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Coordinated Control of Wind turbine and Energy storage system for Microgrid Stability

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Abstract

In recent decades, the development of renewable energy has accelerated significantly due to several factors such as changing energy needs, the problem of global warming, and the depletion of fossil fuels. Wind energy is one of the renewable generation sources that can be used to achieve the EU's 2030 targets at a lower cost. However, its intermittent and stochastic nature could significantly impact the reliability and stability of the electricity system. Therefore, there is a clear necessity to mitigate power fluctuations to make the most of wind energy. To fill this gap, this paper presents a centralized control strategy based on a droop controller and a storage-integrated controller for a grid-connected variable speed wind power system (permanent magnet synchronous generator) (PMSG) to manage and stabilize the power output during intermittency periods. The main objective is to provide a stable U/f when a fluctuation event occurs. A grid failure scenario was tested to see how the control system behaves in the event of an unexpected fluctuation and its role in the stability of the power system under varying wind speed and load conditions. The effectiveness of the proposed control method was tested using MATLAB/Simulink on a small power system. The simulation results demonstrate the control system's performance in the stability of the U/f during grid interruption.

Keywords: Droop Control, Energy Storage system, Wind turbine, Microgrid.

1. Introduction

Following the EU's 2030 directives, which call for a 40% reduction in greenhouse gas emissions, a 32% improvement in energy efficiency, and a minimum of 32% renewable energy in final consumption, many countries around the world are adopting new strategies to meet these targets. Among the different energy sources [1], wind energy is the one that is attracting the most attention from governments, universities, utilities, and industry. Today, wind energy is a mature and reliable technology with significant development potential worldwide. This resource has many advantages such as being 100% natural, renewable and sustainable energy, this energy is not subject to any risk of shortage, unlike the underlying fuel energies (nuclear, thermal...) but despite its advantages, its power fluctuates due to variations in wind speed, which can have serious repercussions on the stability and the grid performance.

For wind energy conversion systems (WECS), there are many fixed and variable speed wind turbines in the world [2], [3]. The WECS can provide a high-efficiency drive. To this end, several research studies show that a variable speed wind turbine using a PMSG with back-to-back converters is very promising [4]. There are several control methods for wind turbines, for example, in [5] A new control strategy has been implemented for a grid-connected variable speed wind energy system. The currents in the machine are controlled using an indirect vector control technique. The further study provided in [6] a new contribution to wind power system control, a resilient nonlinear active and reactive power control using an Adaptive Backstepping approach based on a dual-fed induction generator is employed, and the system's stability is proved using the Lapugnoy technique. The functional analysis of a small wind power system with a variable speed permanent magnet synchronous generator (PMSG) and a lead-acid battery (LAB) for residential applications was performed by Barote et al in reference [7]. The effectiveness of four various types of energy storage systems to minimize wind power oscillations, particularly at low wind speeds, is examined in Reference [8]. It also describes the battery's working mechanism and different charging and discharging procedures. Other researchers presented in [9] a fuzzy model to explain a wind turbine whose power is regulated by altering the blade angle of attack and turning the nacelle upwind. Reference [10] proposes a grid interface system for wind turbines that uses a permanent magnet synchronous generator (PMSG). A bridge between the generator and the grid is formed by integrating a three-switch buck rectifier on the generator side and a Z-source inverter on the grid side. Thus, the use of robust wind turbine control algorithms is desirable for both stabilization and monitoring. The chosen control must be robust, in the sense that it must ensure low sensitivity to disturbances. Indeed, the use of conventional control techniques for this type of system is probably not the best approach. This has led to advanced control techniques such as sliding mode control [11], backstepping control [12], and predictive control [13].

The above articles and many others in the literature have not all included the integration of an energy storage system with a droop controller to eliminate unexpected fluctuations and maximize the reliability of the energy supply. An ESS is designed to mitigate the impact of wind turbine variations by providing a fast response time and high performance. To overcome the shortcomings of conventional techniques, we focused on developing a technique for controlling a PMSG wind turbine using an energy storage system and droop control technique. The battery-based energy storage system is fed by a bidirectional DC converter and is connected to the DC link of the PMSG's back-to-back power converters.[14]. The control system ensures that excess wind energy is stored in the batteries when the generator speed increases [15-16]. In addition, in the case of wind speed changes, the energy storage system integrated into PMSG wind turbine systems can be used to boost the generator's output within the capacity of the energy storage system.

