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The Implementation of PV-Battery Storage-Wind Turbine-Load- on Grid System

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ABSTRACT

The system is designed to promote the use of renewable energy sources and reduce dependence on non-renewable energy sources such as fossil fuels. The system comprises several components, including photovoltaic (PV) panels, wind turbines, battery storage, load management, and the main grid. The integration of these components provides a reliable and stable source of electricity for households and businesses, particularly in areas prone to power outages. The battery storage system helps to balance the intermittent nature of renewable energy sources, providing a more consistent supply of electricity. Additionally, this system can reduce the carbon footprint of the electricity generation process and contribute to mitigating the effects of climate change. Overall, the implementation of a PV-battery storage-wind turbine-load-main grid system has the potential to transform the way we generate and consume electricity, creating a more sustainable and resilient energy system for future generations.

INTRODUCTION

The exponential rise in energy demand and growing concerns about the negative impact of fossil fuels on the environment have led to an increase in the utilization of renewable energy systems (RES) for sustainable power supply [1,2]. RES relies on renewable sources, such as wind, solar, tides, and rain, which are natural resources that are constantly replenished by natural processes [3]. The wind turbine is by far the most widespread type of renewable energy-producing device. Wind production has evolved over the last decade so that you can now establish and run massive clusters of wind systems to produce wind farms [4,5]. Furthermore, wind turbines are also being created particularly for placement on the ocean shores, where there is a constant high wind blowing. Solar energy source, on the other hand, offers numerous advantages and have been used in many applications [6,7]. It relies on cells that practically transformed the sunlight into DC electrical energy. The DC power is subsequently converted to AC electric power using suitable power electronics converters. Small photocell arrays can be installed on the roof or used in a single residence and wired to supply power directly to the electric system. Also, a huge number of solar modules can be grouped and connected to deliver electricity directly to the grid [8-13].

Because renewable energies are derived from nature, they are dependent on the weather, therefore they are susceptible when only a single source is used to establish a reliable power grid [14,15]. By combining several sources of renewable power, such as solar wind, which supplement each other during the day and at night both in the winter and summer [16,17,18]. The hybridization of renewable sources can provide smooth, and stable output to power grids at a lower cost than investments in individual renewable technologies. Moreover, a hybrid system that incorporated a storage system (such as a battery) offers more flexibility, in the sense that the surplus energy produced by the wind engine and solar can be stored and used when the wind and sunshine, and electricity are not being produced [19,20]. The hybrid renewable energy system can be categorized into standalone and grid-connected [21]. In the grid-connected, the system may include a non-renewable source. To integrate the hybrid system into a grid, the micro-grid system is first been modeled to analyze the different scenarios and design a control strategy in an event of faults [22,23].

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LITERATURE REVIEW

The implementation of a PV-battery storage-wind turbine-load-main grid system has the potential to significantly contribute to the transition towards clean and sustainable energy. This system combines various renewable energy technologies to ensure a stable and reliable power supply, while also reducing greenhouse gas emissions and promoting energy independence. Simulation results have shown that such a system can effectively meet the electricity demand of a given area, while minimizing reliance on the main grid and reducing the costs associated with energy consumption. The utilization of battery storage technology in the system ensures the availability of power during periods of low renewable energy generation, while excess electricity can be fed back into the main grid, contributing to the local energy supply.

Moreover, the implementation of this system has positive environmental impacts, reducing greenhouse gas emissions, and promoting sustainable development. Additionally, it reduces reliance on traditional fossil fuel-based energy sources, which are often associated with price volatility and geopolitical risks. The PV-battery storage-wind turbine-load-main grid system presents a promising solution to the energy challenges faced by many regions worldwide, with the potential to facilitate the transition towards a sustainable and clean energy future.

This article presents a modeling and simulation of a grid-connected PV-Battery-Wind-load hybrid system with fault control. The article is organized as follows: section 2 provides the system description, section 3 presents the components of mathematical modeling, and the simulation and simulation results are discussed in Sections 4 and 5 respectively. Finally, the report is concluded in section 6.

