

Modelling and Simulation of Grid-Connected DC Micro-grid with Solar-Wind Hybrid Energy Conversion Sources

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Abstract

A hybrid renewable energy system integrates multiple sources, including photovoltaic (PV) systems, wind energy systems with permanent magnet synchronous generators (PMSG), fuel cells, and alternating current (AC), and all contribute as energy sources. Batteries and super-capacitors are used to store excess energy from these sources, which are connected to a DC microgrid. This study explores the modelling and simulation of a grid-connected system powered by a hybrid solar-wind energy conversion system. The integration of renewable energy sources, such as PV arrays and wind turbines with PMSG, is crucial in developing a resilient and sustainable energy infrastructure. The primary aim of this study was to simulate and analyse the performance of this hybrid system by incorporating a battery-based energy storage unit to enhance reliability and ensure energy continuity. The optimal sizing of renewable energy power is contingent upon the mathematical model of the system components. This study focused on examining different load conditions to achieve the objectives. This paper details the mathematical modelling of various renewable energy systems using the MATLAB platform.

Keywords: DC micro-grid • Hybrid renewable energy system • Maximum Power Point Tracking • Simulation studies

1. Introduction

The global energy landscape is changing rapidly because of the growing demand for sustainable energy and the transition from fossil fuels to renewable technologies. Solar, wind, hydro, geothermal, and tidal energy are increasingly utilized for electricity generation, with solar and wind achieving economic grid parity. Harnessing these renewable sources enhances a nation's energy security and independence. Extending the national grid to remote villages in developing countries, such as Nepal, is challenging. In this context, a clean power supply through solar or hybrid solar/wind systems offers a practical solution. Successful mini-grid projects have encouraged the adoption of such systems in ru-

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ral communities. Bhandari and Pradhan (2020) However, the availability of renewable energy resources depends on local conditions, such as solar irradiation, wind speed, and temperature. High reliance on renewable energy resources introduces challenges in energy management and requires innovative approaches to maintain stable power system performance.

Grid-connected DC microgrids that combine solar and wind energy conversion systems (WECS) are increasingly employed to provide clean and sustainable electricity in off-grid areas. These systems reduce dependence on fossil fuels, improve energy efficiency, and support backup power, peak shaving, and demand-side management in residential, commercial, and industrial applications. The integration of photovoltaic (PV) panels and wind turbines reduces greenhouse gas emissions and contributes to a sustainable energy future.

Hybrid AC/DC micro-grids, when connected to the main power grid, further enhance overall energy system stability. Li et al. (2023) Grid-connected DC microgrids can operate independently while supplying surplus energy to the grid during peak demand or outages. Their bidirectional energy flow enables both energy injection into and withdrawal from the grid, thereby improving system flexibility and reliability. Mondal (2024) This study focuses on modelling and simulating a grid-integrated DC microgrid with a hybrid solar-wind system. Gajbhiye (2022) The use of a DC bus offers advantages, such as improved power quality, reduced conversion losses, and easier integration of renewable energy sources. Combining solar photovoltaic (PV) panels with wind turbines enhances the overall system efficiency and reliability by leveraging multiple energy resources.

The modelling and simulation of hybrid solar-wind systems under variable load conditions were performed to determine the optimal sizing and system performance. Li et al. (2023) MATLAB was used to develop the mathematical models of the renewable energy systems. Gajbhiye (2022) The study highlights that while the voltage remains relatively stable under varying loads, the current fluctuates according to the load changes.

These insights provide a better understanding of the real-time operational behavior of hybrid microgrid systems, addressing gaps in experimental data and the existing literature.

Previous studies have investigated hybrid renewable energy-based microgrid systems, focusing on their development, analysis, and operational evaluation. The limitations identified include inadequate integration of energy storage models with practical energy management strategies and insufficient validation of power quality and system reliability under realistic operating conditions. A hybrid microgrid was analyzed under grid-connected and off-grid modes with multiple load profiles to assess its operational flexibility. Energy storage devices were modelled to ensure reliability and a continuous power supply.

The architecture of hybrid solar PV and wind energy systems includes several components for energy conversion and control. Mishra (2014) In solar PV systems, maximum power point tracking (MPPT) is used to maximize the energy output, and a boost converter increases the DC voltage. The DC output was then converted to AC using a three-phase pulse-width modulation (PWM) inverter operating at 50 Hz. In wind energy conversion systems, permanent magnet synchronous generators (PMSG) are driven by two-mass drive-train-based wind turbines. Both systems were tested under individual and combined loads of 1 kW each.

