Modeling and Control of an Islanded DC Microgrid with a Solar–Wind–Battery System

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Abstract

Islanded DC microgrid are an efficient and reliable way to integrate renewable energy sources in standalone and remote power systems. In comparison with AC microgrid, DC architectures reduce the stages of power conversion and improve efficiency, as well as simplify the control; however, how to maintain stable operation under variable renewable generation is yet a big challenge. This paper is concerned with the modeling and centralized control of an islanded DC microgrid that consists of solar photovoltaic, wind energy, and battery energy storage systems using MATLAB/Simulink. This paper discuss a centralized control approach, which regulates the DC bus voltage and coordinates the power flow among renewable sources and batteries through global system measurements. Simulation studies are carried out under dynamic operating conditions of change in solar irradiance, wind speed, and load demand. The results obtained show that under the proposed control strategy, the DC bus voltage remains within ±2% of its reference value at all instances of the operating period. The photovoltaic power is between 7-10 kW, whereas the wind power increases up to 8-9 kW under transient conditions. The battery compensates for the net power imbalance and, hence, smoothly switches between discharging and charging modes while keeping the state of charge within a safe window of 40-80%. These results confirm that centralized control provides effective voltage regulation, robust power management, and stability operation of islanded DC microgrid with hybrid renewable energy sources.

Keywords: Battery energy storage system, centralized control, DC microgrid, islanded operation, renewable energy, voltage regulation

1. Introduction

Increasing penetration of renewable energy resources and the need for stable power in distant and separate areas have triggered the evolution of microgrid technology. Traditional main power generation networks entail limitations in terms of losses in the transmission network, the cost of infrastructure, and environmental factors, especially in the case of serving distant areas. Under these requirements, DC micro-grids have been recognized as an attractive option because of compatibility with renewable energy sources and a simpler control structure compared to AC micro-grids (Guerrero et al., 2011; Kumar et al., 2017).

The solar photovoltaic cell, battery energy storage system, and other modern loads commonly use DC, thus making the DC microgrid superior to the AC microgrid due to efficiency levels that DC microgrid can manage, which the AC microgrid cannot handle effectively due to the losses involved (Kumar et al., 2017). Various researchers have illustrated that the DC microgrid system has the capability to offer improved voltage regulation, lower system losses, and improved system reliability when controlled correctly (Al-Ismail, 2021; Dragičević et al., 2016). The major technical issues that occur during an islanded system include intermittency of power sources, load changeability, and the lack of grid support that causes instability of the DC bus voltage levels (Dragičević et al., 2016; Lu et al., 2023).

Realistic mathematical modeling of renewable energy sources and storage components is imperative for making accurate microgrid analysis and control implementations possible. Well-verified models and schemes of PV systems and MPPT algorithms have gained extensive usage for simulating non-linear system responses based on different climate conditions (Esram & Chapman, 2007; Villalva et al., 2009). Detailed mathematical models of wind turbine and generators facilitate investigations of system responses based on varying wind speeds (Knudsen & Nielsen, 2012). Models and SOC estimation of batteries are vital for optimal management and stable system operations (Fagundes et al., 2024) .

Yet, the application of centralized control strategies is still prevalent in the existing islanded DC MGs because they can utilize global information available in the system for coordinated active power management tasks, as well as for DC bus voltage regulation (Guerrero et al., 2011; Shamkhi et al., 2025). The work presented in this paper deals with modeling, analysis, and centralized control design for an islanded DC MG interconnecting solar, wind, and battery-based power sources. The purpose is to examine the system performance under different operating scenarios, as well as the applicability of centralized controls for ensuring voltage stability in MGs.

2. Methodology

2.1 System Architechture

Fig.1 presents the general power architecture and energy interfacing structure of the proposed islanded hybrid DC microgrid. The system has been composed by a wind turbine coupled with a PMSG followed by a three-phase rectifier, a solar PV array interfaced through a DC-DC boost converter with MPPT control, and a battery ESS connected through a bidirectional DC-DC converter. All the subsystems have been integrated through a common DC bus, which supplies the DC load. This configuration can realize autonomous power flow control, efficient renewable energy utilization, and stable islanded operation.

