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Optimizing Wind-PV-Battery Integration for Sustainable Development

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Abstract: *The increasing demand for sustainable energy solutions and the drawbacks of fossil fuel-based power generation have propelled the development of renewable energy-based microgrids. This paper presents a MATLAB/Simulink model for the optimized integration of wind, solar photovoltaic (PV), and battery energy storage in a DC microgrid. The model aims to enhance system efficiency, ensure power reliability, and optimize energy management. A SEPIC converter interfaces the solar PV array with the DC bus, while the wind turbine is connected via an AC/DC rectifier. A lithium-ion battery storage system is integrated using a bidirectional DC-DC converter, enabling both charging and discharging to maintain supply-demand equilibrium. The model includes maximum power point tracking (MPPT) algorithms for solar and wind sources, load-following control strategies, and a battery management system (BMS). Simulation results validate the dynamic response of the system under varying load and generation conditions, illustrating improved voltage regulation, load sharing, and battery utilization*

Keywords: DC Micro Grid, PV Panel, Battery, wind turbine

I. INTRODUCTION

The authors proposed a control technique for managing grid interface current in a DC microgrid that does not require a separate grid interface converter. Instead, the battery's DC-DC converter is employed to directly manage the interface current, which reduces interference from PV generation and load fluctuations. The system is theoretically modelled, and two important transfer functions are developed to describe its dynamic behaviour. Experimental results demonstrate the strategy's ability to maintain steady grid current under shifting PV and load situations [1]–[3].While DC microgrids offer excellent performance as distribution networks, their protection systems remain underdeveloped. Most research to date has focused on topology, control, and energy management, with limited attention to fault detection and isolation. This paper reviews the current state of DC microgrid protection strategies and highlights key areas for future research, including the development of advanced electronic protection devices and integrated control-protection coordination methods [4]-[6].The paper presents a MATLAB/Simulink-based simulation model of a fully decarbonized DC microgrid integrating solar PV and wind energy as renewable sources. A SEPIC converter connects the solar PV, while an AC/DC converter links the wind generator. A lithium-ion battery provides energy storage via a bidirectional converter, enabling both charging and discharging to balance supply and demand. Power flows dynamically between the DC bus, loads, and battery based on generator availability. The simulation includes results for load voltage, current, power, and battery charging/discharging behaviour [7]-[9].

II DC MICRO GRID

Figure.1 shows the DC microgrid operating at 200V integrates solar photovoltaic and wind energy sources along with a 6.5Ah lithium-ion battery for energy storage. The solar PV and wind generator outputs are conditioned using individual DC-DC boost converters to step up their variable voltages to match the 200V DC bus. The wind turbine, coupled with a

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permanent magnet synchronous generator (PMSG), first converts variable AC to DC using a rectifier before being boosted [10]. A bidirectional DC-DC converter connects the battery to the microgrid, allowing it to charge when excess renewable power is available and discharge during power shortfalls. This setup ensures efficient power flow, voltage regulation, and reliable supply to DC loads under varying generation and consumption conditions.

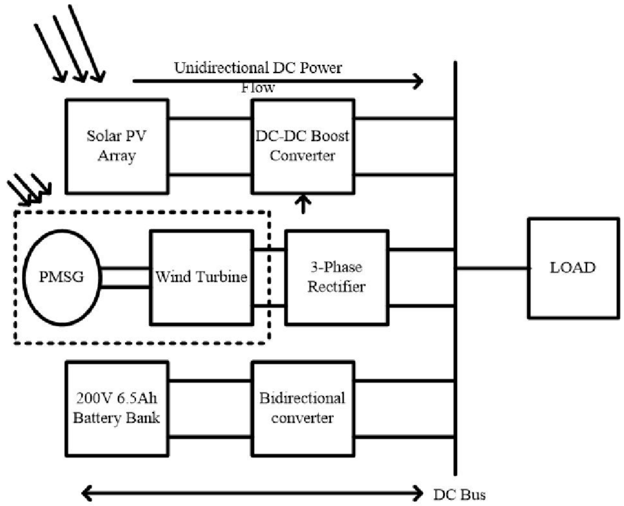

Figure.1 DC microgrid system

III TECHNICAL ANALYSIS

Modeling of the PV system

$$p = nV_{pv}I_{pv} \quad (1)$$

$$I_{pv} = I_{sc}\left(1 - C_1\left[e^{\left(\frac{V_{pv}-\Delta v}{C_2 V_{oc}}\right)} - 1\right]\right) + \Delta I \quad (2)$$