2. Description System

The research presented in this work is for a variable-speed wind power system (Permanent Magnet Synchronous Generator (PMSG)) and an energy storage system, as indicated in Figure 1. The structure includes a diode rectifier bridge, a DC-DC boost converter equipped with an MPPT controller to maximize the output power of the wind turbine and adjust the speed of the generator according to the wind speed. The DC bus is connected to a DC-DC converter and the input of the voltage source inverter (VSI) to ensure fast energy transfer.

A variable residential load is fed from the wind farm and the grid when the wind farm is disconnected. The ESS is made up of a DC-DC buck/boost converter that is connected to the back-to-back converters' DC link. A transformer connects the wind-battery system to the power grid.

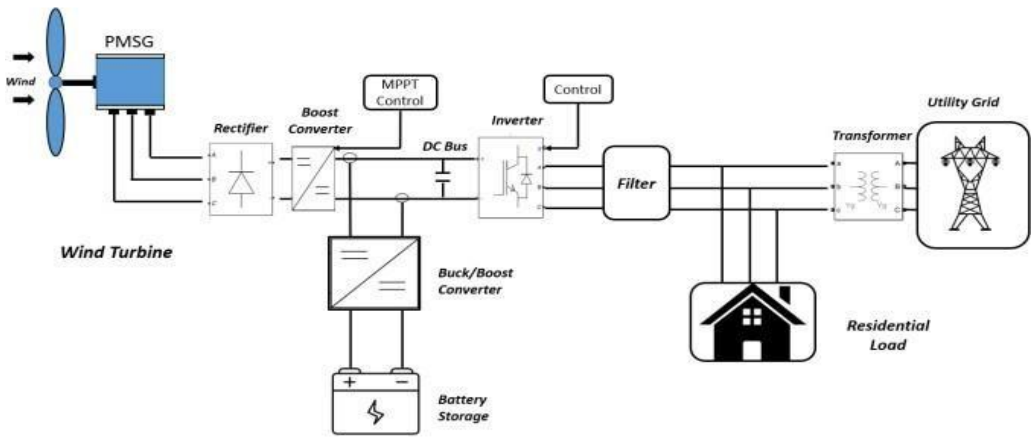

Fig 1. Configuration of PMSG wind turbines using ESS

2.1 Energy Storage System (ESS)

Renewable generation systems, such as solar photovoltaic (PV) and wind power, have a major impact on clean energy production. Due to the intermittent nature of these resources, and energy storage system (ESS) is integrated to provide sustainable energy, particularly when operating in standalone mode.[16]. The integration of an ESS into a wind energy system ensures better voltage and frequency response, especially during wind and load variations. The relationship between battery power (%) and battery SOC can be formulated as follows:

$$SOC(t_1) = \frac{1}{C_{BAT}} \int_{t_0}^{t_1} P_{BAT}(\tau) d\tau + SOC(t_0) \tag{1}$$

Where; C_{BAT} is the battery capacity (kWh), and $SOC(t_0)$ is the battery SOC at initial time t_0 For simplicity, the battery power is considered linear concerning the variation of the battery SOC, and the memory effect is ignored. However, the optimization methods in this paper are still applicable to other SOC models. In this paper, the energy storage system (ESS) consists of a lead-acid battery and a bi-directional buck-boost DC-DC converter connected to the microgrid back-to-back converters' DC connection as illustrated in Figure 2.

This converter aims to maintain a constant DC link voltage despite changes in source and load power. The DC link voltage is controlled by a PI control strategy. The system operates in buck or boost mode, depending on the supply voltage conditions of the wind turbines. Due to the variation of the supply voltage, the system can switch from buck to buck-boost mode and back to boost mode.

The inverter control system compares the reference value of the VDCref voltage with the current-voltage available on the DC bus, and through a PI controller, it generates an ibatref. The battery reference current is then compared to the ibat current to generate the switching signals (boost). If the current state of charge of the battery is below the SOC max, the inverter operates in Buck mode. Otherwise, if the battery's state of charge is maximum, the inverter will program the battery to discharge.

As a result, the ESS is turned on to absorb the different energy between the generator and the grid to maintain the DC link voltage.

