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DESIGN AND SIMULATION OF IOT CONTROLLED AND MONITORED MICROGRID SYSTEM

Naziya Haseen, **Dr MOHD Ilyas**, Department of Electronics & Communication Engineering, Al-Falah University, Faridabad, India
Dr Safdar Tanweer, Department of CSE, Jamia Hamdard

Abstract
The increasing integration of renewable energy sources into power systems necessitates advanced control and monitoring mechanisms to ensure system stability, efficiency, and reliability. This paper presents the design and simulation of an Internet of Things (IoT) controlled and monitored microgrid system. The proposed model employs IoT technologies to achieve real-time data acquisition, processing, and control of microgrid components. The system integrates renewable energy sources, energy storage, and smart loads while providing adaptive control through advanced algorithms. A MATLAB/Simulink simulation is conducted to validate the performance of the proposed system. Results demonstrate significant improvements in energy efficiency, load management, and fault detection capabilities. This paper presents the design and simulation of an IoT-controlled and monitored microgrid system comprising photovoltaic (PV) panels, wind turbines, battery storage, and a diesel generator. The proposed microgrid aims to enhance energy efficiency, reliability, and sustainability by integrating multiple renewable energy sources with conventional backup systems. The system's IoT-based control and monitoring infrastructure enables real-time data acquisition, remote control, and decision-making through intelligent algorithms. This work demonstrates the potential of IoT-enabled microgrids to meet the energy demands of modern, smart infrastructures while reducing dependence on fossil fuels and minimizing carbon emissions. The simulation results validate the system's effectiveness and provide insights into its practical implementation.
Keywords
Microgrid, IoT, Renewable Energy, MATLAB/Simulink, Real-time Monitoring, Energy Efficiency

Introduction
The increasing demand for sustainable energy solutions has spurred the growth of microgrids that integrate distributed energy resources (DERs) such as solar photovoltaic (PV), wind turbines, and energy storage systems (ESS). Microgrids offer localized energy generation and consumption, reducing dependency on centralized grids and minimizing transmission losses. However, the integration of variable renewable energy sources poses challenges in maintaining grid stability and efficiency. The evolution of smart grids has been a significant development in the field of energy management. A microgrid, a localized energy system consisting of distributed energy resources (DERs) and loads, operates either autonomously or connected to the main grid. The integration of the Internet of Things (IoT) into microgrid systems has revolutionized their control and monitoring, enabling enhanced energy efficiency, resilience, and reliability. IoT-controlled and monitored microgrid systems leverage real-time data acquisition, cloud computing, and intelligent algorithms to optimize energy generation, distribution, and consumption. The rapid growth of renewable energy sources such as solar and wind further underscores the need for advanced monitoring and control mechanisms to maintain stability and efficiency in microgrid operations. This paper explores the design and simulation of an IoT-controlled and monitored microgrid system. It focuses on the integration of IoT devices for real-time data monitoring, predictive analytics, and automated control to ensure an energy-efficient and sustainable power supply. The system's design incorporates key elements such as smart sensors, controllers, and communication protocols to achieve seamless operation. The simulation highlights the potential benefits, including reduced energy losses, cost savings, and enhanced system reliability. The Internet of Things (IoT) has emerged as a transformative technology for real-time monitoring and control of complex systems. By enabling

seamless communication among devices, IoT facilitates the efficient operation of microgrids. This paper aims to design and simulate an IoT-enabled microgrid system to address these challenges, emphasizing energy efficiency and system resilience.

Literature Review

The integration of IoT in microgrid systems has been widely studied, with significant advancements in control, monitoring, and optimization techniques. This section reviews key contributions to the field, highlighting the role of IoT in enhancing the performance, reliability, and sustainability of microgrids.

The concept of microgrids as a decentralized energy management system has been extensively explored. Lasseter [1] introduced the foundational framework for microgrids, emphasizing their potential to operate autonomously or in grid-connected mode. Subsequent works focused on control strategies to ensure stability during islanded operation [2].

The advent of IoT has significantly enhanced microgrid functionalities. Xu et al. [3] proposed an IoT-based smart microgrid management system that utilizes real-time data to optimize energy generation and consumption. The integration of IoT devices enables predictive analytics and fault detection, as demonstrated in several studies on home energy management systems [4].

