v}{c}\right)^{k-1} e^{-\left[(v/c)^k\right]}. \tag{1}$$

$$\phi_w = 1 - e^{-\left[(v/c)^k\right]}, \quad (k > 0, c > 1). \tag{2}$$

In the HOMER simulation program, the value for the output power P_{rwind} is determined using a linear interpolation calculation, as depicted in the equation provided below:

$$P_{\text{rwind}} = \begin{cases} P_0 + V\dfrac{P_1 - P_0}{V_1}\,(0 < V < V_1), \\ P_1 + V\dfrac{P_2 - P_1}{V_2 - V_1}\,(V_1 < V < V_2), \\ \vdots \\ P_n + V\dfrac{P_n - P_{n-1}}{V_n - V_{n-1}}\,(V_{n-1} < V < V_n). \end{cases} \quad (3)$$

2.3 Capacitors

Throughout the duration of this investigation, the capacitance values and voltages are linked to both the anode and cathode of the capacitor. The mathematical operation of integrating the function Pc(t) with respect to t, symbolised as W, quantifies the change in energy stored in the capacitor inside the comparable circuit between the time instances t(n-1) and t(n+1). The fluctuation in energy of the capacitor can be visually represented in the following manner:

$$\Delta W = \frac{1}{2}u_c^2(t_{n+1})\cdot C(t_{n+1}) - \frac{1}{2}u_c^2(t_{n-1})\cdot C(t_{n-1}) = \int_{t_{n-1}}^{t_{n+1}} P_C(t)\mathrm{d}t. \quad (4)$$

u_c (t) is capacitor voltage. The series resistance of the capacitor is R_s. The sedate value for the capacitor is as seen by $C_{(t)}$. $Us_{(t)}$ is the series resistance voltage. Fig. 1 illustrates how the total instantaneous power and the instantaneous resistance power are used to describe the instantaneous power of the capacitor.

$$P_C(t) = u(t)\cdot i(t) - i^2(t)\cdot R_s. \quad (5)$$

Simpson's Rule is used to compute the integration.

$$\Delta W = \frac{1}{2}[u_c(t_{n+1}) - R_s i(t_{n+1})]^2\cdot C(t_{n+1}) - \frac{1}{2}[u_c(t_{n-1}) - R_s i(t_{n-1})]^2\cdot C(t_{n-1}). \quad (6)(7)$$

Rs is constant, and u and i can be measured.

2.4 Battery Output Power

Based on the investigation, it can be determined that the principal source of power for the load is obtained from the inverted power of the battery. The output power of the inverter is commonly referred to as Pout, whilst its input power is typically marked as Pin. As a result, the efficiency can be estimated by utilising the subsequent equation.

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}}. \quad (8)$$

$$P_{\text{in}} = P_{\text{out}} + P_{\text{ioss}} = p_0 + kp^2. \quad (9)$$

$$\eta = \frac{p}{p + p_0 + kp^2} = 1 - \frac{p_0 + kp^2}{p + p_0 + kp^2}. \quad (10)$$

$$p_0 = \frac{9}{11}\left(\frac{10}{9\eta_{10}} - \frac{1}{9\eta_{100}} - 1\right)^2. \quad (11)$$

$$k = \frac{1}{\eta_{100}} - p_0 - 1. \quad (12)$$

2.5 Converters

Converters possess the capability to transform electrical power from an alternating current (AC) bus to a direct current (DC) bus. The bidirectional converter is defined as follows:

$$P_{\text{con,AC}} = \begin{cases} R_{\text{inv}}\cdot\eta_{\text{inv}}, & P_{\text{con,DC}} > R_{\text{inv}}, \\ P_{\text{con,DC}}\cdot\eta_{\text{inv}}, & 0 < P_{\text{con,DC}} < R_{\text{inv}}, \\ \dfrac{P_{\text{con,DC}}}{\eta_{\text{rec}}}, & -R_{\text{rec}} < P_{\text{con,DC}} \le 0, \\ \dfrac{R_{\text{rec}}}{\eta_{\text{rec}}}, & P_{\text{con,DC}} < -R_{\text{rec}}. \end{cases} \quad (13)$$

The power on the alternating current (AC) side is indicated as P_{con}, AC. A positive value indicates power inversion, while a negative value indicates power rectification. The total power on the direct current (DC) side is denoted as P_{con}, DC. The maximum power allowed during rectification, which represents the maximum capacity, is denoted as R_{rec}.