METHOD

Firstly, photovoltaic (PV) panels are installed to generate electricity from sunlight. The PV panels are connected to a battery storage system, which allows excess energy generated during daylight hours to be stored for later use. Secondly, wind turbines are installed to generate electricity from wind energy. The wind turbines are connected to the same battery storage system as the PV panels. Thirdly, the load, which represents the electricity consumption of the system, is connected to the battery storage system. The load can be anything from residential homes to commercial buildings or industrial processes. Finally, the entire system is connected to the main grid, which allows excess energy generated by the PV panels and wind turbines to be fed back into the grid. This also allows the system to draw electricity from the grid when the PV panels and wind turbines are not generating enough energy to meet the system's demand. The implementation of this system requires careful planning and design to ensure that the components are properly sized and integrated to meet the system's energy demand. Additionally, the system must be monitored and maintained to ensure its continued operation and reliability.

System description

The grid-connected hybrid PV-wind-battery-based system is shown in Figure 1. The proposed hybrid system consists of a 300 W PV module, a 150 W wind turbine, battery storage of 30 Ah capacity, and control strategies. The system can be used to serve households. Faults within the system can be controlled by using circuit breakers to isolate faulty components. The main grid is connected through transformers to provide further protection and fault control in the system [24,25,26].

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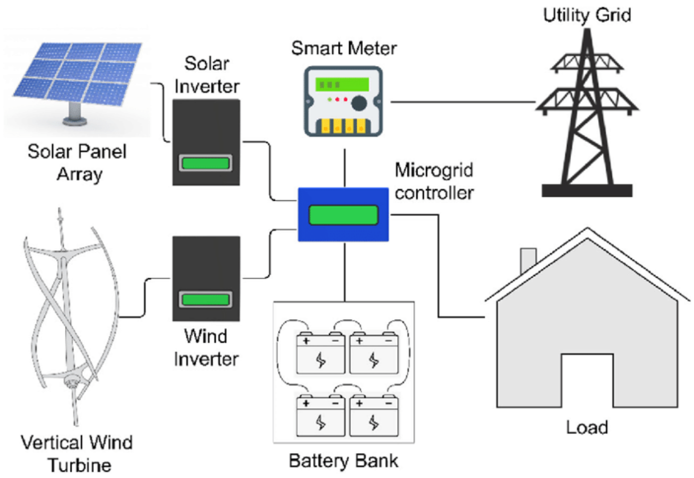

Figure 1. Grid-connected hybrid PV-wind-battery based system

This section provides the mathematical modeling of the main system components; the PV cell, the wind turbine, and the battery storage system. The components' dynamics are expressed in terms of ordinary differential equations and transfer functions.

PHOTOVOLTAIC CELL MODEL

A PV cell can be described as a semiconductor device that absorbs light energy and converts it to electricity. For this study, the single-diode PV equivalent circuit (Figure 2) is considered. In this circuit, the energy losses due to the leakage current and the current flowing true the cell are represented by the shunt resistance (Rsh) and series resistance (R_s) [27,28].

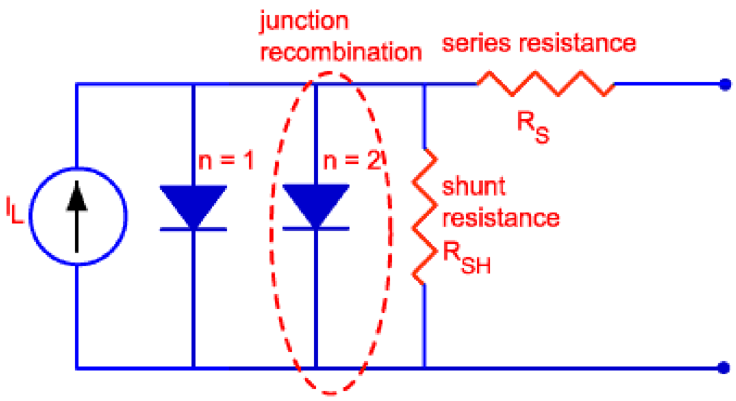

Figure 2. PV cell single diode equivalent circuit [28]

The mathematical model can be derived from the equivalent circuit as follows [29]: Applying Kirchoff's current law (KCL), the PV current I, is expressed by equation (1).