Communication technologies play a pivotal role in IoT-based microgrids. Khaitan and McCalley [5] highlighted the importance of robust communication protocols for effective cyber-physical system design in smart grids. Similarly, Pipattanasomporn et al. [6] demonstrated the use of multi-agent systems to achieve distributed control and coordination within microgrids.

Energy management in IoT-enabled microgrids has also been a focus of research. Shareef et al. [7] reviewed intelligent controllers and demand response mechanisms for improving energy efficiency. Advanced algorithms, such as machine learning-based optimization techniques, further enhance the operational efficiency of microgrids [8].

The integration of renewable energy sources in microgrids introduces variability in power generation, necessitating advanced control strategies. Zambrano-Asanza et al. [9] presented an IoT-based energy management system for optimized microgrid operations, addressing challenges posed by intermittent renewable energy. Farhangi [10] emphasized the critical role of IoT in enabling smart grid functionalities, paving the way for a more sustainable energy future. The literature underscores the transformative impact of IoT on microgrids, from real-time monitoring to intelligent decision-making. However, challenges such as cybersecurity risks, scalability, and interoperability remain areas of on-going research.

Advances in Microgrid Technology with IoT

Microgrids have evolved significantly over the past decade, driven by advances in DERs and control strategies. Various configurations of microgrids, including grid-connected and standalone systems, have been studied extensively. Key challenges include the intermittent nature of renewable energy sources, effective load balancing, and fault tolerance. The global transition to renewable energy sources has accelerated the need for advanced energy management systems. Microgrids, as localized energy systems, offer a sustainable solution by integrating various energy sources and enabling efficient energy distribution. The advent of the Internet of Things (IoT) has transformed the way microgrids are monitored and controlled, ensuring enhanced reliability, flexibility, and efficiency. This document explores the design and simulation of IoT-controlled and monitored microgrid systems, highlighting their key components, benefits, challenges, and future potential.IoT refers to a network of interconnected devices that communicate and exchange data in real time. When applied to microgrids, IoT enables seamless integration of sensors, actuators, communication protocols, and cloud-based analytics platforms. This integration facilitates real-time monitoring, predictive maintenance, and autonomous control of microgrid components. Microgrids typically comprise renewable energy sources (e.g., solar panels, wind turbines), energy storage systems (e.g., batteries), and loads (e.g., residential or industrial consumers). IoT enhances microgrid operations by providing real-time insights into power generation, storage, and consumption patterns, thus optimizing energy flow and improving overall system resilience. IoT applications in power systems have focused on real-time data acquisition, predictive analytics, and intelligent control. Technologies such as wireless sensor networks (WSNs), cloud computing, and edge devices have enabled advanced microgrid monitoring and control systems. Studies highlight the role of IoT in enhancing operational efficiency and providing adaptive control mechanisms.

Hybrid Microgrid System

A microgrid with a hybrid energy system comprising photovoltaic (PV) panels, wind turbines, diesel generators, battery storage, and grid connectivity represents a versatile and efficient energy management system. This configuration integrates renewable energy sources with conventional and backup power systems to ensure reliability, efficiency, and sustainability. The hybrid microgrid system, integrating PV, wind, and diesel generators, offers a sustainable and reliable energy solution for diverse applications. By leveraging renewable energy sources and incorporating advanced storage and control systems, these microgrids can meet the growing energy demands while reducing environmental impact. While challenges such as high costs and system complexity exist, advancements in technology and innovative operational strategies promise a bright future for hybrid microgrids. These systems represent a crucial step toward achieving global energy sustainability and resilience.

Photovoltaic (PV) System

PV module modeling

Modeling a photovoltaic (PV) module involves representing the electrical behavior of the solar cells in the module under different conditions. This is typically achieved using mathematical models and equivalent electrical circuit shown in Fig-1 .

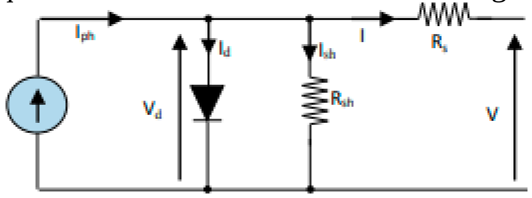

Figure-1 Equivalent circuit of solar cell

$$I = I_{ph} - I_d - I_{sh} = \{ I_{SCR} + K_i(T-T_r)\} \left(\frac{G}{1000}\right) - I_0\left[\exp\left(\left(\frac{q}{aKT}\right)(V+IR_s)\right)-1\right] - \left(\frac{V+I*R_S}{R_{sh}}\right) \quad (1)$$

I_{ph} is solar generated voltage, Iph depend on solar radiation and cell temperature .