$$V_{PV} = V_{mpp}\left[1 + 0.0539\log\left(\frac{I_T}{I_{st}}\right)\right] + \beta_0 \Delta T \quad (3)$$

$$C_1 = \left(1 - \frac{I_{mpp}}{I_{sc}}\right)e^{\frac{-V_{mpp}}{C_2 * v_{oc}}} \quad (4)$$

$$C_2 = \frac{V_{mpp}/\left(V_{oc} - 1\right)}{In\left(1 - \frac{I_{mp}}{I_{sc}}\right)} \quad (5)$$

$$\Delta V = V_{pv} - V_{mpp} \quad (6)$$

$$\Delta I = \alpha_0\left(\frac{I_T}{I_{st}}\right)\Delta T + \left(\frac{I_T}{I_{st}} - 1\right)I_{sc} \quad (7)$$

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$$\Delta T = T_{cell} - T_{st} \quad (8)$$

$$T_{cell} = T_A + 0.02 I_T \quad (9)$$

The solar PV module used in the DC microgrid is rated for a maximum power output of 215.13 W. It has an open-circuit voltage (Voc) of 36.90 V and a short-circuit current (Isc) of 8.01 A. The module operates most efficiently at its maximum power point (MPP), where the voltage (Vmpp) is 30.3 V and the current (Impp) is 7.10 A. The module consists of 22 solar cells connected in series, contributing to its voltage characteristics. These electrical parameters are crucial for designing the DC-DC boost converter and implementing an effective MPPT algorithm to ensure maximum energy extraction under varying environmental conditions.

Table. 1 DC-DC converter system parameters

S.No	Parameter	Rating	Unit
1	Maximum power, Pamx	215.13	W
2	Open circuit voltage, Voc	36.90	V
3	Short-circuit current, Isc	8.01	A
4	Voltgae at maximum power-point,Vmpp	30.3	V
5	Current at maximum power-point,Impp	7.10	A
6	Number of cells per module	22	-

Modeling of the wind turbine generator

$$p = \frac{1}{2} c_p \pi r^2 \rho v^3 \quad (10)$$

$$\lambda = \frac{\omega r}{v} \quad (11)$$

$$C_p(\lambda, \beta) = 0.5176\left(\frac{116}{\lambda_i} - 0,4\beta - 5\right) e^{\frac{-21}{\lambda_i}} \quad (12)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^2} \quad (13)$$

$$T = \frac{P}{\omega} \quad (14)$$

$$\begin{aligned} \frac{d}{dt} i_d &= -\frac{R_s}{L_d} i_d + \frac{L_q}{L_d} p \omega_r i_q + \frac{1}{L_d} v_d \\ \frac{d}{dt} i_d &= -\frac{R_s}{L_d} i_d + \frac{L_q}{L_d} p \omega_r i_q - \frac{\omega_r}{L_q} \psi_{pm} + \frac{1}{L_q} v_q \end{aligned} \quad (15)$$

$$T_e = 0.75\left[\psi_{pm} + \left(L_d - L_q\right) i_d i_q\right] \quad (16)$$

Modeling of the battery bank

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$$E_b = E_0 + \int_0^t V_b I_b dt \tag{17}$$

$$\frac{SOC(t)}{SOC(t-1)} = \int_{T-1}^{t} \frac{P_b(t)\eta_b}{V_{bus}} dt \tag{18}$$

3.4 Modeling of the power converters

$$V_{0(ripple)} = \frac{I_{0(av)}\delta}{fL} \tag{19}$$

$$i_{0(ripple)} = \frac{V_s\delta}{fL} \tag{20}$$

$$V_{0(av)} = \frac{V_s}{1-\delta} \tag{21}$$

IV SIMULACTION RESULTS

Figure 2 illustrates the interconnection of a DC microgrid, which integrates solar panels, wind turbines, and a battery storage system. The wind energy converter transforms AC power generated by the wind turbine into DC power. Similarly, the solar panel system converts sunlight directly into DC electricity through its associated converter.Figure 3 presents the internal configuration of the wind turbine system, detailing the key components involved in energy generation and conversion.Figure 4 shows the speed and torque converter used to control the performance of the wind turbine. The controller is designed to decouple the direct axis (D-axis) and quadrature axis (Q-axis) components of the current for efficient vector control.Figure 5 demonstrates the reference current generator, which plays a crucial role in regulating power flow and maintaining stability within the microgrid system.