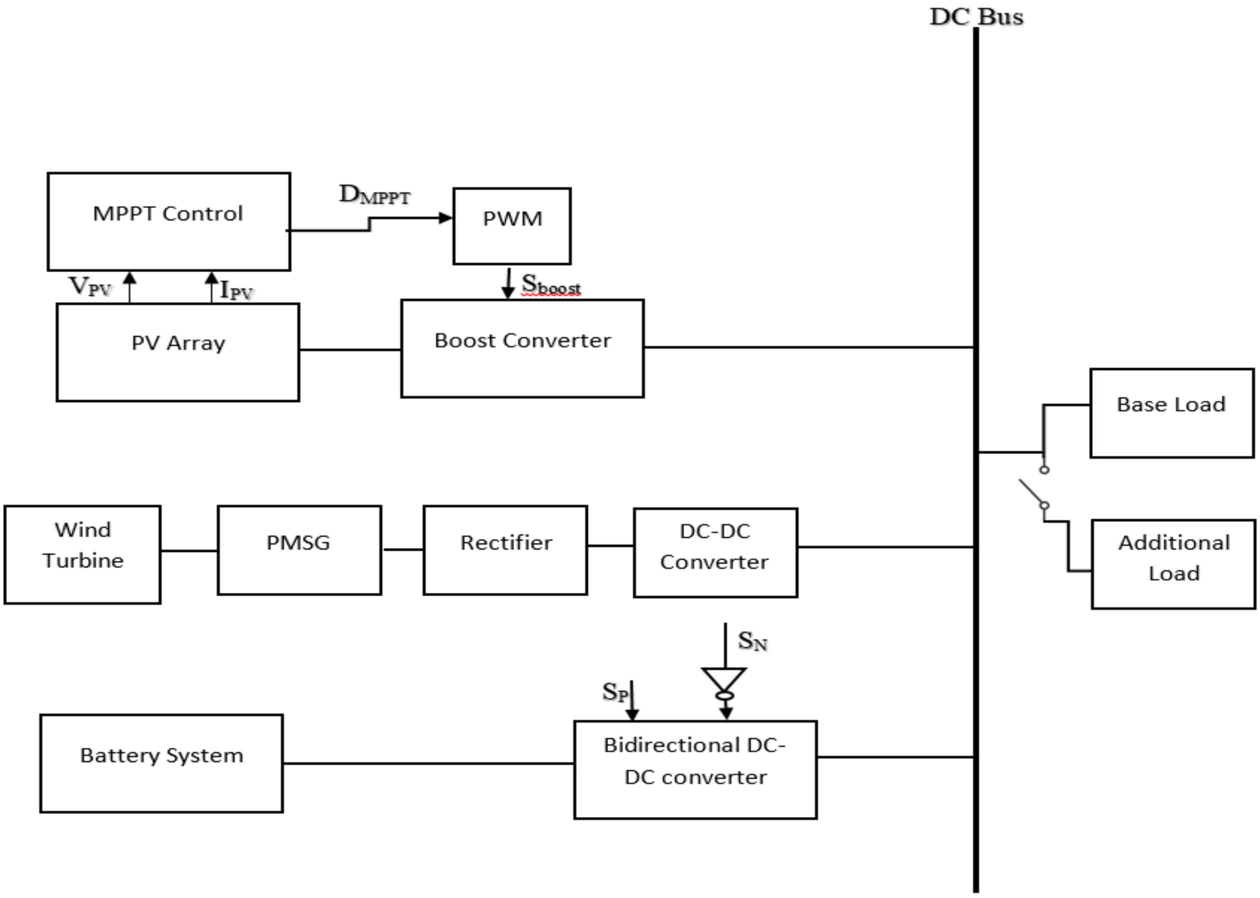

Fig. 1: Block diagram of the proposed islanded hybrid solar-wind-battery based DC microgrid system

2.2 Photovoltaic System Model

The commonly used single-diode equivalent circuit, which accurately describes the nonlinear current–voltage characteristics under variable irradiance and temperature circumstances, is used to describe the photovoltaic (PV) array. The mathematical equation for the PV output current is:

$$I_{pv} = I_{GC} - I_o \left[exp^{\left(\frac{eV_d}{KFT_c}\right)} - 1 \right] - \frac{V_d}{R_P} \tag{1}$$

The instantaneous PV output power is given by:

$$P_{PV} = V_{PV} * I_{PV} \tag{2}$$

To ensure that the maximum power is extracted from the PV system in varying environmental conditions, a perturb and observe (P&O) maximum power point tracking algorithm is incorporated in the system(Esram & Chapman, 2007). A unidirectional DC-DC boost converter is used as the DC bus interface circuit with the PV array.