I_0 is the reverse saturation current of diode.

$$I_o = I_{rs}\left\{\frac{T}{T_r}\right\} \exp\left[\frac{qE_{go}}{aK}\right] \left(\frac{1}{T_r} - \frac{1}{T}\right)] \quad (2)$$

Sr.	Represented by	Parameters
1	V	Output voltage of solar cell
2	I	Output current of solar cell
3	I_{SCR}	short circuit current of solar cell
4	Ki	Short circuit temperature coefficient
5	T_r	Reference temperature
6	I_{rs}	Saturation current at reference temperature
7	T	Temperature (K)
8	K	Boltzmann constant (1.38*10-23 J/K),
9	Rsh	Shunt resistance of PV cell in ohm

Table-1 Solar cell parameters[9,10]

N_s, is number of series solar cells in a module
N_p, is number of parallel solar cells in a module
If Ns is the number of series solar cell per module and Np is parallel solar cell per module,
The solar output current I
I=N_pI_{ph}- N_pI_0 [exp (($\frac{q}{aKT}$)($\frac{V}{N_s}$ +$\frac{IRs}{N_p}$))-1}- $\frac{N_p}{R_{sh}}$($\frac{V}{N_s}$ +$\frac{IR_s}{N_p}$)] (3)

Wind Power System

PMSG generator model Most manufacturers choose the PMSG wind turbine with a voltage source converter (VSC) because it is more dependable and efficient. Its gearless design, lack of a dc excitation mechanism, and capacity to capture the most wind power are its benefits over a doubly fed induction generator (DFIG). Figures 3a and 3b show a simplified PMSG equivalent circuit d − q coordinate frame model. Equations (4) and (5) provide the current equations for the d− and q− axes in the generator's dq-coordinate model, while Equation (6) establishes the electromagnetic torque in the rotor, Te [12,14].

$$\frac{di_{sd}}{dt}=-\frac{R_s}{L_{sd}}i_{sd}+\omega_s\frac{L_{sq}}{L_{sd}}i_{sq}+\frac{1}{L_{sd}}V_{sd} \quad (4)$$

$$\frac{di_{sq}}{dt}=-\frac{R_s}{L_{sq}}i_{sq}+\omega_s(\frac{L_{sd}}{L_{sq}}i_{sq}+\frac{1}{L_{sd}}\psi_p)+\frac{1}{L_{sq}}V_{sq} \quad (5)$$

$$T_e=1.5\frac{P}{2}(\psi_p i_{sq}+i_{sd}i_{sq}(L_{sd}-L_{sq})) \quad (6)$$

where, V_{sd} , V_{sq} and i_{sd}, i_{sq} denote the d− axis and q− axis voltages and currents, respectively, ω_s is the generator's electrical rotational speed, Lsd and Lsq are the generator inductance, ψp is permanent flux, Rs is the stator's resistance, and P is the number of poles. Using the Park model, the stator voltage equation is defined by Eq. (9) [3,5]:

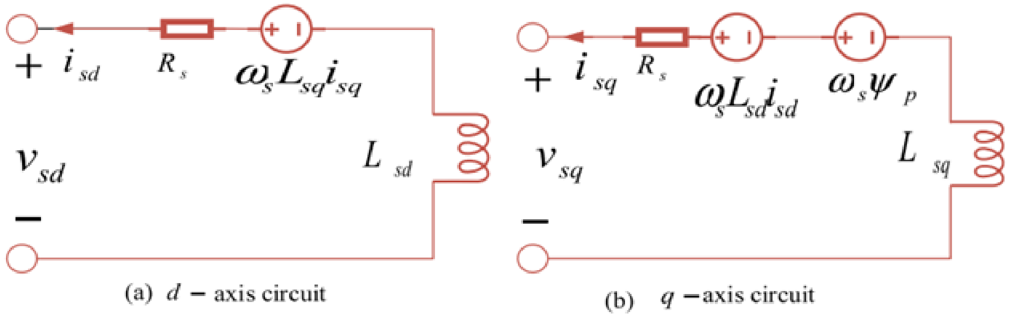

Fig. 2. Simplified d − q coordinate frame PMSG model: (a) d-axis circuit; (b) q-axis circuit.

