



Performance Investigation of a Hybrid Energy System with Battery Support under Grid Connected Operation

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ABSTRACT

This paper presents an advanced energy management strategy for an AC-DC micro grid powered by a hybrid configuration of renewable energy sources, specifically wind and solar photovoltaic (PV) systems, integrated with battery energy storage systems (BESS). With the increasing penetration of renewable energy into the grid, significant challenges arise in maintaining system stability due to their intermittent and stochastic nature. To address these challenges, a Model Predictive Control (MPC) framework is proposed to coordinate the active power flow and enhance the dynamic performance of the micro grid. The proposed strategy ensures seamless interaction between generation units and storage devices, maintaining power balance under varying load and generation conditions. Simulation results validate the effectiveness of the proposed method in achieving reliable, flexible, and secure operation of the micro grid. The approach demonstrates improved transient response, reduced power fluctuations, and enhanced grid stability, thereby supporting the integration of high levels of renewable energy into the power system.

Key Words: Hybrid, Wind, Solar and Battery storage system.

INTRODUCTION

The rising use of electrical appliances for performing basic household tasks has significantly enhanced daily comfort and convenience. However, this increased reliance on electric devices has also led to a noticeable surge in residential electricity demand. To meet this growing requirement, both renewable and non-renewable energy sources are being integrated into the power generation network [1]. While this integration supports the rising demand, it also introduces greater complexity in managing power flow, stability, and system coordination due to the diverse characteristics of different generation sources. In recent years, environmental concerns and the need for sustainable energy development have motivated governments to incorporate a higher share of renewable energy into the national grid [2]. Renewable technologies such as photovoltaic (PV) panels, fuel cells (FC), wind turbines



(WT), ultra-capacitors, and geothermal systems are increasingly being considered to reduce carbon emissions and promote green energy [3]. Among these, solar and wind energy systems [4], [5] are the most widely adopted worldwide due to their lower installation cost, ease of deployment, and favourable cost-to-power conversion ratio. Unlike fuel-based technologies such as fuel cell stacks and biogas generators, solar and wind systems do not require continuous fuel input, making them more practical for diverse applications.

Wind turbines have emerged as dependable renewable energy sources due to their effective power regulation capabilities. With advancements in turbine design, offshore wind generation has gained significant research interest. Among various technologies, Doubly Fed Induction Generators (DFIGs) are widely used for their high efficiency and controllability. Maximum Power Point Tracking (MPPT) is achieved by regulating rotor speed based on wind variations [6]. Over recent decades, several control strategies have been developed to enhance DFIG performance [7]–[11]. For instance, Liu et al. [10] and Xu et al. [11] introduced control methods to mitigate transient oscillations caused by wind speed fluctuations, while Nyan and Song [12] proposed a voltage conditioning technique to minimize harmonics and smoothen power exchange in DFIG systems. In contrast, photovoltaic (PV) systems offer a simpler and cleaner alternative with minimal mechanical wear, no noise, and negligible environmental impact. The scalability of PV technology has led to the deployment of large-scale solar farms with multi-gigawatt capacity to meet rising energy demands [13], [14]. Grid integration of PV power is typically achieved using either single-stage or two-stage converter topologies. While the single-stage approach reduces hardware complexity, it presents challenges in control implementation. Voltage Source Inverter (VSI) configurations are commonly employed to regulate power injection into the grid.

Seasonal variations affect the availability of renewable sources—solar energy is more prominent in summer, while wind energy is more abundant in winter. This complementary nature has encouraged researchers to integrate both sources for improved reliability [15]. However, such hybrid systems introduce challenges related to power quality, stability, and consistency. Electrical Energy Storage Systems (EESSs) have been identified as effective solutions to mitigate power fluctuations and enhance system reliability [16]–[18]. EESSs help manage the intermittency of renewable sources by storing energy for use during high demand, high-cost periods, or when generation is insufficient [19]–[21]. EESS technologies are categorized based on function—high-power systems like supercapacitors, SMES, batteries, and flywheels [22], and energy management systems including fuel cells, bulk batteries, solar cells, and flow batteries [23]–[25]. In terms of form, energy can be stored chemically, thermally, or mechanically and converted to electricity as needed. Electrical Energy Storage Systems (EESS) are essential for managing power fluctuations and ensuring



reliability in hybrid renewable systems. To further enhance performance, Hybrid Energy Storage Systems (HESS) has gained importance, offering improved flexibility and operational stability [26]. However, frequent charge-discharge cycles significantly influence battery lifespan, necessitating careful system design. To enhance supply security in PV and wind-based systems, incorporating a third energy source is recommended. The choice of this additional source should align with the specific advantages and storage characteristics of the overall system.