2.3 Wind Energy Conversion System Model

The mechanical power extracted from the wind turbine is modeled as a function of wind speed and turbine parameters (Knudsen & Nielsen, 2012):

$$P_m = C_p(\lambda, \beta)\frac{\rho A}{2}\ v_{wind}^3 \tag{3}$$

Where, ρ is air density, A is the swept area, C_p is the power coefficient, λ is the tip-speed ratio, β is the pitch angle, and v is wind speed. The mechanical torque applied to the generator shaft is:

$$T_m = \frac{P_m}{\omega_r} \tag{4}$$

The wind turbine drives a permanent magnet synchronous generator, and the generated three-phase AC power is converted to DC using a diode rectifier and DC–DC converter interface (laabjerg et al., 2004).

2.4 Battery Energy Storage System Model

The battery energy storage system is represented by an equivalent electrical circuit that includes an open-circuit voltage source and internal resistance (Chen & Rincon-Mora, 2006). The voltage at the battery terminal is defined by:

$$V_b = V_{oc} - I_b R_b \tag{5}$$

The state of charge (SOC) of the battery is calculated using Coulomb counting. The formula is:

$$\text{SOC (t)} = \text{SOC (0)} - \frac{1}{Q_{nom}}\int_0^t i_{bat}(\tau)d\tau \tag{6}$$

Q_nom represents the stated battery capacity. A bidirectional DC–DC converter allows for regulated battery charging and discharging according to system needs and SOC limitations (Fagundes et al., 2024; Wang et al., 2020).

2.5 Centralized Control Strategy

A centralized control method has been adopted to control the DC bus voltage as well as the power transfer between the renewable energy sources and the battery energy storage system. When operating in island mode, the DC bus voltage shows direct information about the microgrid power balance, and any deviation from the desired value shows generation-load imbalance (Guerrero et al., 2011; Lu et al., 2023).

The centralized controller measures the DC bus voltage and generates a battery current reference based on the voltage error:

$$e_v(t) = V_{dc,ref} - V_{dc}(t) \tag{7}$$

A proportional–integral controller is used to compute the battery current command:

$$I_{bat,ref}\,(t) = K_p e_v(t) + K_i \int_0^t e_v\,(\tau)d\tau \tag{8}$$

The battery charges when extra renewable power raises the DC bus voltage over its reference, and discharges when the voltage falls owing to insufficient generation. Battery operation is limited to specified state-of-charge restrictions to ensure safe and dependable performance (Fagundes et al., 2024;

Shamkhi et al., 2025; Wang et al., 2020). Renewable sources extract maximum power, while the battery compensates for power imbalance, resulting in stable DC bus voltage management under changing operating conditions (Al-Ismail, 2021; Kumar et al., 2017).

3. Results and Discussion

Time-domain simulations in MATLAB/Simulink are conducted for the proposed islanded DC microgrid with centralized control under various operating conditions such as solar irradiance, wind speed, and load demand variations. The results of the study are dealt with by the DC bus voltage regulation, battery response, and power balance, which is represented by Equations. (7) and (8).

3.1 DC Bus Voltage Regulation

Fig. 2 represents the DC bus voltage response under dynamic operating conditions. When renewable generation or load demand fluctuates, a transient power imbalance occurs. The centralized controller detects variations in the DC bus voltage from its reference and generates a corrected battery current instruction based on equations (7) and (8). The DC bus voltage remains within ±2% of its reference value during the simulation. The rapid restoration of voltage after disturbances demonstrates the effectiveness of the implemented centralized voltage control technique.