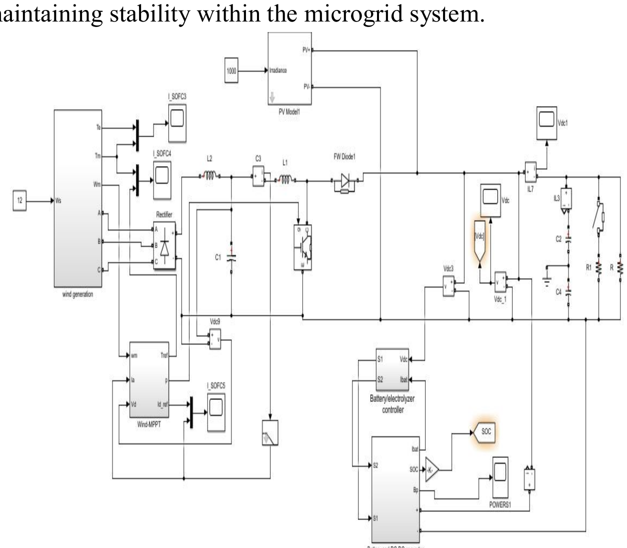

Figure.2 DC micro grid interconnection

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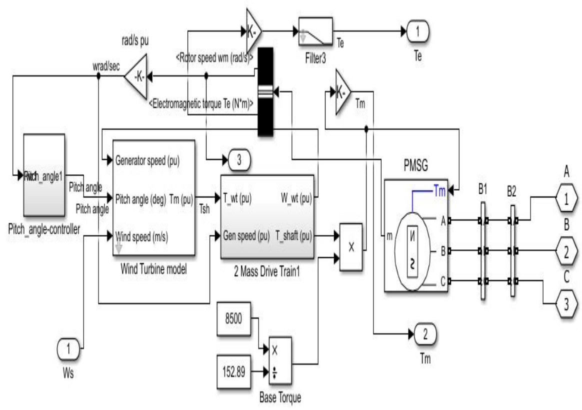

Figure.3 wind turbine subsystem connections

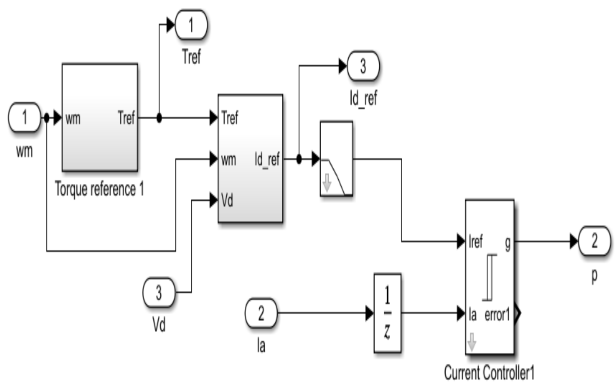

Figure.4 Speed to Torque Converter

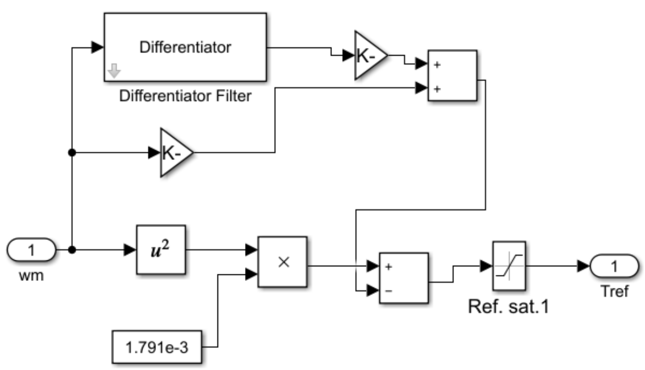

Figure.5 Reference torque generator

Figure 7 shows the reference current generator. In this block, a multiplexer multiplies the speed and torque inputs to produce the reference voltage required for current regulation. Figure 8 displays the speed and torque output waveforms. The torque reaches a magnitude of 50 N·m, while the speed peaks at 150 rad/s. Figure 9 illustrates the output voltage and current waveforms of the wind generator. Notably, the output voltage is highly distorted up to 0.05 seconds, and a similar distortion is observed in the current waveform during this initial period. Figure 10 presents the bi-directional

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battery charger circuit. The system features a 200V, 6.5Ah battery, and uses four IGBT switches to manage charging and discharging operations, enabling controlled energy flow in both directions.