Standalone AC or DC micro-grids typically suffer from multiple energy conversion stages, which reduce overall efficiency. To overcome this limitation, hybrid AC/DC microgrids with grid connections through bidirectional converters have been proposed. Deshmukh (2021) This approach reduces losses, improves efficiency, and enhances reliability. Simulation studies under dynamic conditions with varying solar irradiance and wind speeds demonstrated that the hybrid system maintains stable operation, minimizes conversion losses, and effectively uses batteries to stabilize the DC bus during load variations. These results confirm that hybrid AC/DC microgrids provide a practical solution for the efficient integration of renewable energy sources into the grid.

2. Methodology

This study develops a hybrid renewable energy system comprising a photovoltaic (PV) array, wind turbine, permanent magnet synchronous generator (PMSG), DC-DC converters, an AC-DC converter, an inverter, and battery energy storage system. The system was designed and simulated in MATLAB/Simulink to evaluate the performance of the hybrid generation model. Maximum Power Point Tracking (MPPT) techniques were applied to both the PV and wind turbine systems to improve energy conversion efficiency. A bidirectional DC-DC converter was used to control the charging and discharging of the battery storage system.

2.1 Modelling of the Hybrid System

The hybrid system comprised three main components: wind energy, photovoltaic, and battery energy storage systems. Mathematical models were developed for each component to represent their operating behavior. The overall architecture of the hybrid PV-wind-battery microgrid is illustrated in Figure 1, which depicts the common DC bus, bidirectional converters, and grid connection.

2.1.1 Wind Turbine and Generator Model

The wind turbine model was developed based on the relationship between wind speed and turbine output power. Kausiak (2008) Wind speed varies with height above the ground and can be expressed as

$$v_2 = v_1 \left(\frac{h_2}{h_1} \right)^\alpha \quad (1)$$

Where v_1 , v_2 and α are the wind speed at heights h_1 and h_2 , respectively, and is the wind shear coefficient. The mechanical power extracted from the wind turbine is expressed as

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

where ρ is the air density, A is the rotor swept area, V_{wind} is the wind speed, and C_p is the power coefficient, which depends on the tip speed ratio λ and pitch angle β Sohoni and Kulkarni (2016). The power coefficient is defined as

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_i} - C_3\beta - C_4 \right) e^{-\frac{C_5}{\lambda_i}} + C_6\lambda \quad (3)$$

where C_1 to C_6 are turbine constants and λ_i is given by

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (4)$$

The mechanical torque of the turbine can be written as

$$T_m = \frac{P_m}{\omega_m} \quad (5)$$

A wind turbine drives a permanent-magnet synchronous generator (PMSG). The electrical model of the PMSG is described in the dq reference frame Wu (2011); (?); Wang (2014). The stator current equations are

$$\frac{di_d}{dt} = \frac{1}{L_d} (v_d + p\omega_g L_q i_q - R_d i_d) \quad (6)$$

$$\frac{di_q}{dt} = \frac{1}{L_q} (v_q - p\omega_g (L_d i_d + M_i f) - R_q i_q) \quad (7)$$

The electromagnetic torque of the generator is expressed as

$$T_e = 1.5p [\phi_m i_q + (L_d - L_q) i_d i_q] \quad (8)$$

where i_d and i_q are the stator currents, v_d and v_q are the stator voltages, L_d and L_q are the stator inductances, ϕ_m is the permanent-magnet flux linkage, and p is the number of pole pairs. The PMSG-based wind turbine parameters used in the simulation are listed in Table 2 to ensure an accurate representation of the generator dynamics and power output.

2.1.2 Photovoltaic System Model

The PV module was modelled using a single-diode equivalent circuit ?. The output current of the PV module is given by:

$$I_{pv} = I_{GC} - I_0 \left[\exp \left(\frac{eV_d}{KFT_c} \right) - 1 \right] - \frac{V_d}{R_p} \quad (9)$$

where I_{GC} is the photocurrent, I_0 is the diode saturation current, V_d is the diode voltage, and R_p is the parallel resistance.

The photocurrent mainly depends on solar irradiation and cell temperature and is calculated as:

$$I_{GC} = [\mu_{sc}(T_c - T_r) + I_{sc}] G \quad (10)$$

where I_{sc} is the short-circuit current and G is the solar irradiance. The single-diode model of the PV cell used in the simulation is illustrated in Figure 2.