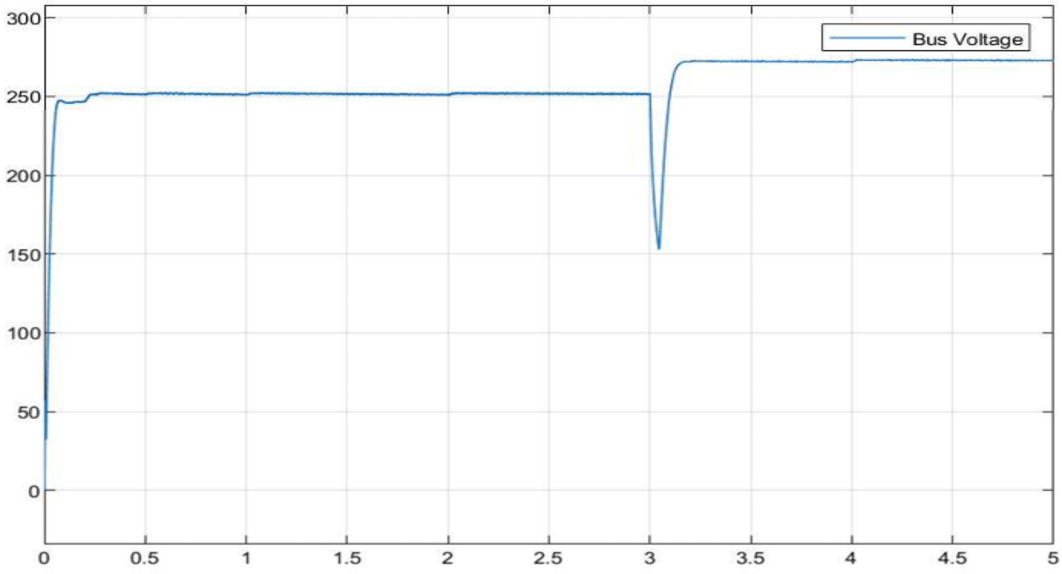

Fig. 2: DC bus voltage profile

3.2 Battery SOC Response

Fig. 3 shows the SOC profile of the battery energy storage system during operation. The SOC increases smoothly and gradually from approximately 54.96% to 55.01% over the simulation interval, reflecting that the battery operates mainly in charging mode. This is an indication of the occurrence of the condition whereby the total power generated by the renewable photovoltaic and wind subsystems is greater than the load demand.

Under these conditions, the centralized controller senses an increase in DC bus voltage due to excessive renewable energy and sends a command for a positive battery charging current based on the voltage error defined by Eq.7 while using the PI control described by Eq.8. One can note from that there is no sharp variation or oscillations around the SOC, which proves that battery current is well commanded and the stability of the charging/discharging process is maintained. One can also observe that the SOC has varied slightly, which means the battery is mainly used as a buffer to absorb the excess renewable energy rather than acting as a major source of power supply.

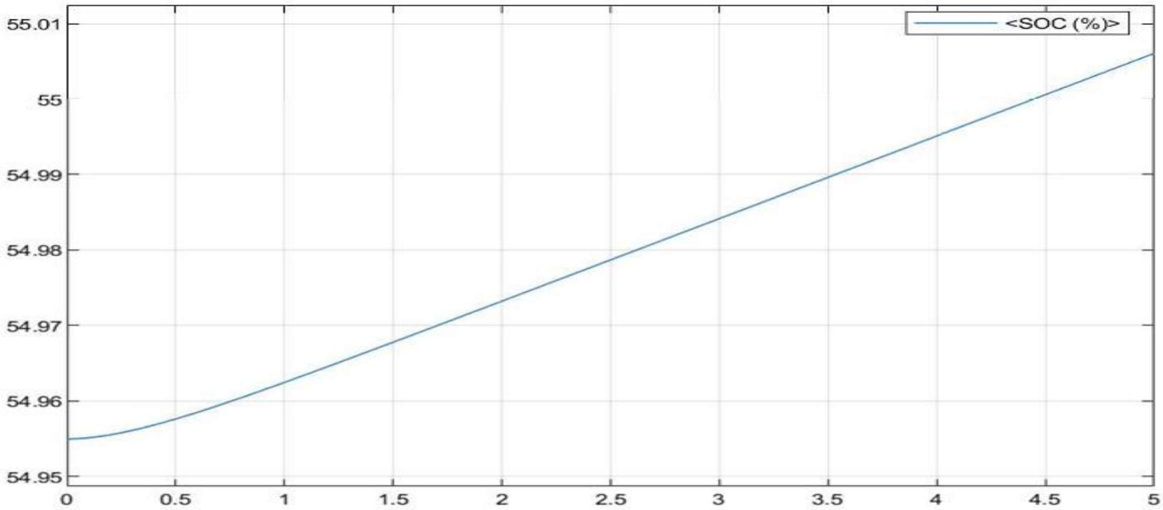

Fig. 3: Battery SOC Response

3.3 Power Balance Analysis

The combined power curves in Figure 4 demonstrate the collaborative efforts of the islanded DC microgrid when centralized control is employed. Prior to the 3rd second, the solar source is generating a combined power of 9-10 kW, while the wind source is generating a combined power of only 1 kW. During this phase, the battery is in the discharging mode to meet the remaining deficit.