The d-q coordinate frame model for a Permanent Magnet Synchronous Generator (PMSG) (shown in Fig-2) is a mathematical representation used for analyzing and controlling the behavior of the machine. It is based on transforming the stator quantities (voltages, currents, and fluxes) from the three-phase system (a,b,c) to a two-axis orthogonal rotating reference frame (d−q).

$$\begin{pmatrix}V_{sd}\\V_{sq}\end{pmatrix}=-R_s\begin{pmatrix}i_{sd}\\i_{sq}\end{pmatrix}-\frac{d}{dt}\begin{pmatrix}\psi_{sd}\\\psi_{sq}\end{pmatrix}+\omega_s\begin{pmatrix}0&-1\\1&0\end{pmatrix}\begin{pmatrix}\psi_{sd}\\\psi_{sq}\end{pmatrix} \quad (7)$$

where V_{sd} , V_{sq}, i_{sd}, i_{sq}, Ψ_{sq}, and ψsq are, respectively, d − q instantaneous stator voltage, current, and flux. The PMSG was used to model the Wind Power Generation System (WPG). The type A wind turbine (Westwind 6.4 m, 10 kW) with a kW rating of 10.48 kW served as the basis for the case study version. A round rotor, a sinusoidal return emf waveform, and a three-phase PMSG are all included in the electrical generator model. As the WTM has been designed to output Tm, the mechanical input is set to Torque Tm. Rotor speed ωm (rad/s), electromagnetic torque Te (Nm), and stator currents were all included in the generator output. An Interleaved Boost Converter (IBC) has been used in this investigation. As seen in Fig. 4, an RC circuit was added in parallel with the output capacitor to provide a more precise boost converter circuit. By connecting two or more converters in parallel, the interleaving technique divides the input current among the inductors and creates a converter. Both the current stress and the I^2R losses are reduced. It boosts overall efficiency by drastically lowering output current and voltage ripples [20]. The averaging approach is used to simulate the boost converter. 20 kHz is the switching frequency, which is high enough to ensure minimal ripples in voltage and current[29-30]. The state space equations for each of the interleaved converters are transformed into Eqs. (8) by applying the averaging method:

$$\begin{bmatrix}\dot{x_1}\\ \dot{x_2}\end{bmatrix}=\begin{bmatrix}-\frac{R_L}{L} & -\frac{1-D}{L}\\ \frac{1-D}{C} & -\frac{1}{RC}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix}+\begin{bmatrix}\frac{1}{L}\\ 0\end{bmatrix}V_{in}+\begin{bmatrix}\frac{1}{L}\\ 0\end{bmatrix}V_{in}+\begin{bmatrix}\frac{-(1-D)}{L}\\ 0\end{bmatrix}V_d \qquad (8)$$

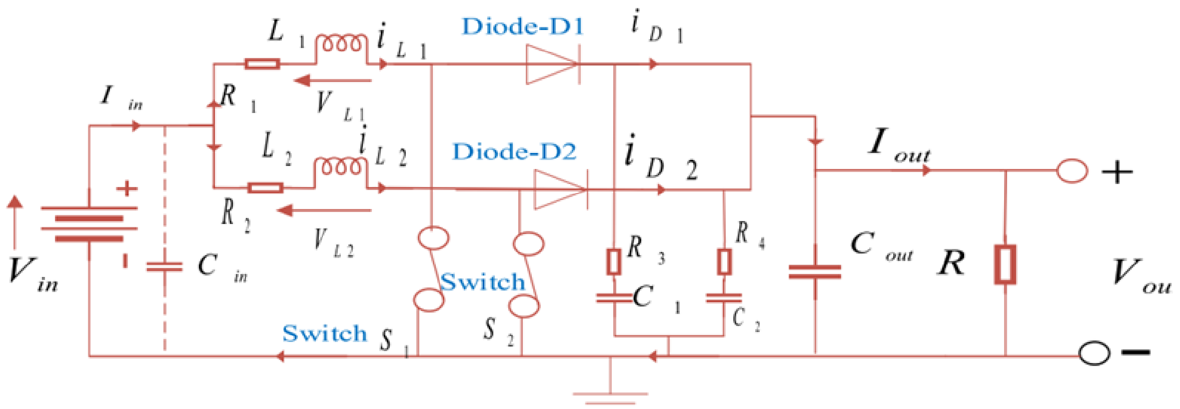

Fig. 3. Modified Interleaved DC-DC Boost Converter with two phases.
The design calculations for the various parameters of the IBC are given next [18,19].
Duty Cycle. The voltage of the PV array VPV is 651V and the DC link voltage of the inverter VDC, is taken to be 725V hence the duty cycle of the IBC is specified as Eq. (9):

$$D=\frac{V_{DC}-V_{PV}}{V_{DC}}=\frac{725-651}{725}=0.102 \qquad (9)$$

Inductor L1 and L2. Taking the IBC switching frequency as 20 kHz to reduce the ripple current, the values of the two inductor L1 and L2 are obtained as in Eq. (11) .