$$I = I_{ph} - I_d - I_{R_{sh}} \tag{1}$$

Where I_{ph} is the photon current, I_d and $I_{R_{sh}}$ are the currents through the diode and the current through the shunt resistance, respectively. The diode's current I_d is given by:

$$I_d = I_o\left(e^{\left(\frac{V_d}{V_T}\right)} - 1\right) \tag{2}$$

Where I_o is the saturation current, the voltage across the V_d and V_T can be defined as:

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$V_d = V + IR_s$

$V_T = \frac{KTnN_s}{q}$

Where the constants T is the temperature, K is the Boltzmann constant, n is the diode ideality factor, Ns is the number of series-connected cells, and q is the electron charge. The shunt current can now be expressed as:

$$I_{sh} = \frac{IR_s + V}{R_{sh}} \quad (3)$$

The photon current is expressed as

$$I_{ph} = (I_{sc} + K_i(T - T_r))G \quad (4)$$

By obtaining the information about the constants from the manufacturer's datasheet the behavior of the PV can be obtained upon simulating the above mathematical model.

WIND POWER SYSTEM MODEL

The wind turbine control power production is present in three stages as shown in Figure 3. In the first stage, the air's kinetic energy is transformed into mechanical energy. In the second stage, the turbine is coupled to a gearbox to regulate the speed torque which serves as input to the generator. The generator converts the mechanical rotation to electricity. The electrical energy is then converted to various voltage levels using inverters and converters [30].

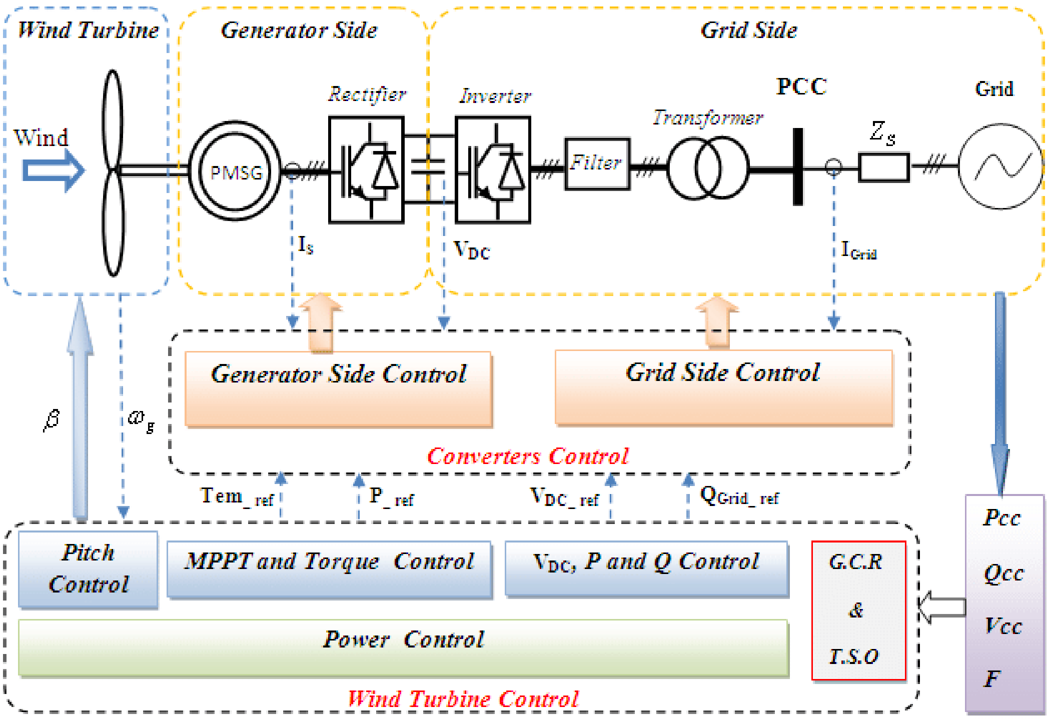

Figure 3. The wind turbine control modeling

The modeling of the wind turbine, therefore, entails the derivation of the mathematical equations describing the relationships of the power produced and transformed within and between the various stages. The wind speed is related to the wind turbine power using equation (5).