Various studies have introduced advanced control strategies for hybrid renewable energy systems. A modified algorithm targeting 5th and 7th grid voltage harmonics was proposed in [27] to smooth active and reactive power output. A two-layer constant power control scheme for DFIG-based wind farms using supercapacitors (SC) connected to the DC link was detailed in [28]. Cost-effective power generation and a basic control loop for battery banks were explored in [28]. An energy-sharing strategy between SCs and batteries was presented in [29], where SCs handle peak loads and batteries supply average power. In these configurations, DC-DC converters manage energy flow between storage elements and the DC bus, with some setups omitting the converter for the battery connection. The previously discussed works primarily emphasize control strategies and power source coordination, without thoroughly addressing system efficiency and optimal design. In this study, a Model Predictive Control (MPC) approach is employed to ensure stable and reliable micro grid operation. A third energy source is integrated into the grid-connected PV-Wind system to enhance supply continuity. The proposed hybrid PV-Wind-Battery Energy Storage System (BESS) architecture is designed with a minimal number of control loops and power electronic converters, aiming to reduce system complexity while maintaining optimal performance.

The structure of the paper is as follows:

Section I presents the introduction. Section II provides a detailed overview of the proposed hybrid grid-connected system architecture. System modelling and the associated control strategies are outlined in Section III. Section IV discusses the simulation setup along with the obtained results. Finally, Section V summarizes the key findings and concludes the study.

SYSTEM DESCRIPTION

The operation of a DC micro grid powered by renewable energy sources is centred on a common DC bus, which connects various generation and storage units. As shown in Fig. 1, the system integrates wind turbines, solar photovoltaic (PV) panels, and a battery energy storage system (BES), each contributing power denoted as P_{Wind} , P_{PV} and P_{BES} respectively. The wind turbine converts wind energy into electrical power, while the PV panels generate DC electricity from sunlight. Both sources are interfaced through power converters to



maintain stable voltage and efficient energy transfer to the DC bus. Since renewable generation is variable, the BES plays a crucial role by storing excess power and supplying energy when needed through a bidirectional DC-DC converter. All power flows converge at the Point of Common Coupling (PCC), where the micro grid connects to the utility grid.

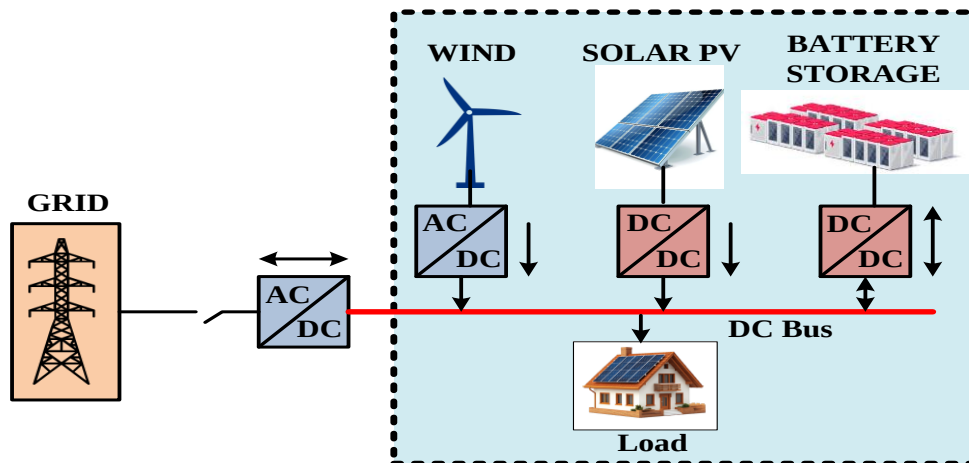


Fig.1 Proposed Hybrid energy system

A. Wind turbine:

In the block diagram, the wind turbine is shown as one of the primary energy sources feeding power into the micro grid. The wind turbine works by capturing wind energy using rotating blades that drive a generator to produce electrical power. This generated power, labelled as P_{Wind} , is directed towards the point of common coupling (PCC) through suitable power conversion equipment that ensures the voltage and current are compatible with the DC bus. Since wind speed varies over time, the power generated is not constant. Hence, the associated converter adjusts the power output before it is delivered to the grid or local loads. The wind system thus contributes to the overall energy availability in the micro grid, especially when wind conditions are favourable.