At t ≈ 3 s, a decrease in PV output to 7–8 kW is noticed because of low irradiance level, while the wind power shows a steep rise to 8–9 kW. To meet this excess output level, the battery changes smoothly from discharge to charging mode to absorb the excess power. Consequently, despite all these variations, the power on the DC bus remains steady at 11–12 kW with a brief transient. These outcome validations successfully validate that the proposed centralized control strategy is effective in dealing with the intermittent outputs of renewables while retaining voltage regulation and power stability.

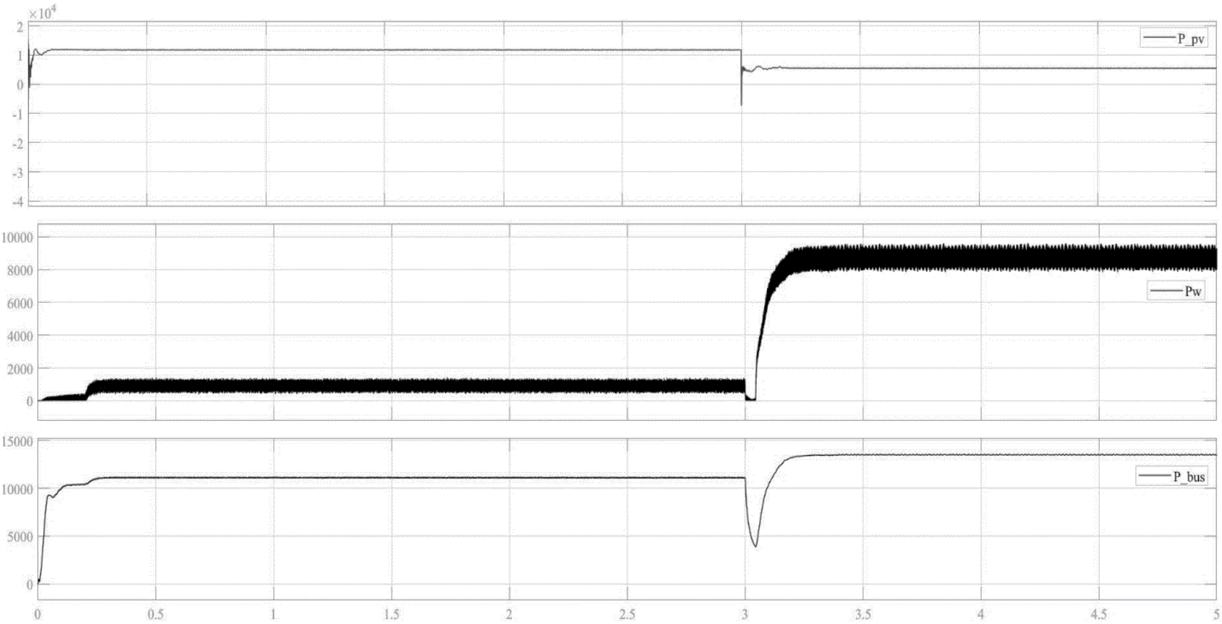

Fig. 4: Combined power plots (PV, wind and Bus)

4. Conclusion

The modeling and centralized control of an islanded DC microgrid that combines solar photovoltaic, wind, and battery energy storage systems were examined in this study. Using MATLAB/Simulink, detailed component models were created and assessed under dynamic operating circumstances. The proposed centralized control strategy successfully monitored the DC bus voltage and managed power sharing effectively.

The simulation outcomes indicate that the control strategy ensures the DC link voltage sustains within ±2% of the reference value in the event of solar irradiance, wind speed, and load change. Analysis of the power balance indicates that the PV output fluctuates between 7-10 kW, the wind output enhances up to 8-9 kW, while the battery ensures a changeover from discharging to charging or vice versa to counter the power discrepancies. The battery level of charge sustains between 40-80% to remain within the safe operational level.

These results verify the efficacy of centralized control for effective voltage regulation, power management, and stable operation in the islanded DC microgrid with the renewable energy sources.

Conflicts of Interest

The authors declare no conflict of interest.

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