The saturation current is expressed as:

$$I_0 = I_{0\alpha} \left(\frac{T_c}{T_r} \right)^3 \exp \left(\frac{eV_g}{KF} \left(\frac{1}{T_r} - \frac{1}{T_c} \right) \right) \quad (11)$$

This model allows the PV output to vary according to temperature and solar radiation. The overall architecture of the hybrid PV-wind-battery microgrid is shown in Figure 1.

2.1.3 Modeling of Battery Energy System

A battery energy storage system was included to balance the power generation and load demand ?. The battery state of charge (SOC) is defined as:

$$SOC = SOC_0 - \frac{1}{Q_N} \int_0^t i_{Bat} dt = SOC_0 - \frac{it}{Q_N}, \quad it = \int_0^t i_{Bat} dt \quad (12)$$

where SOC_0 is the initial state of charge, Q_N is the nominal capacity of the battery, and i_{Bat} is the battery current.

The terminal voltage of the battery can be expressed as:

$$v_{Bat} = v_{OC} - R_{in} \cdot i_{Bat} \quad (13)$$

where v_{OC} is the open-circuit voltage and R_{in} is the internal resistance ?. The battery system characteristics, including the nominal voltage, capacity, and number of series modules, are listed in Table 3.

2.1.4 Control of the Photovoltaic System

To extract maximum power from the PV array, a Maximum Power Point Tracking (MPPT) controller is implemented. In this study, the incremental conductance (INC) algorithm was used. The MPPT controller adjusts the duty cycle of the DC-DC converter so that the PV system operates at its maximum power point under changing solar conditions.

2.1.5 Hybrid System Simulation Model

A complete hybrid PV–wind system was implemented in MATLAB/Simulink. A wind turbine with a PMSG, PV array, battery storage system, and power electronic converters was integrated into a single simulation platform. The model allows the evaluation of power generation, voltage behavior, and energy storage performance under different operating conditions. The overall structure of the hybrid system is illustrated in Figure 1. The MATLAB/Simulink implementation of the hybrid microgrid is presented in Figure 3.

3. Results and Discussion

Solar irradiance, wind speed, and battery storage data were used as inputs for the simulation. The I–V and P–V characteristics of the PV module are presented in Figure 4, which illustrates the dependence of the module output current and power on solar irradiation and operating voltage. As the solar irradiation increased, both the maximum power output and short-circuit current correspondingly increased. The power output of the

wind turbine system under varying wind conditions is shown in Figure 5.

The dynamic behaviors of the PMSG stator current components, i_{sd} and i_{sq} , are depicted in Figure 6. Here, i_{sd} is effectively controlled to zero to optimize generator operation, whereas i_{sq} varies according to wind speed fluctuations, thereby generating the electromagnetic torque T_e . The battery charging and discharging responses are illustrated in Figure 7, demonstrating the role of the energy storage system in balancing the gen-

eration and load demand.

The grid voltage, inverter current, and grid current waveforms are shown in Figure 8, highlighting the stable operation of the system under hybrid generation. The combined power profiles of the system components, including P_{WT} , P_{PV} , P_{Bat} , P_{Grid} , and P_{Load} , are presented in Figure 9. Finally, the total active power generated by the hybrid wind-PV system is summarized in Figure 10, confirming the effective coordination of renewable generation and storage.

4. Tables and Figures

Table 1: Solar module specification

Parameter	Value
Maximum Power	250.205 W
Open Circuit Voltage (V_{OC})	37.4 V
Voltage at Maximum Power Point (V_{mp})	30.7 V
Current at Maximum Power Point (I_{mp})	8.15 A
Short Circuit Current (I_{SC})	8.66 A
Temperature Coefficient of V_{OC}	-0.36901%/°C
Temperature Coefficient of I_{SC}	0.086998%/°C
Parallel Strings	2
Series Connected Modules per String	15

Table 2: Wind turbine generator parameters

Parameter	Value
Base Wind Speed	12 m/s
Maximum Power at Base Speed	1 p.u.
Number of Phases	3
Back-EMF Waveform	Sinusoidal
Stator Phase Resistance (R_s)	0.198 Ω
Armature Inductance	0.000975 H
Flux Linkage Established by Permanent Magnets	0.1688 Wb
Number of Pole Pairs	4
Operating Frequency	50 Hz