B. Solar Photovoltaic (PV) system:

The PV system in the diagram represents another renewable source connected to the DC micro grid. It generates electrical energy by converting sunlight into DC power using solar panels. The produced power, shown as P_{PV} is fed into the DC bus via a converter that maintains proper voltage levels and maximizes power extraction using techniques like maximum power point tracking (MPPT). Solar generation is predictable during daylight hours but varies with cloud cover and time of day. Despite this variability, PV systems offer clean and maintenance-friendly power, which makes them a reliable part of the micro grid during sunny periods.

C. Battery Energy Storage System (BES):



The BES, marked in the diagram as the third unit, plays a vital supporting role in the micro grid. It is connected to the DC bus and can either supply or absorb power, depending on the system's needs. This is represented as P_{BES} in the diagram. A bidirectional DC-DC converter allows the battery to charge when there is surplus energy (e.g., during high solar or wind generation) and discharge when the demand exceeds supply. This function helps balance energy flow, regulate voltage, and improve the stability of the micro grid, particularly during periods of rapid changes in generation or load.

All three components wind, solar PV, and the battery system work together to form a coordinated power system connected at the PCC. Their combined output, denoted as (P_{st}) is either supplied to local loads or exported to the utility grid through the PCC. The frequency at the PCC is an important parameter for grid synchronization. The integration of variable renewable sources with a controllable storage system ensures that the total power fed into the grid is steady and reliable. This cooperative operation increases the efficiency and resilience of the micro grid while making effective use of renewable resources.

SYSTEM MODELLING AND CONTROL METHODOLOGY

A. Modelling of solar PV system:

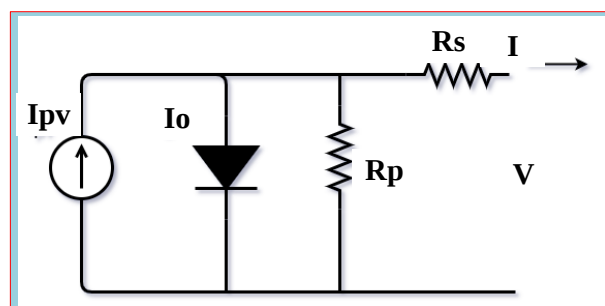


Fig.2 Equivalent circuit of a single solar PV cell

A photovoltaic (PV) array consists of multiple solar cells, each capable of generating charge carriers when exposed to incident light. The behaviour of an individual solar cell can be represented using an equivalent circuit that includes a current source in parallel with a diode. As shown in Fig. 2, the simplified circuit model of a single solar cell includes a current source, a Shockley diode, a parallel (shunt) resistance R_p , and a series resistance R_s . The electrical characteristics of the cell can be described mathematically using the equation provided in Eq. (1).

$$I = I_{pv} - I_o \left[e^{\frac{qV}{akT}} - 1 \right] \quad (1)$$

Equation (1) does not capture all the characteristics of a solar cell. However, incorporating both series and parallel resistances into the model provides a more accurate representation,



especially under practical operating conditions. The series resistance R_s represents the internal resistance between the solar cell and its external terminals.

$$I = I_{PV} - I_o \left[e^{\frac{V + R_s I}{V_t a}} - 1 \right] - \left(\frac{V + R_s I}{R_p} \right) \quad (2)$$

Based on the series and parallel arrangement of solar cells within a PV array, Equation (2) can be modified accordingly. Increasing the number of cells connected in parallel raises the overall current output of the array, while increasing the number of cells in series results in a higher output voltage. The current generated due to the influence of solar irradiance and temperature is denoted as I_{pv} , as expressed in Equation (3). Both irradiance and temperature have a significant impact on the performance of a solar cell.