$$P_w = 0.5\rho Av3C_p(\beta, \lambda) \quad (5)$$

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Where v represents the wind speed, ρ is the air density, v represents the wind speed, A the effective area and C_p is known as the power coefficient. The C_p can be expressed in terms of the pitch angle β and tip speed ratio λ using equation (6).

$$C_p = 0.5176\left(\frac{116}{\lambda_j} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_j}} + 0.0068\lambda \quad (6)$$

Where;

$$\frac{1}{\lambda_j} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \quad (7)$$

$$\lambda = \frac{\omega_w R}{v} \quad (8)$$

where R is the blade ratio, ω_w is the turbine rotor speed. The maximum Cp is obtained as 0.48 in [f], at a β = 0o and a nominal tip speed λ = 8.1.

The current, voltage, and power of the permanent magnet synchronous generator (PSMG) can be described by the following system of differential equations (Ko):

$$\frac{di_d}{dt} = \frac{v_d}{L_d} - \frac{R}{L_d}i_d + \frac{L_q}{L_d}pi_q\omega_m$$

$$\frac{di_q}{dt} = \frac{v_q}{L_q} - \frac{R}{L_q}i_q + \frac{L_q}{L_d}pi_d\omega_m - \frac{\lambda p\omega_m}{L_q} \quad (9)$$

$$L_d = L_q = \frac{L_{ab}}{2}$$

The ω_m represent the rotor velocity, ρ is the total number of pole pairs, λ is the induced flux and R is the stator resistance. The subscripts d and q are used to indicate the direct and quadrature-axis components, respectively. The phase-phase inductance is given by L_{ab}. Now, equation (10) can be used to describe the stator's active and reactive power [31].

$$P_s = v_d i_d + v_q i_q, \qquad Q_s = v_d i_q - v_q i_d \quad (10)$$

Furthermore, the torque equation is given by:

$$T_e = 1.5\rho\left(\lambda i_q + \left(L_d - L_q\right)i_d i_q\right) \quad (11)$$

Finally, the AC output is transformed to a DC voltage using a diode rectifier. The rectifier output voltage is given by the following equation (f1):

$$v_0(t) = V_0 + \sum_{i=6,12,18......}^{\infty} V_i Cos(n\omega_o t + \pi) \quad (12)$$

And the dc voltage component is:

$$V_0 = \frac{3V_{m,L-L}}{\pi} \quad (13)$$

And the amplitude is:

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$$V_i = \frac{6V_{m,L-L}}{\pi(i^2-1)} \quad i = 6, 12, 18 \ldots.. \tag{14}$$

where $V_{m,L-L}$ is the line-line peak voltage of the wind turbine output.

BATTERY STORAGE MODEL

To model the dynamic charging and discharging of the battery can be modeled as described in [7], as shown in Figure 4, by the following equations:

Discharging Mode $(i_l > 0)$ (15)

$$E_{discharge} = f_1(i_t, i_l, i, Exp) = E_0 - K\frac{Q}{Q-i_t}i_l - K\frac{Q}{Q-i_t}i_t + L^{-1}\left(\frac{Exp(s)}{Sel(s)}.0\right)$$

Charging Mode $(i_l < 0)$

$$E_{charge} = f_2(i_t, i_l, i, Exp) = E_0 - K\frac{Q}{i_l+0.1Q}i_l - K\frac{Q}{Q-i_t}i_t + L^{-1}\left(\frac{Exp(s)}{Sel(s)}\frac{1}{S}\right) \tag{16}$$

Herein, the symbol Q represents the battery's maximum capacity in (Ah), and K is the polarization constant expressed in V/Ah. E_0 is a constant voltage, Sel(s) is the selection of battery mode, with 1 indicating charging and 0 indicating discharging, and Exp(s) is the voltage exponential dynamic. i_l and i represent the dynamics of the low-frequency current and the battery current, respectively.