Table 3: Data and parameters of the battery system

Parameter	Value
Battery Voltage (V_{Bat})	12 V
Rated Capacity (C_{Bat})	48 Ah
Number of Modules in Series	35
Rated Battery Voltage	$12 \times 35 = 420$ V

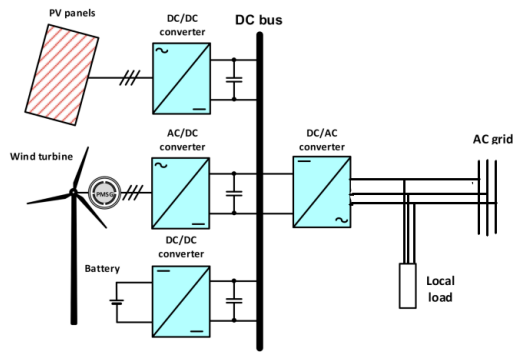


Figure 1: Block diagram of grid connected hybrid renewable energy system with common dc bus

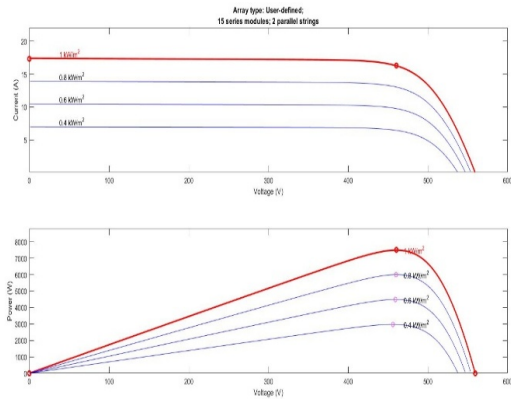


Figure 4: I-V and P-V output characteristics at different irradiances.

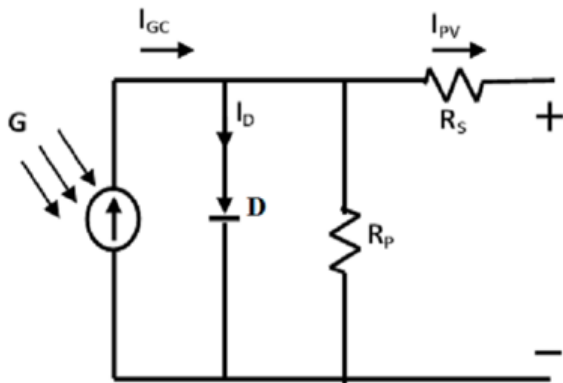


Figure 2: Single diode PV cell equivalent circuit

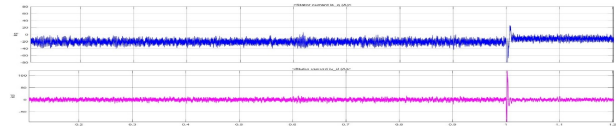


Figure 5: the courses of components i_{sd} , i_{sq} of stator current vector of PMSG

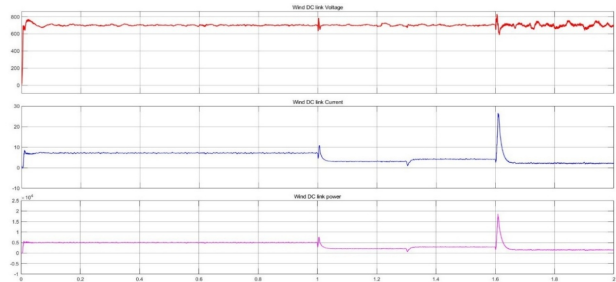


Figure 6: Wind system output (kWh)

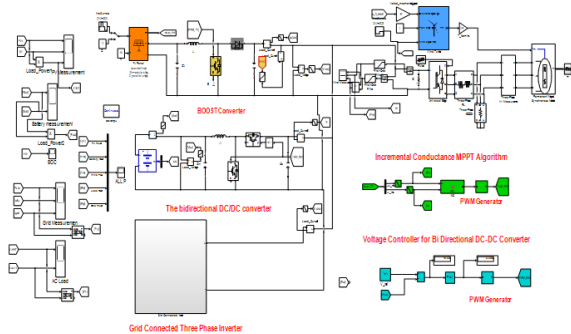


Figure 3: MATLAB/SIMULINK hybrid micro-grid including PV, wind turbine, inverter, MPPT, battery storage, and grid interface