$$I_{PV} = (I_{PVN} - K_i \Delta T) - \left(\frac{G}{G_n} \right) \quad (3)$$

B. Modelling of wind energy conversion system:

The large-scale deployment of wind turbines has faced certain challenges, primarily due to the variable nature of wind speeds and the significant initial investment required. To predict and analyse the power output from wind turbines, several modelling approaches are available, including linear and quadratic methods, as well as statistical models like the Weibull distribution. The mechanical power generated by the wind turbine is presented in Eq. (1).

$$P_w = \frac{1}{2} \rho A C_p(\lambda, \beta) V_{wind}^3 \quad (4)$$

Where ρ is the air density, C_p is the power coefficient depends on the λ known as tip speed ratio and β known as the pitch angle. A is the swept area, V_w is the wind speed. The ration of blade tip speed to wind speed is given in Eq. (2).

$$\lambda = \frac{\omega_t R}{V_{wind}} \quad (5)$$

Where ω_t is the rotor speed of the wind turbine and R is the turbine radius. The dynamic equation for the rotational momentum of the turbine is given as below Eq. (3) & (4).

$$J \frac{d\omega_t}{dt} = T_{aero} - T_{em} - B\omega_t \quad (6)$$

$$T_{aero} = \frac{P_{wind}}{\omega_t} \quad (7)$$

Where T_{aero} is the aerodynamic torque, T_{em} is the electromagnetic torque in the generator and B is the viscous coefficient. The electromagnetic torque model produced by the generator is given as

$$T_{em} = \frac{3}{2} p \lambda_m i_q \quad (8)$$



Where p is the number of poles, λ_m is the flux linkage, i_q is the q-axis stator current.

C. Battery energy storage system

The battery charging and discharging of BESS is shown in fig.3. Battery energy storage system plays a vital role in maintaining energy balance within a hybrid power system by ensuring continuous power availability, independent of real-time renewable energy output. It accumulates surplus energy generated by solar and wind sources during periods of low load or high production, and supplies this energy when the demand surpasses generation, such as during night-time or periods of low wind activity. Additionally, the battery contributes to overall system stability by offering rapid support for voltage regulation and frequency control.

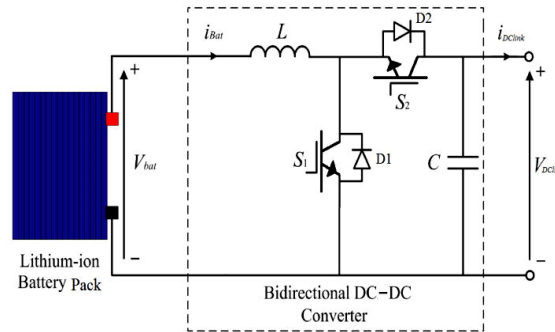


Fig.3 Charging and discharging control of BESS

The charge capacity of the battery can determine by the C_{min} and C_{max} usually given by the manufacturer is given as below Eq.6.

$$C_{min}(t) \leq C(t) \leq C_{max}(t) \quad (9)$$

Where C_{min} is the minimum charge capacity and C_{max} is the maximum charge capacity of the battery. The maximum charge capacity of the battery is given as

$$C_{max} = C_n \times \omega \quad (10)$$

Where C_n is the nominal charge capacity of the battery and DOD is the depth of discharge of the battery.

$$C_{min} = \{1 - DOD\} \times C_n \quad (11)$$

When the total generated power is greater than the power demanded by the grid, the battery begins to store the excess energy. During this charging process, the state of charge (SOC) of the battery can be calculated using the following expressions.

$$soc_b(t) = soc_b(t-1) + \eta_b \left\{ E_{PR} \eta_{inv} - \frac{E_d(t)}{\eta_{inv}} \right\} \quad (12)$$



If the power demand from the load exceeds the combined output of the photovoltaic (PV) system and wind turbine (WT), the battery system is required to supply the shortfall. As a result, the battery discharges, and its state of charge (SOC) is updated accordingly.

$$soc_b(t) = soc_b(t-1) + \{E_{PR}(t)\eta_{inv} - E_d(t)\} \quad (13)$$

RESULTS AND DISCUSSIONS

A hybrid renewable energy system comprising a wind energy conversion system, a solar photovoltaic array, and a battery energy storage system has been developed and integrated with the utility grid. The system configuration is modelled and simulated in the MATLAB/Simulink environment to evaluate its dynamic performance and operational behaviour under varying generation and load conditions. The detailed modelling aspects, control strategies, and simulation results are systematically presented in the subsequent sections. Figure 4 illustrates the dynamic response of key system parameters under varying load conditions. The simulation is conducted over a time window from 0.4s to 1.6s. During this period, the wind speed is maintained constant at 12m/s, and the solar irradiance is fixed at 1000 W/m² to ensure steady renewable energy input. Initially, from 0.4s to 0.5s, only Load-1 is connected, drawing approximately 1A.