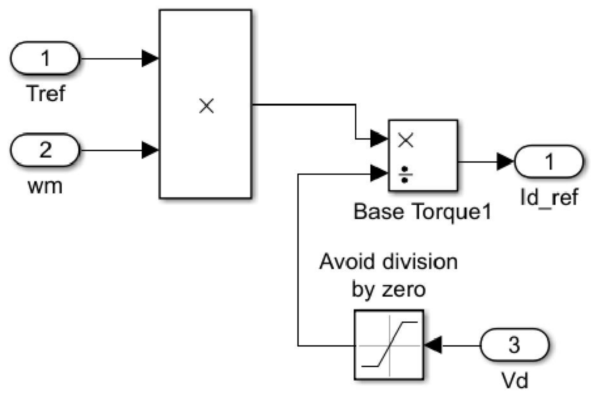

Figure.7 Reference current generator

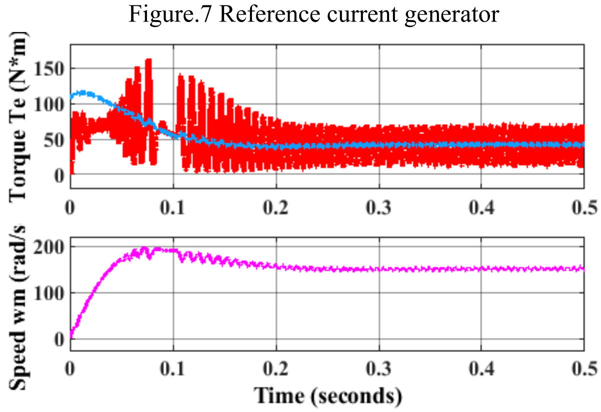

Figure.8 wind turbine output waveforms

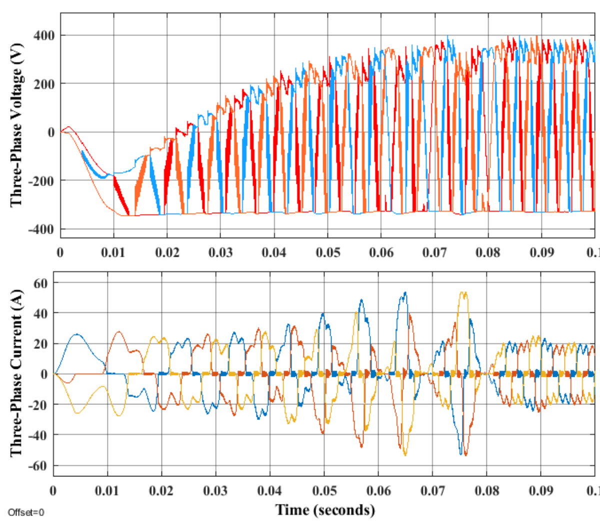

Figure.9 wind generator outputs voltage and current

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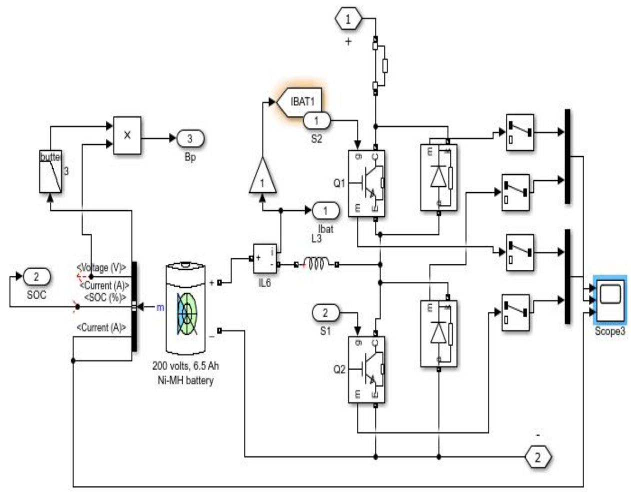

Figure.10 bio-directional battery charger circuit

Figure 11 shows the switching pulses for the bi-directional DC-DC converter. In this circuit, switches S1 and S2 operate in a complementary manner, enabling controlled charging and discharging of the battery.Figure 12 displays the battery voltage, current, and State of Charge (SOC). The battery voltage is 320 V, the SOC is 50%, and the current magnitude is -50 A, indicating discharging mode.Figure 13 presents the output voltage of the PV panel, reflecting the solar energy contribution to the DC microgrid.Figure 14 illustrates the voltage and current of the DC microgrid, providing insight into the overall system performance and power flow dynamics.