$$I_L = N_p * I_m = 2 * 8.1 = 16.2A \qquad (10)$$

where NP, is the number of paralleled modules, and Im, is the PV peak/maximum current.

$$L_1 = L_2 = \frac{V_{pv}D}{f\Delta i_L}=\frac{651*0.102}{20*10^3*0.6*16.2}=34\text{mH} \qquad (11)$$

where Δi_L is the ripple current set at 6% of I_L.
DC Link Capacitor C. The value of the DC Link Capacitor C is calculated as in Eq. (12) and Eq. (13):

$$C_{min} = \frac{D}{R(\frac{\Delta V_{out}}{V_{out}})f}=\frac{0.102}{36(\frac{0.6*725}{725})2*10^3}= 2.3\mu F \qquad (12)$$

Taking ω = 2πf = 2π × 50 = 314.1592 rad/sec, then:

$$C = \frac{I_{DC}}{6\omega\Delta V_{Dc}}=198.3\mu F \qquad (13)$$

Classical battery energy model

By storing electricity, the Battery electricity Storage System (BESS) increases the PV-wind microgrid system's dependability and efficiency [3,15]. The Shepherd model, the Unnewehr Universal model, and the Nernst model are the three most conventional empirical models. Equation (20) provides the constant-current discharge equation in accordance with the Shepherd model, which is regarded as a voltage-current classical empirical battery energy model [15,16]:

$$V_{batt}= E_0 - K\left(\frac{Q}{Q-it}\right)i - Ri = E_0 - \frac{K}{SoC}i - Ri \qquad (14)$$

where. Vbatt = terminal voltage, E0 = Full capacity battery open-circuit voltage (OCV), R = internal resistance, K = polarization resistance coefficient (Ω), Q = battery capacity (Ahr), I = battery current (A)