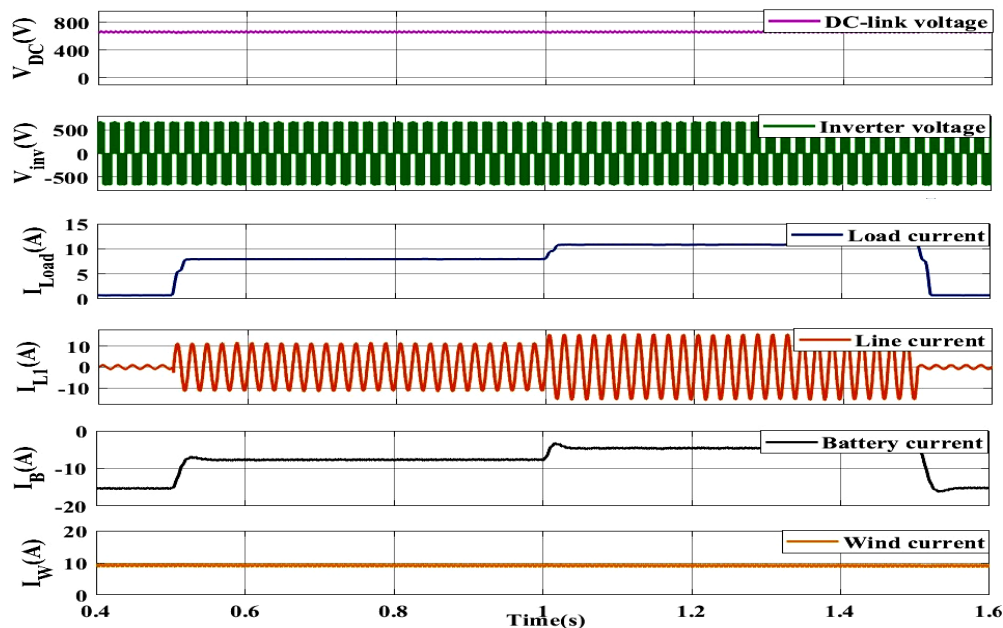


Fig.4 Dynamic performance of the system parameters during battery charging

Under this condition, the battery operates in the charging mode, with a charging current of –15A, indicating surplus power in the system. At 0.5s, Load-2 is introduced, increasing the total load demand to 8A. As a result, the battery charging current decreases from –15A to



approximately -8A , reflects a reduction in surplus power available for storage. Subsequently, at 1.0s , Load-3 is added, bringing the total load current to 12A . To accommodate this additional demand, the battery continues to charge but with further reduced current, decreasing to around -3.5A . Throughout the entire operation, both the DC-link voltage and the inverter output voltage remain stable and within desired limits, thereby demonstrating the robustness and voltage regulation capability of the control strategy implemented in the hybrid energy system.

Figure 5 illustrates the active power distribution among the major components of the hybrid energy system, including the load, wind turbine, solar PV array, and battery energy storage system (BESS). The renewable generation comprises 6 kW from the wind energy conversion system and 4.8 kW from the solar PV array, resulting in a combined generation capacity of 10.8 kW . During the initial operating interval from 0.4 s to 0.5 s , only Load-1 is connected to the system, drawing approximately 500 W . The excess renewable energy is directed toward charging the battery, which absorbs 10 kW , while the remaining 0.3 kW accounts for system losses, including converter losses and filter dissipation. At 0.5 s , the system experiences a step increase in demand as Load-2 is switched on, increasing the total load power to 5.5 kW . In response, the battery charging power is reduced to 5 kW , maintaining system balance. The slight power mismatch of 0.3 kW continues to represent inherent losses within the system components. Further, at 1.0 s , Load-3 is introduced, increasing the cumulative load demand to 7 kW . To meet this additional requirement, the battery continues to operate in charging mode but with a reduced input of approximately 3.5 kW . The system consistently maintains a power loss of around 0.3 kW , indicating a stable but non-negligible internal loss across all loading conditions. These observations highlight the effectiveness of the control strategy in ensuring coordinated power sharing among the renewable sources, battery, and load, while maintaining energy balance and minimizing power mismatch under varying load profiles.