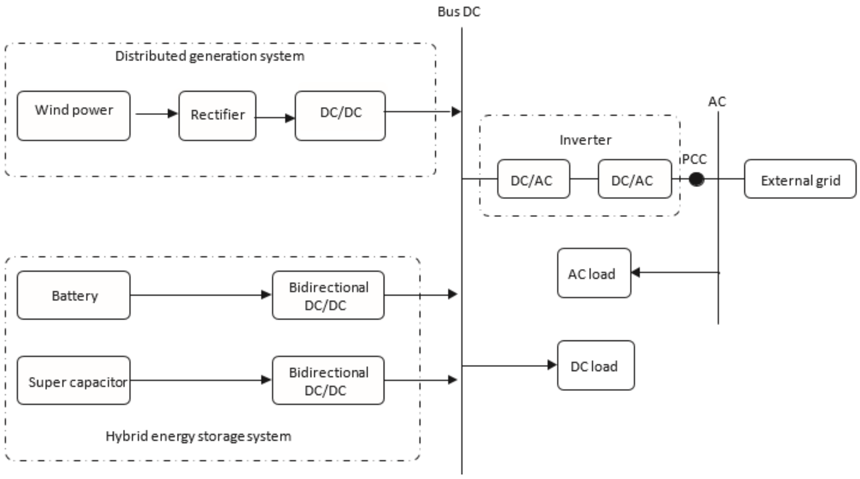

Fig. 1. Wind hybrid energy storage generation system

3. RESULTS

In order to assess the efficacy and practicality of the suggested control methodology, a load surge simulation is performed on a wind-solar complementing framework that is connected to the grid. The framework is constructed using MATLAB/Simulink. The parameters for the sun map and boost chopper circuit have been established as follows: The wind speed exhibited a range of 9 m/s to 10 m/s before subsequently returning to its initial value of 9 m/s. The circuit exhibits an input and output capacitance of 600 microfarads, an inductance of 6 millihenries, and a battery resistance of 27 ohms. Figs. 1 and 2 demonstrate that the utilisation of the optimised wind control period results in a more rapid attainment of the intended state in comparison to the traditional control epoch frame. The reduction in oscillation suggests an improvement in the precision and speed of tracking the optimised frame. Fig. 3 illustrates that under certain control settings, the optimised wind-solar complementary system achieves performance consistent with the test values when the focused light intensity is 1000W/m2 and the wind speed is 8m/s. The system reaches a fail-safe state in around 0.16 seconds. The control of the photovoltaic system requires around 0.05 seconds to achieve the fail-safe state. On the other hand, it is worth noting that a conventional wind control system exhibits a time delay of approximately 0.115 seconds before achieving a stable state. However, it is important to highlight that the resulting inaccuracy in this system is approximately 0.23%, which is notably larger compared to the two aforementioned methods. The wind-solar complementing framework, when effectively controlled, leads to extended periods of steady-state operation with less variations. At a time interval of 0.3 seconds, the prevailing wind speed in the surrounding environment undergoes a change, namely an increase, from 8 metres per second to 10 metres per second. Concurrently, the control curves of the two frames demonstrate differing levels of variation. The wind-solar replenishment frame, when optimised, has a steady state recovery time of roughly 0.073 seconds. This optimised frame also demonstrates improved gear shifting speed and reduced variationsOn the other hand, the conventional wind control time frame demonstrates a time length of 0.09 seconds to achieve a state of coherence, accompanied by significant modifications in the curve. At a time interval of 0.6 seconds, there is an observed fluctuation in the overall intensity of light, characterised by both an increase and subsequent reduction.

The range of values for solar irradiance is between 1000 and 600 W/m2. Following the optimisation process, it is typically observed that the wind-solar complementing framework requires approximately 0.05 seconds to achieve a stable state. The aforementioned error is four times larger in magnitude compared to the optimal wind-solar integration system, with a duration of around 0.089 seconds. The two yield control bends exhibit distinct variations. At time t=1s, the brightness of the surrounding environment increases from 600 W/m2 to 800 W/m2, while the wind velocity decreases from 10 m/s to 8 m/s. In order to achieve a stable condition, traditional control photovoltaic systems are utilised to optimise the time required for the wind-solar hybrid system to reach equilibrium. The process of wind management necessitates a