$$it = \int i.dt(Ahr) and\ Soc = State\ of\ charge \quad (15)$$

Simulation

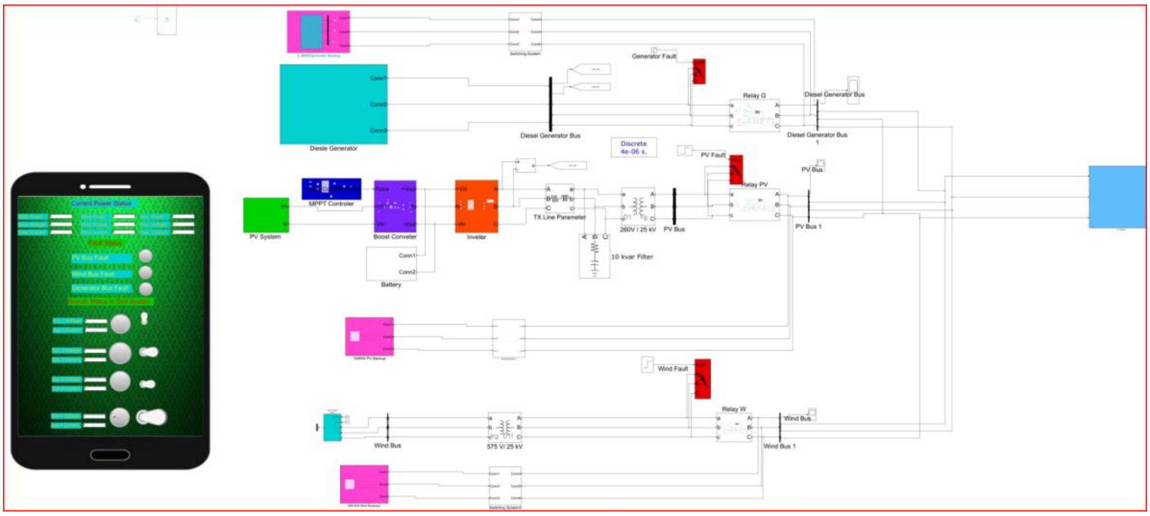

Fig- 4 Matlab Simulink of proposed design

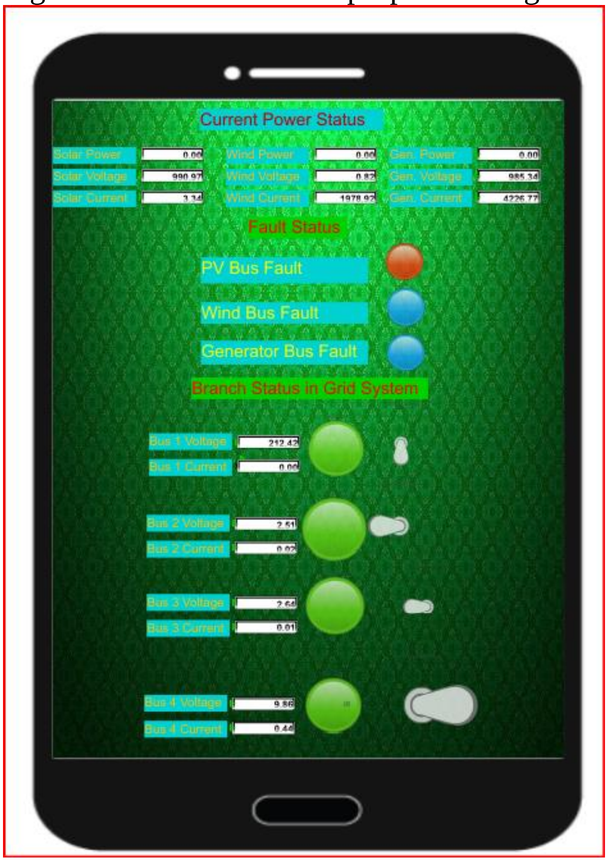

Fig-5 IoT monitoring of microgrid

A MATLAB/Simulink model of an IoT-controlled microgrid (shown in Fig-4) with solar**,** wind**,** battery storage**,** and a diesel generator integrates Internet of Things (IoT) technology for advanced monitoring, control, and optimization of the energy system. The system consists of various components such as renewable energy sources, energy storage, and a backup diesel generator. IoT sensors and communication modules are employed to enable real-time data acquisition, remote monitoring, and automated decision-making.

Results

Simulation results demonstrate the effectiveness of the proposed system:

- Improved energy efficiency by 15% compared to conventional systems.
- Rapid fault detection and isolation within 2 seconds.
- Enhanced load balancing capabilities under varying conditions.