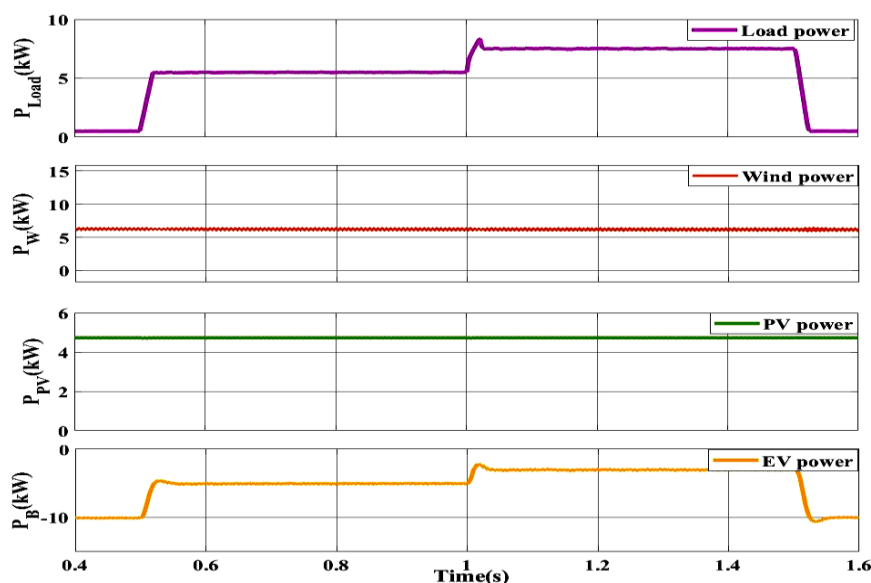


Fig.5 Active power profiles during battery discharging

The figure 6 shows the dynamic behaviour of key electrical parameters in a grid-connected hybrid energy system from 0.4 s to 1.6 s. The DC-link voltage remains stable, indicating effective voltage regulation. The inverter output voltage maintains a balanced sinusoidal waveform suitable for grid connection. Load current increases stepwise, corresponding to the sequential addition of loads, and decreases after 1.0 s as loads are disconnected. Line current follows a similar trend with smooth sinusoidal waveforms. The battery current rises at 0.5 s, indicating charging, and gradually decreases as load demand reduces. Wind current remains constant, reflecting steady wind power generation throughout the simulation. Figure 7 presents the active power distribution among key elements of the hybrid energy system. Initially, up to 0.5 s, only Load-1 is active, consuming approximately 8 kW, while surplus renewable energy charges the battery at 2.5 kW and system losses account for 0.3 kW. At 0.5 s, the addition of Load-2 raises the total load demand to 14 kW, prompting the battery to discharge 3 kW to maintain power balance. Subsequently, at 1.0 s, the activation of Load-3 lowers the total load to 10 kW, allowing the battery to resume charging at a reduced rate of 0.5 kW. Throughout all scenarios, system losses remain around 0.3 kW, demonstrating effective power management and control coordination.