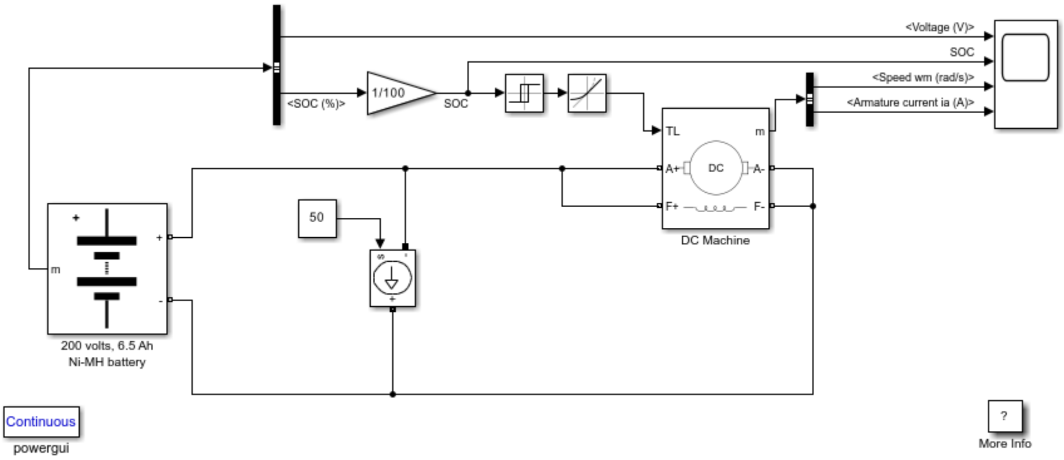

Figure 4. Battery model

Thus, the following transfer function model is defined:

$$\frac{Exp(s)}{Sel(s)} = \frac{A}{\frac{1}{Bi(t)}S + 1} \tag{17}$$

Where A and B represent the exponential voltage and the capacity (Ah^{-1}).

RESULT AND DISCUSSION

The proposed system modeled in subsection 3, is simulated in this section. The simulation is done using Matlab/Simulink software along with its various tools boxes including the simscape electrical toolbox. Table 1, present Solar PV Modules S-energy manufacture data sheet. Table 2, shows temperature characteristic

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TABLE1: 300W Solar PV Module S-Energy manufacturer Data Sheet:

Rated Power (Pmax)	300 w
Voltage at Power max (Vmp)	35.6V
Current at Power max(Imp)	8.44 A
Short Circuit Current (Isc)	8.88 A
Open Circuit Voltage (Voc)	44.9 V
Module Efficiency	15.38% / 15.13%

Table 2: Temperature Characteristics:

Temperature Coefficient of Isc	0.056 / ℃
Temperature Coefficient of Voc	-0.301 / ℃
Temperature Coefficient of Power	-0.398 / ℃

The simulation model of the PV system is shown in Figure 5. The system is developed by using the equations (1) - (4). Figure 6, shows the overall PV module. The datasheet for the simulation is given in Table 1 and Table 2.