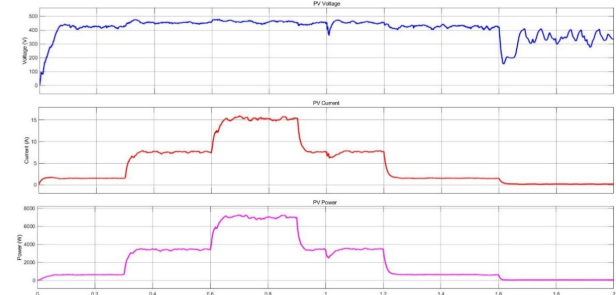


Figure 7: PV model's I-V and P-V output characteristics

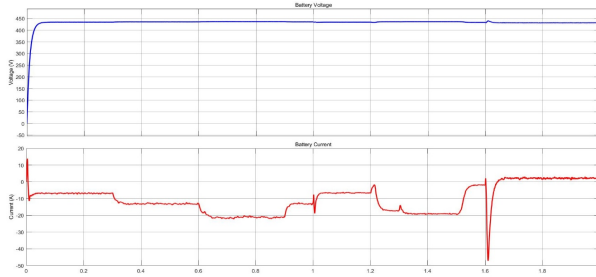


Figure 8: Battery system output waveforms

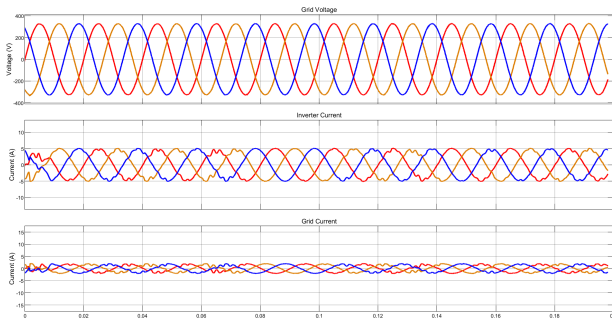


Figure 9: Grid Voltage, inverter current, and Grid Current

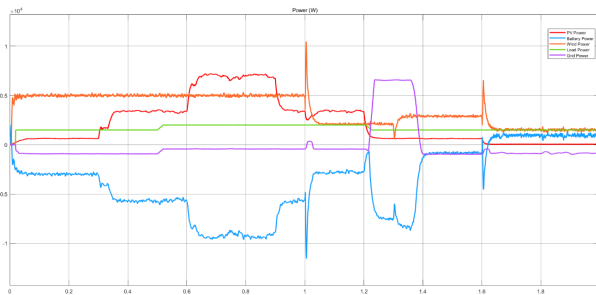


Figure 10: Wind turbine and generator output powers PWT, photovoltaic power PPV, battery power PBat, grid power PGrid, and load power PLoad

5. Conclusion and Recommendation

In this study, a novel PV/WT hybrid power system integrated with a grid is proposed and modelled. System components and an appropriate power flow controller were included in the designed algorithm. The model was created using the MATLAB/SIMULINK software package and a dialog box similar to those found in the SIMULINK block libraries. The simulation tests demonstrated the effective use of solar photovoltaics, wind turbine generators, and battery storage systems, as well as the good operating characteristics of their subsystems. The overall structure of the hybrid energy system, which consists of a wind/PV/battery energy system, pro-

vides a good and reliable energy system. All energy sources in the system are capable of supplying power, and any power drop can be compensated for by additional energy from other sources. When surplus power is generated, it can be sent to the AC grid or stored in a battery. Even under low wind speed or poor solar irradiation conditions, the studied renewable hybrid system can maintain a steady power supply to the load. A converter system with battery energy storage was added and connected to the common DC link to store the excess power. Regardless of whether there is a high or low demand for load electricity, the wind and solar systems are supported by this system. The simulation results demonstrated that the hybrid renewable energy system can possess the necessary technical and energetic qualities. Even under low wind speed or poor solar irradiation conditions, the studied renewable hybrid system can maintain a steady power supply to the load. The extra energy is stored in the battery system if the photovoltaic or wind turbine systems produce more energy than is needed. The extra power is delivered back to the AC grid if the battery is completely charged.

6. Author's declaration

The authors declare no conflicts of interest regarding the publication of this research paper. All contributors agreed to the final draft of the manuscript.

7. Declaration of the conflict of interest

The authors declare that they have no conflicts of interest. All authors contributed to the preparation of the final manuscript.

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