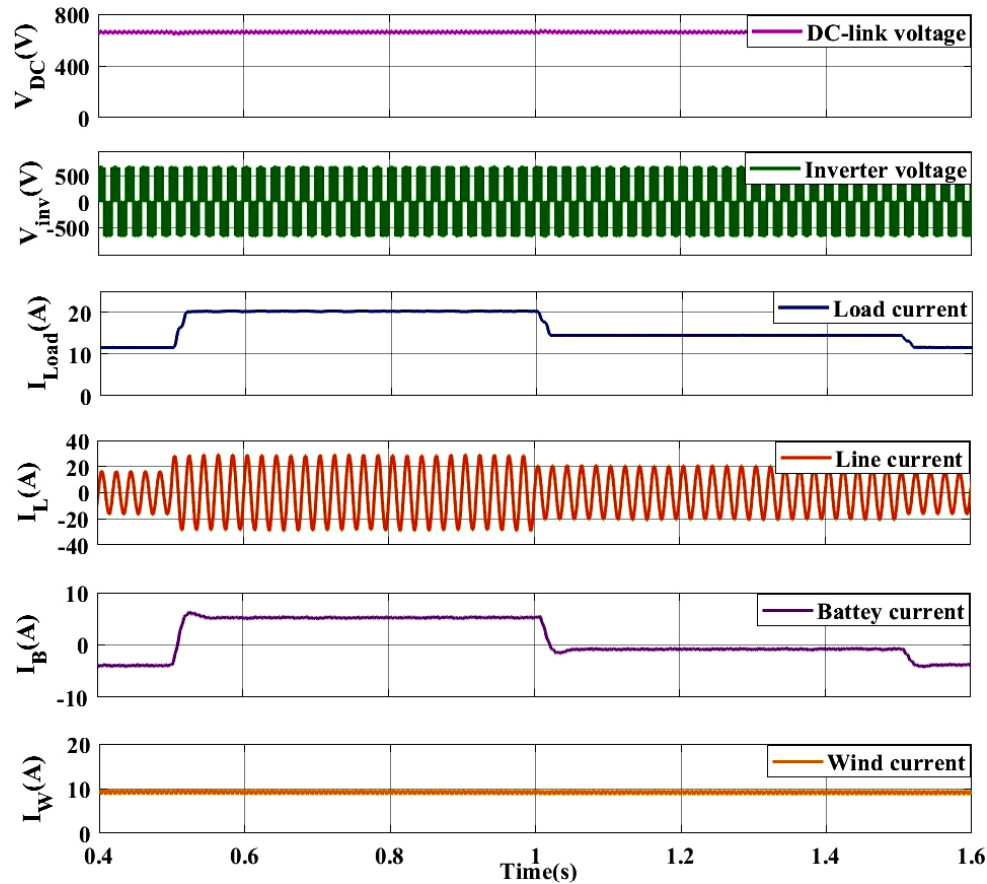


Fig.6 Dynamic performance of the system parameters during battery discharging

Figure 8 illustrates the grid voltage and current waveforms in per unit (p.u.) under step changes in load. The grid voltage remains balanced and sinusoidal throughout the simulation, indicating effective voltage regulation despite dynamic load variations. Initially, the grid current is low, corresponding to a light load condition. At 0.5 s, a sudden increase in current amplitude is observed, reflecting the connection of an additional load and the corresponding rise in power demand. The current remains elevated until 1.0 s, after which a noticeable reduction occurs due to partial load disconnection. Throughout the simulation, the voltage waveform remains unaffected, confirming the stability and reliability of the grid interface during varying load scenarios.