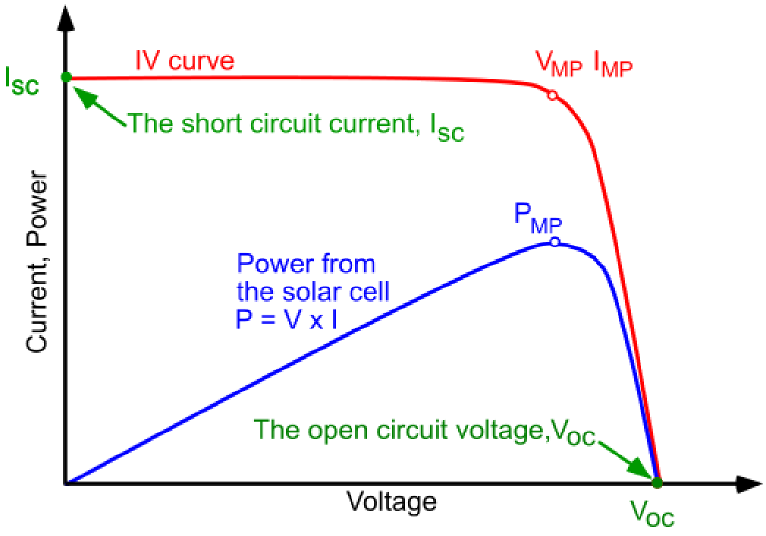

Figure 5. PV Current I

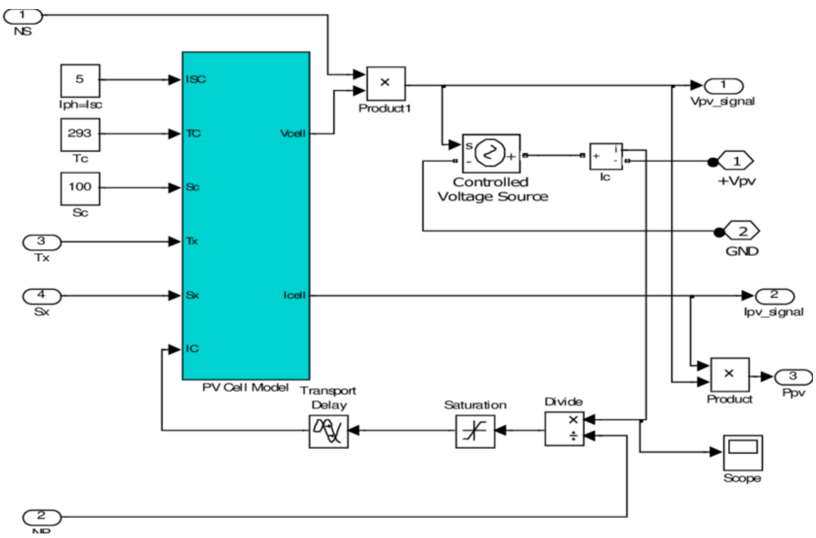

Figure 6. PV Module

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A PV module, also known as a solar panel, is an electronic device that converts sunlight into electrical energy through the photovoltaic effect. It consists of multiple solar cells interconnected in a series and mounted on a rigid or flexible substrate. The most commonly used solar cells are made of silicon and are encapsulated in a durable and weather-resistant material. The amount of electricity generated by a PV module depends on the amount of sunlight received, the efficiency of the solar cells, and the orientation and tilt of the panel. PV modules can be used in a variety of applications, including residential, commercial, and utility-scale solar installations. They are an important technology for the generation of clean and renewable energy and play a crucial role in the transition to a low-carbon economy. The wind turbine is modeled using the Simulink wind turbine block. The main grid is modeled using the Simulink components Figure 7, including a 3-phase supply, and transmission lines. A step-down transformer is used to step down. The overall grid-connected hybrid system is shown in Figure 8.