2.2 Control System strategy

This paper presents a reliable and robust grid interface system for wind turbines using a permanent magnet synchronous generator (PMSG). In addition, since wind power and load are variable, an energy storage device is required to cope with the load disparity [14], [15].

The control system uses voltage-oriented control to decouple active and reactive power regulation and optimizes PMSG control for grid-side and generator-side converters independently. The wind speed profile is passed through a low-pass filter (LPF) to minimize high frequencies caused by rapid speed fluctuations, avoid abrupt speed changes, and operate the wind turbine in a safe location. The backup converter adjusts the electromagnetic torque in response to wind speed to get the most out of the available wind resource.

The droop characteristics are governed by the droop constants, which are implemented by the inverter control block. The values Pref and Qref are given as inputs to the droop control block to compensate for voltage and frequency deviations. This ensures that the frequency and voltage remain close to their set values. The simplified model of the wind power system is given by an injected power source with its P/Q control. This control's goal is to force the active and reactive power outputs to match the setpoints Psp and Qsp, respectively. In reality, Psp is determined by the MPPT of the wind turbine and Qsp is zero. The operation of this model is illustrated in (Fig 3). The two-block proportional integrals (PI) play a role in controlling the active and reactive power at their reference values. The inverter is synchronized with the grid using a robust phase-locked loop (PLL) and the LC filter at the output of the inverter is used to reduce the inverter current harmonics [17-18]. The droop control is given by the following relationships:

$$V_{inv} = V^{*} - nP \tag{2}$$

$$W = W^{*} - mQ \tag{3}$$

The instantaneous current compensator receives the instantaneous grid voltage, the state of the G switch, and the reference currents DQ from the wind turbine to generate a delta-d, delta-q compensation command. This block analyses the source voltage and current based on the concept of instantaneous value. The reactive (or imaginary) instantaneous value is determined at a given time and, consequently, the corresponding value of the compensation current. This allows instantaneous compensation (i.e., instantaneous compensation of reactive power using switching devices). When the state of charge of the battery is lower than SOCmax and I wind-DC is higher than Iref, the difference is used to charge the battery when the grid is disconnected. Then the generated voltages Vdref and Vqref are compared and adjusted by the current and voltage loops to obtain the voltages Vd and Vq needed to control the inverter. The three-level pulse generator with PWM converts the voltage outputs Vd and Vq of the current regulator into triple modulation signals Uref. The control block diagram of a PMSG wind turbine is shown in (Fig 2).