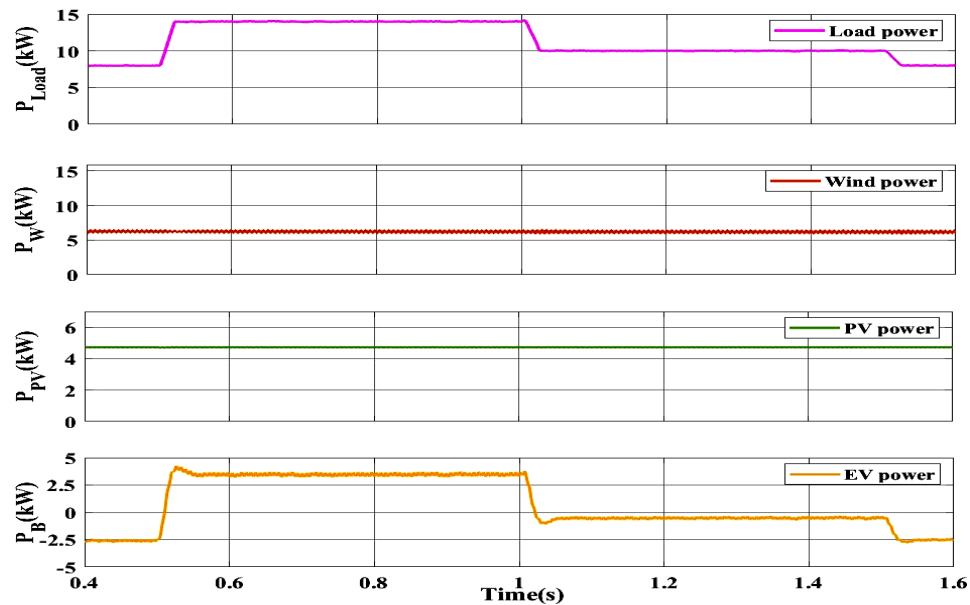


Fig.7 Active power profiles during battery discharging

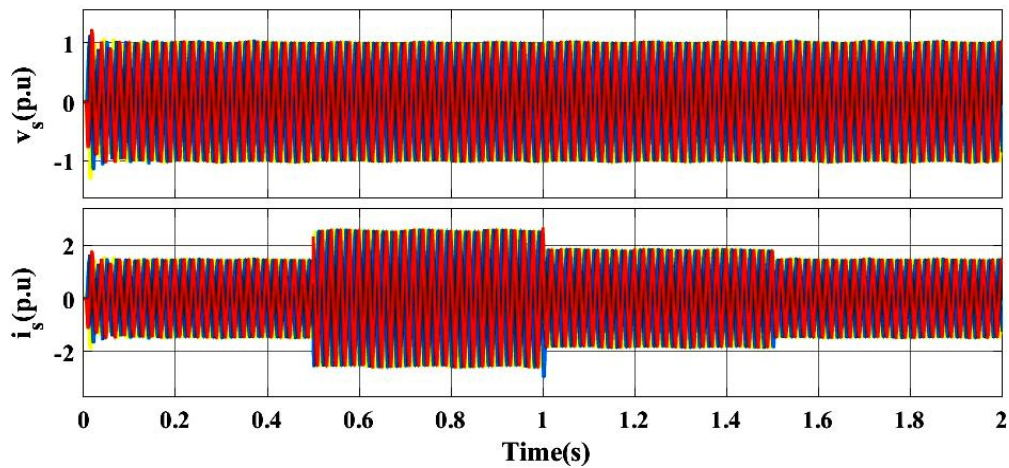


Fig.8 Grid performance during step change in load

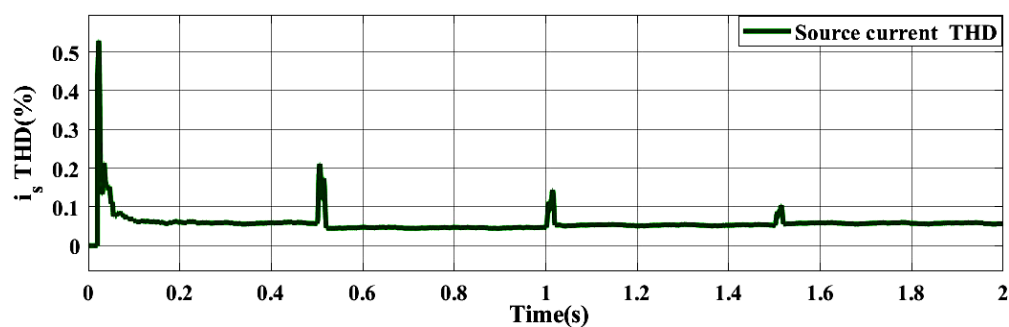


Fig. THD analysis of source current in time-domain

Figure 9 shows the Total Harmonic Distortion (THD) profile of the source current over a 2-second simulation period. Initially, a higher THD peak of around 0.55% is observed due to



transient effects during system start-up. The THD rapidly decreases and stabilizes below 0.1%, indicating effective harmonic suppression. Small spikes are visible at 0.5 s, 1.0 s, and 1.5 s, corresponding to load switching events, but these distortions are momentary and quickly damped. Throughout the operation, the THD remains well within acceptable limits, demonstrating that the control strategy maintains high power quality under dynamic loading conditions.

CONCLUSION

This study introduces an innovative operational strategy and a coordinated energy management framework tailored for a DC micro grid powered by renewable energy sources and supported by a battery-based energy storage system. The proposed methodology offers a practical and scalable solution for integrating a large number of distributed micro grids into the main utility grid, thereby facilitating a higher penetration of renewable energy into the overall power system. By leveraging the flexibility of the energy storage system and the predictive capabilities of the control strategy, the proposed approach enhances the efficiency, reliability, and adaptability of micro grid operations under dynamic operating conditions. The development of this robust and intelligent power management scheme marks a significant advancement toward establishing a more sustainable, resilient, and decarbonized energy infrastructure. It not only supports grid stability but also promotes optimal utilization of clean energy resources in future smart grid applications.

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