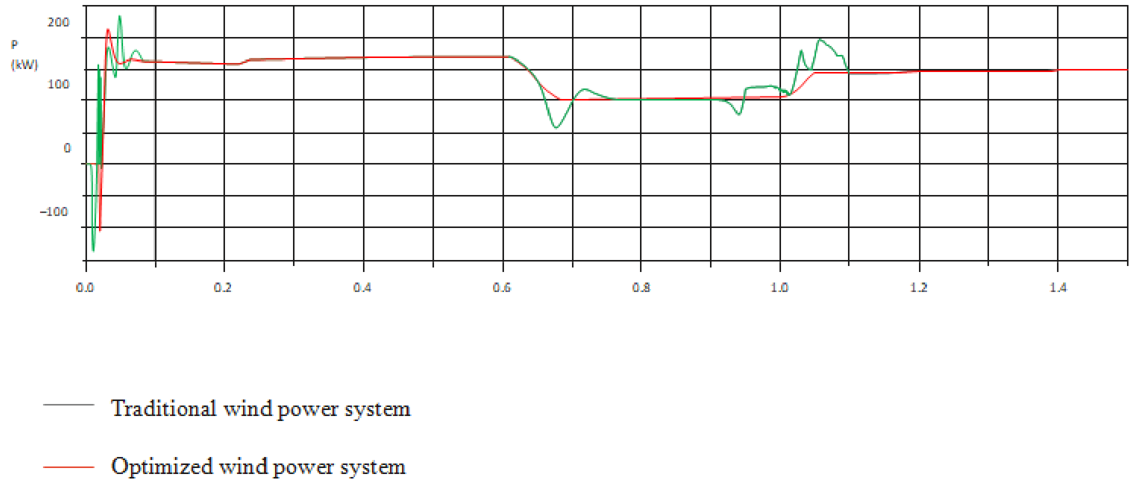

Fig. 2. Output power of traditional and optimized wind turbines

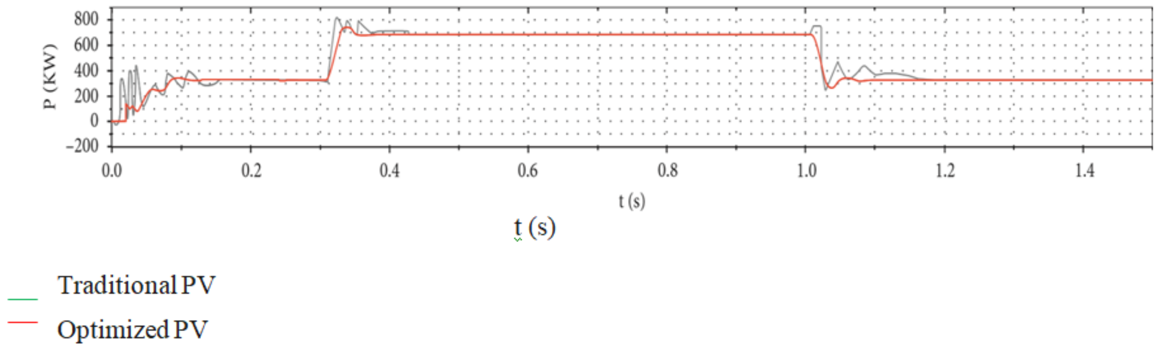

Fig. 3. Power output comparison between traditional and improved solar generators

similar duration to attain a condition of equilibrium, although its generation curve experiences significantly less fluctuation in comparison to the other two ways. Upon acknowledging the aforementioned proposition, it becomes evident that the power output fluctuation curve of the wind-solar hybrid system exhibits a notable reduction in comparison to both a traditional wind power system and a normal photovoltaic system. Furthermore, the power output fluctuation curve exhibits a progressive rise in smoothness when the amount of optimisation is enhanced. When doing a comparison between the complimentary framework and the two alternative options for single-power production, it becomes evident that the typical duration of subsequent operations can be prolonged by around 90%. Consequently, the optimal implementation of the wind-solar complementary system is prevalent.

4. CONCLUSION

This study examined a model for the development of wind energy storage. The optimisation of the wind storage system's capacity is achieved through a systematic step-by-step procedure, which involves the utilisation of a capacitor energy storage device. The utilisation of the conductance-fuzzy dual-mode control technique and the static wind adjustment system is employed in order to optimise energy storage capacity and enhance power stability. The ideal configuration model of the hybrid energy storage system is generated and tested using MATLAB. The subsequent information presents the principal discoveries:

1. The present study investigates the effectiveness of the conductivity amplification technique in improving particle cluster performance. Additionally, the implementation of conductivity-fuzzy dual-mode control and classic fuzzy control methods are examined. The simulations and validations are conducted under varying degrees of light intensity. The results suggest that the use of the conductivity fuzzy dual-mode control strategy leads to a faster and more

accurate attainment of a stable state. Moreover, the programme optimises battery durability and reduces energy consumption.

2. The incorporation of a static wind modification equipment can effectively enhance voltage stability inside a wind farm by mitigating the adverse effects of power fluctuations. The utilisation of MATLAB/Simulink simulation has provided evidence that the power output curve of a wind power generation system equipped with a static wind adjustment device exhibits a lower magnitude in comparison to a conventional wind power generation system. This implies that variations in wind speed result in more pronounced and quick fluctuations in the power output of the wind farm.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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