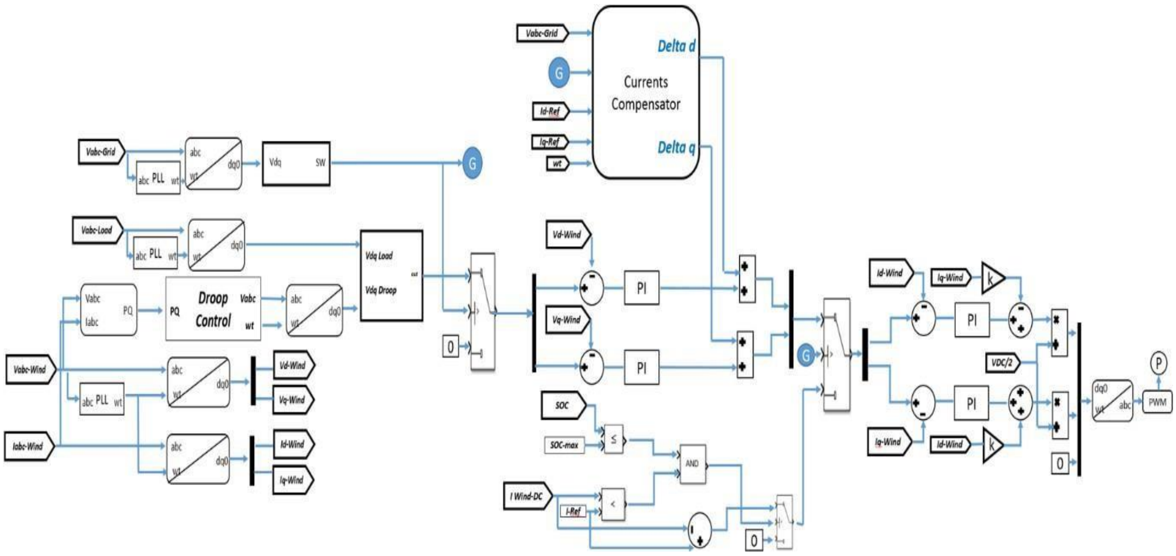

Fig 2. Control block diagram of PMSG

3. Results and discussion

The simulation model of the proposed topology is presented in (Fig 1). The Matlab Simulink simulation tool was used to obtain the required results for the variable speed PMSG system with battery energy storage. The simulation time step used was 4 seconds to capture the actual behavior of the system components. The performance of the proposed control system is investigated under varying load and wind speed conditions (Fig. 3). The system parameters are shown in Table 1.

Table 1. PMSG parameters

Symbol	Description	Value	Unit
P_{WT}	Wind turbine rated power	200	KW
P_L	Load rated power	300	KW
P_{BAT}	Battery rated power	60	KWh
T	Time	4	S