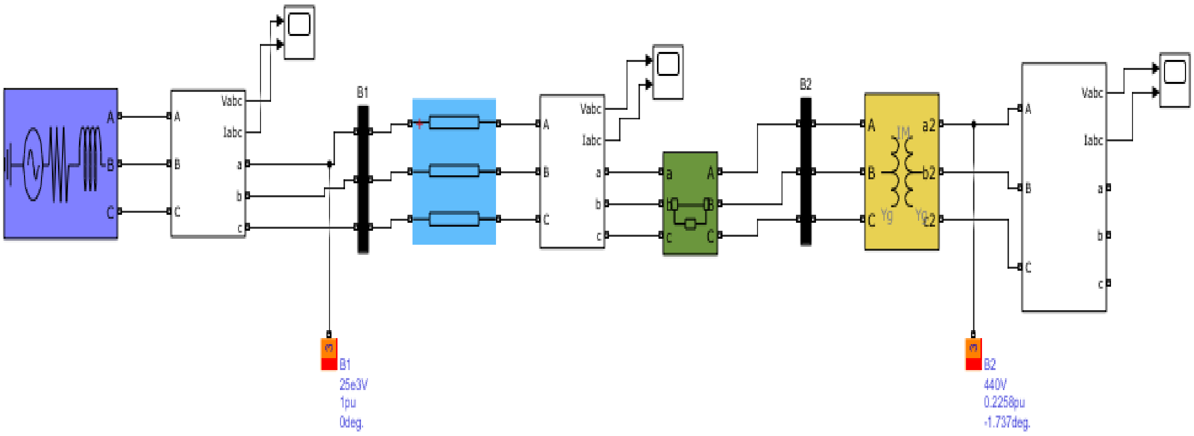

Figure 7. Main grid model

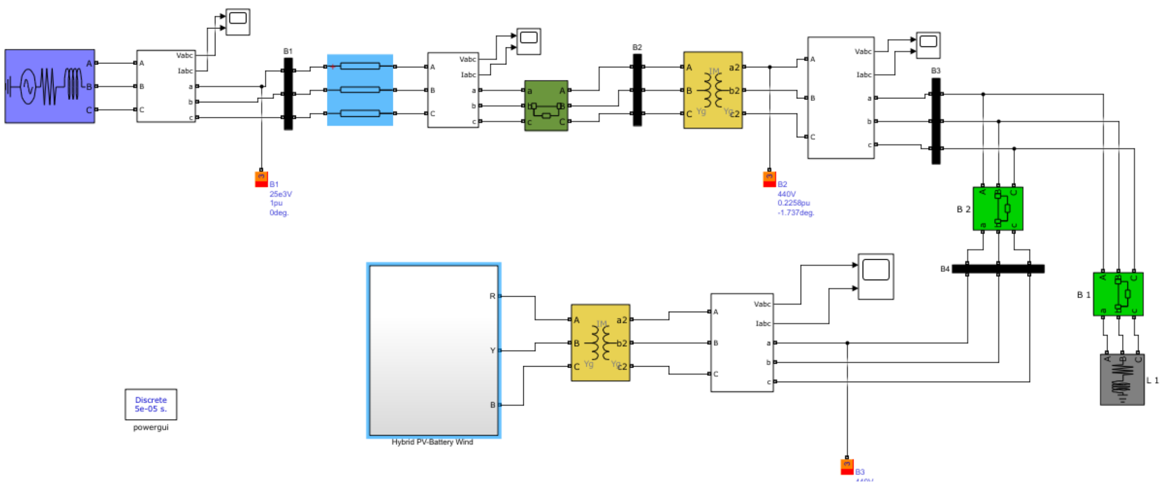

Figure 8. Grid-connected PV-wind-battery-load system model

The grid-connected PV-wind-battery-load system model is a simulation model used to analyse the performance of a hybrid energy system that combines photovoltaic (PV) modules, wind turbines, batteries, and a load connected to the main power grid. This model typically considers the dynamic behaviour of the components and the interaction between them to determine the optimal system design and operation strategy. The PV module converts solar energy into electrical energy, which is then fed into the system. The wind turbine converts the wind energy into electrical energy, which is also fed into the system. The batteries are used to store the excess electrical energy generated by the PV modules and wind turbines during periods of high generation and to supply the load during periods of low generation. The load represents the energy demand of the system, which can vary over time.

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The grid connection allows for excess energy to be fed into the main power grid, and for energy to be drawn from the grid during periods of low generation or high demand. The system controller is responsible for managing the interaction between the different components of the system to ensure efficient operation and minimize energy waste. The performance of the grid-connected PV-wind-battery-load system model can be evaluated based on various metrics, such as the levelized cost of electricity (LCOE), the capacity factor, and the system's reliability. Optimization techniques can also be applied to determine the optimal system design and operation strategy that maximizes the system's performance while minimizing costs.

CONCLUSIONS

In conclusion, the implementation of a PV-battery storage-wind turbine-load-main grid system has several benefits. Firstly, it promotes the use of renewable energy sources, reducing dependence on non-renewable energy sources such as fossil fuels. Secondly, it provides a reliable and stable source of electricity for households and businesses, particularly in areas prone to power outages. Thirdly, the integration of battery storage helps to balance the intermittent nature of renewable energy sources, providing a more consistent supply of electricity. Additionally, this system can reduce the carbon footprint of the electricity generation process and contribute to mitigating the effects of climate change. Overall, the implementation of a PV-battery storage-wind turbine-load-main grid system has the potential to transform the way we generate and consume electricity, creating a more sustainable and resilient energy system for future generations.

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