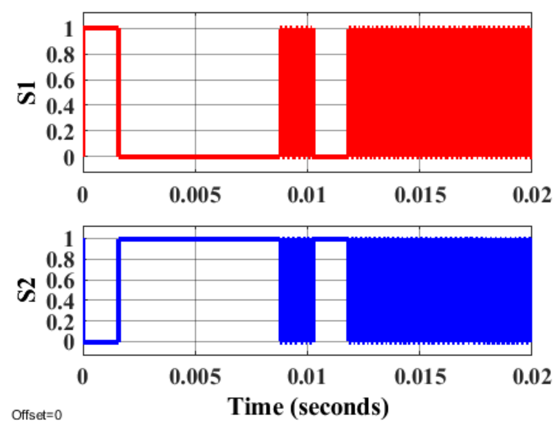

Figure.11 PWM pulses for Battery charger

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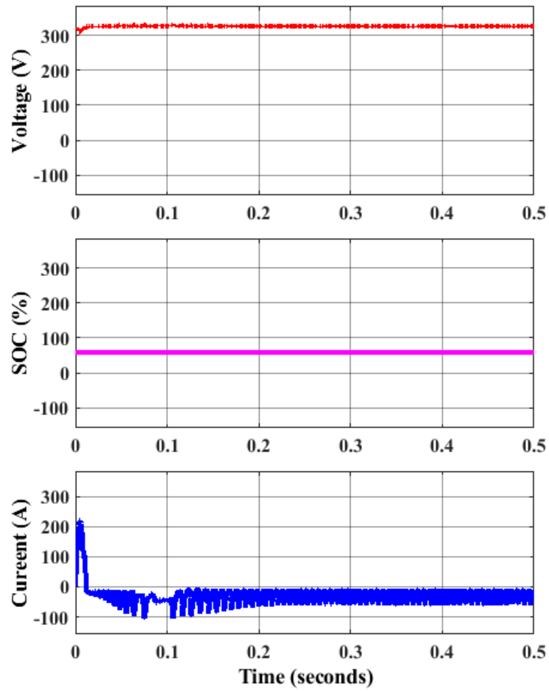

Figure.12 Battery voltage, SOC and current

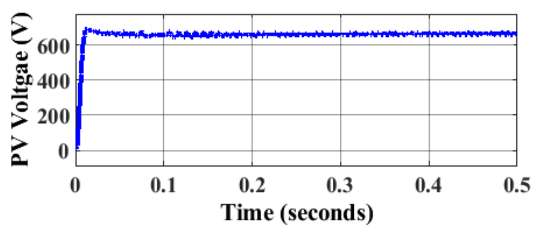

Figure 13. PV Panel Voltage

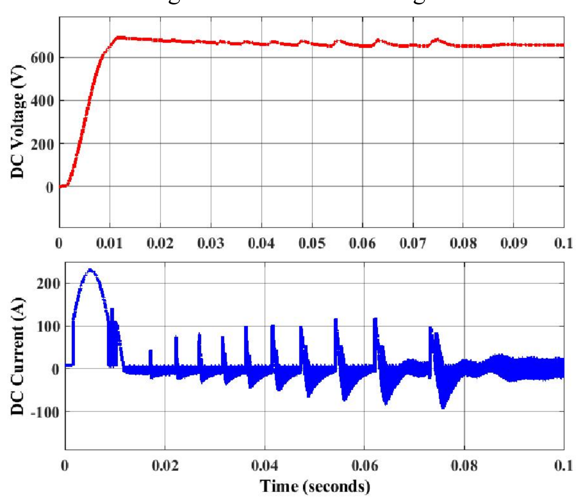

Figure.14 DC Micro Grid Voltage and Current

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V CONCLUSION

This paper presented a DC microgrid integration approach for renewable energy applications. The main objective of this work is to maximize power generation using renewable sources such as solar and wind, contributing to sustainable development goals. The proposed system was designed and simulated using MATLAB/Simulink. The simulation results include key performance metrics such as voltage, current, power output, battery State of Charge (SOC), PV voltage, and wind turbine speed and torque.

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