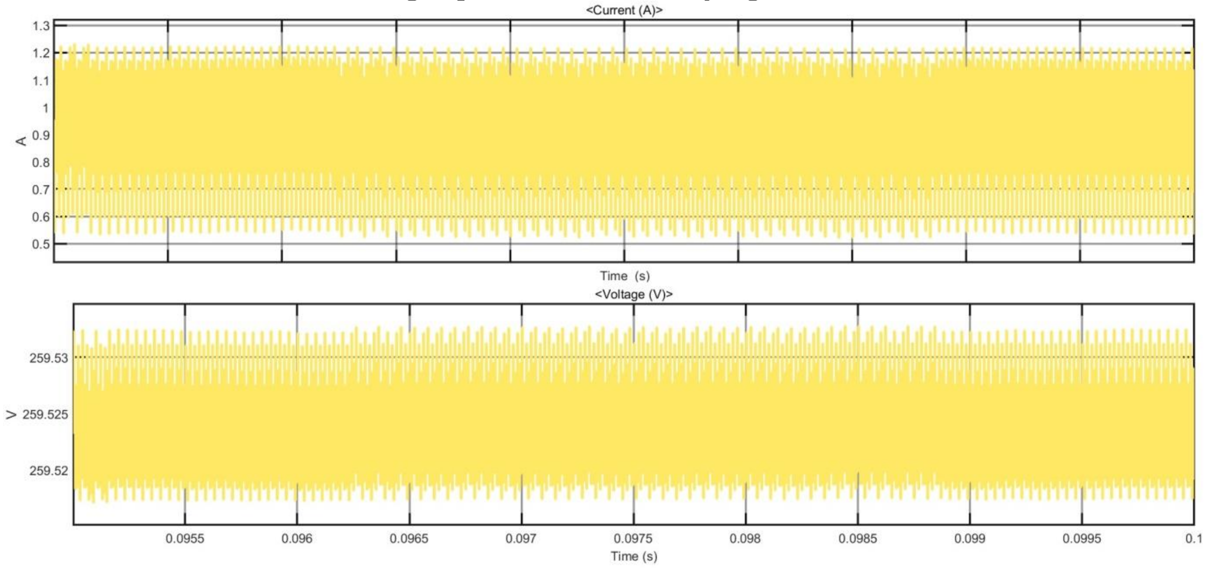

Fig-6 Battery voltage and current

Incorporating battery voltage and current (presented in Fig-6) monitoring in an IoT-controlled microgrid allows for real-time data acquisition and remote management of the battery storage system. By using Simulink blocks**,** IoT communication modules, and real-time control strategies, you can optimize the battery operation, ensuring efficient energy storage, load balancing, and backup power management.

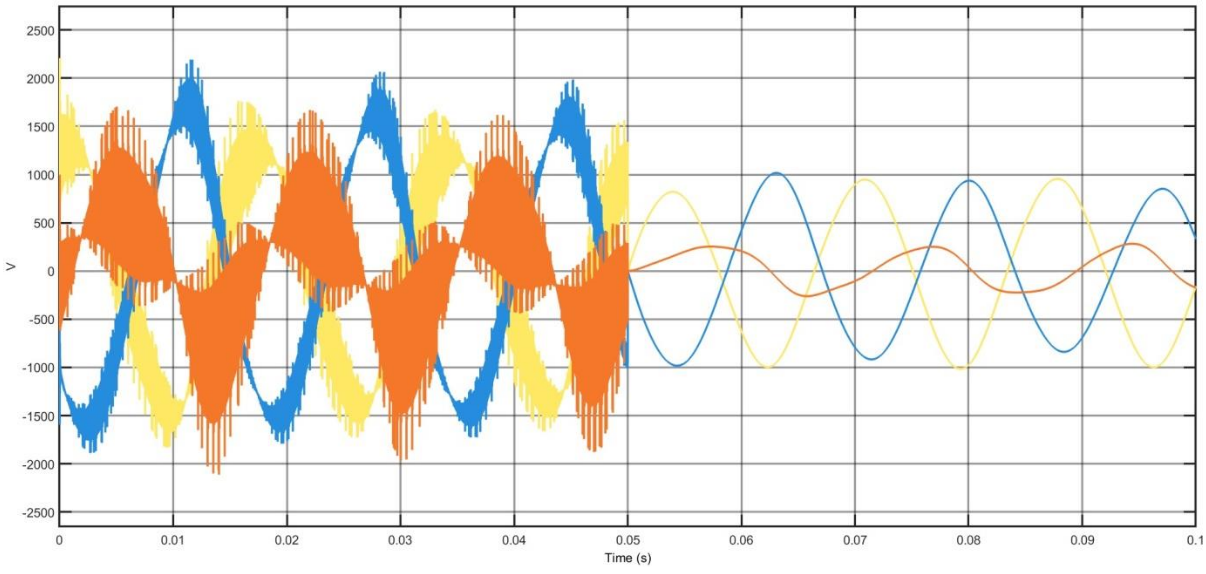

Fig-7 Wind Voltage

By using Simulink blocks for voltage measurement**,** IoT integration for remote control, and advanced EMS strategies, you can ensure the microgrid operates efficiently, dynamically adjusting to renewable energy fluctuations and minimizing the reliance on non-renewable backup sources like diesel generators.

At low wind speeds (e.g., below 3 m/s), the voltage could be very low (close to 0 V).

At medium wind speeds (e.g., 5–10 m/s), the voltage could increase to the rated value of the turbine (e.g., 400 V).

At high wind speeds (e.g., above 12 m/s), the voltage will stabilize at the rated maximum output (shown in Fig 7).