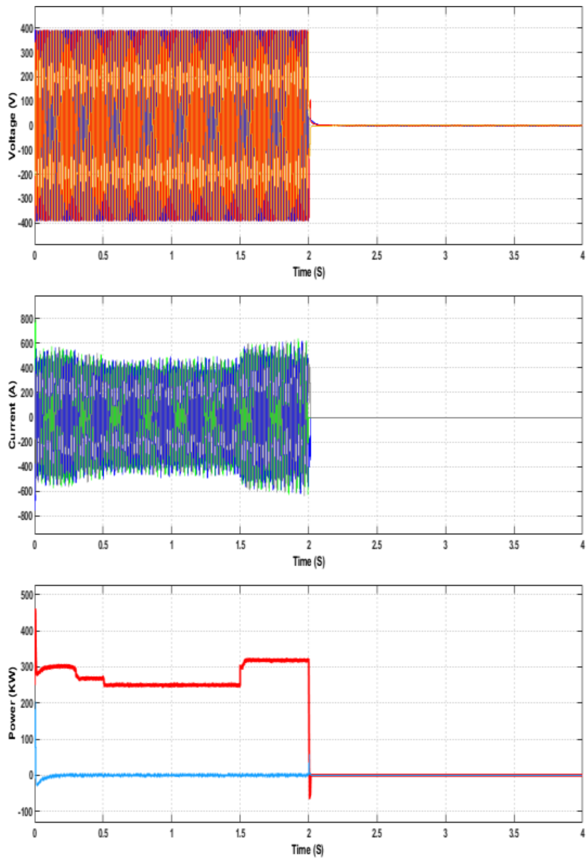

Fig 4. (a) Grid voltage. (c) grid current (b) grid power

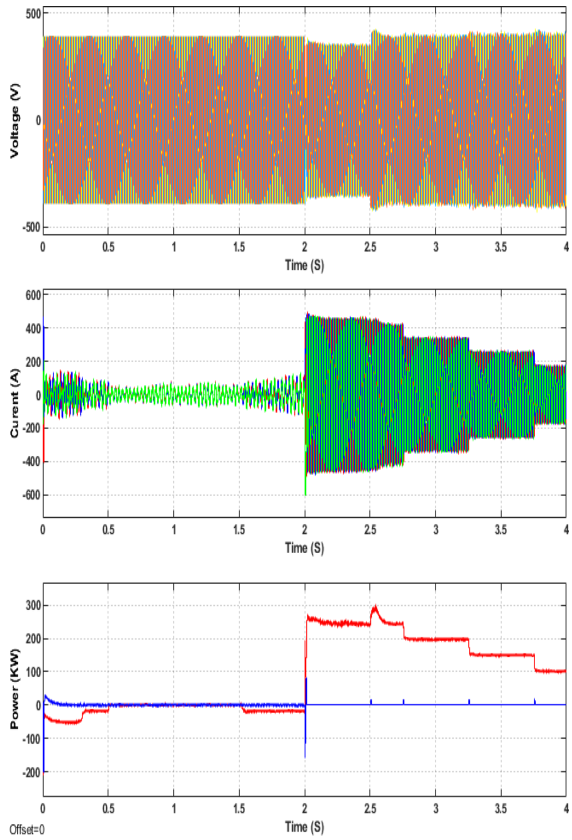

Fig 5. (a) Wind turbine voltage. (c) Wind current (b) Wind and ESS power

Figure 4 shows the behavior of the wind-grid-ESS system in terms of voltage (a), current (b), and power (c) versus time. It can be seen that when the system operates in grid-connected mode, the load demand is met by the grid, and the storage system is charged by the wind generation as shown in Figure 5. From 0 to 2s, it can be seen that the voltage is stable and the current fluctuates (due to load variations). In this case, the grid stabilizes the voltage, and the wind system charges the batteries. When an event occurs, at t=2s the microgrid is disconnected from the grid, so the wind system feeds the load and the batteries start to discharge to ensure system stability and compensate for unexpected fluctuations. It can be seen that there is a slight voltage fluctuation on the load side caused by the islanding of the grid. It can also be seen that the wind weather intermittency does not disturb the load side voltage, and the system operating frequency is regulated within its nominal value. Figure 4 shows the variation of the load voltages and currents, as well as the generator power as a function of time. It can be seen from (Fig.4.c) that the wind system charges the battery from 0 to 0.5s and from 1.5 to 2s to be able to ensure the stability of the power supply during the islanding. It can also be seen that the voltage remains stable despite the disconnection from the grid. The variation of the Iwin-DC current with time and the state of charge of the battery during the change of scenario are shown in (Fig 6) and (Fig 7). We can conclude that the role of the SSE is to absorb the maximum power of the PMSG when the wind speed exceeds certain limits to control the unexpected fluctuations of the wind generation and the grid. However, the terminal voltage and frequency remain constant regardless of the variation. It can also be observed that the control system implemented ensures the stability of the parameter (voltage and frequency) during the wind variation. This combined control strategy of a droop controller and a storage system has improved the results obtained by conventional methods. This demonstrates the effectiveness of the technique developed to smooth the power supplied to the grid and stabilize the frequency and voltage. However, the control system is still in an under-generation situation where the power deficit is filled by battery storage. The simulation results show that the integrated energy generation and storage system can provide a constant power output when the wind speed changes.

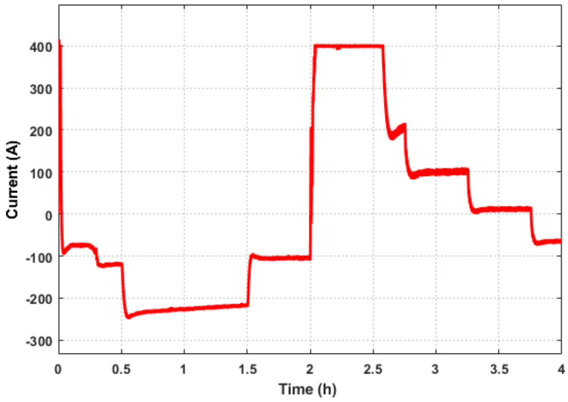

Figure.6 ESS current variation

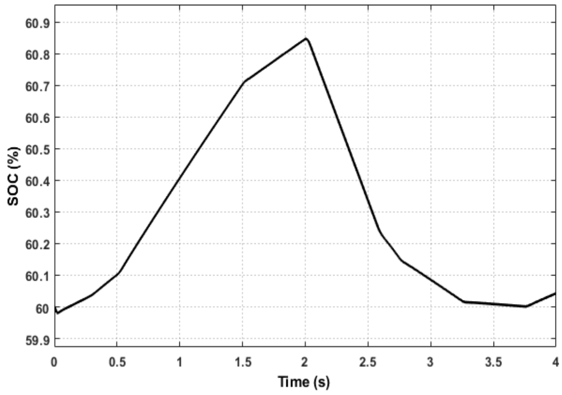

Fig 7. SOC of ESS variation

The simulation results show that the integrated control system and the energy storage system can provide a constant power output under the fluctuating wind generation conditions and during the islanding mode.

4. Conclusion

This paper proposes a control strategy for PMSG wind turbine systems using a grid-connected ESS for the residential load. The control system has been developed to smooth the power output as the wind speed varies and to maintain the voltage and frequency within the predefined margins. The control strategies are developed and tested on a simulation model of a 175 kW PMSG wind turbine in MATLAB/Simulink. The simulation results demonstrate the capability and performance of the implemented control system in dynamically adjusting voltage and frequency in moments of unexpected fluctuation and its role in providing constant power and voltage despite the randomness of the wind speed.

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