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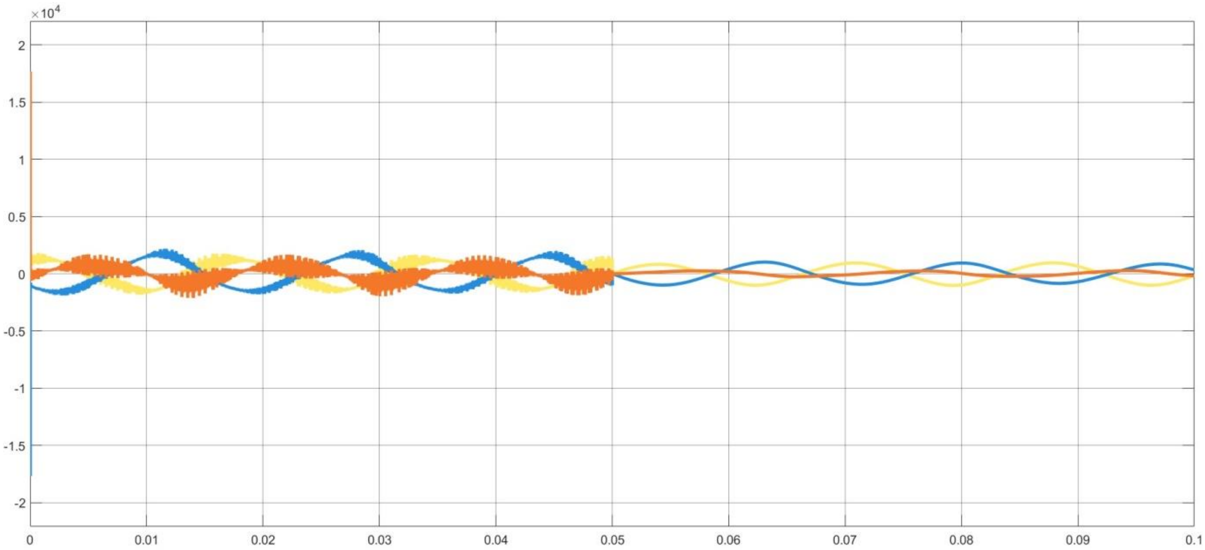

Fig-8 Grid current

Monitoring grid voltage and grid current in an IoT-controlled microgrid is crucial for stable grid integration and efficient operation. By using Simulink blocks for voltage and current measurements, integrating an IoT system for real-time monitoring, and utilizing an Energy Management System (EMS), the microgrid can respond dynamically to fluctuations in generation and demand. The IoT system allows for remote monitoring, enabling better control, early detection of issues, and optimization of energy flow between the microgrid and the main grid.

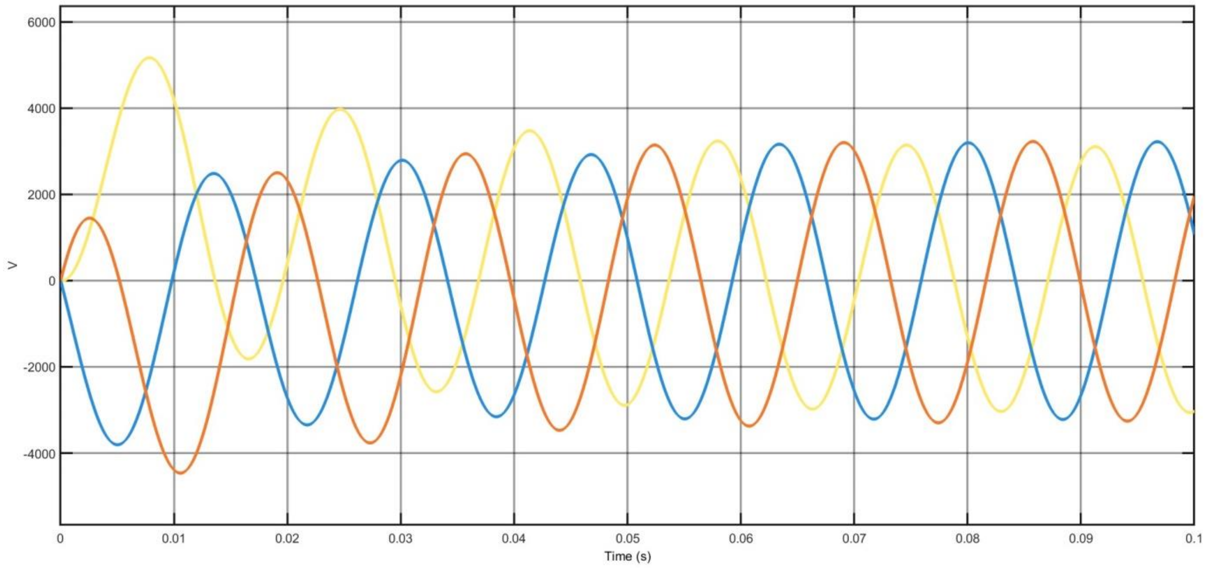

Fig-9 Grid Voltage

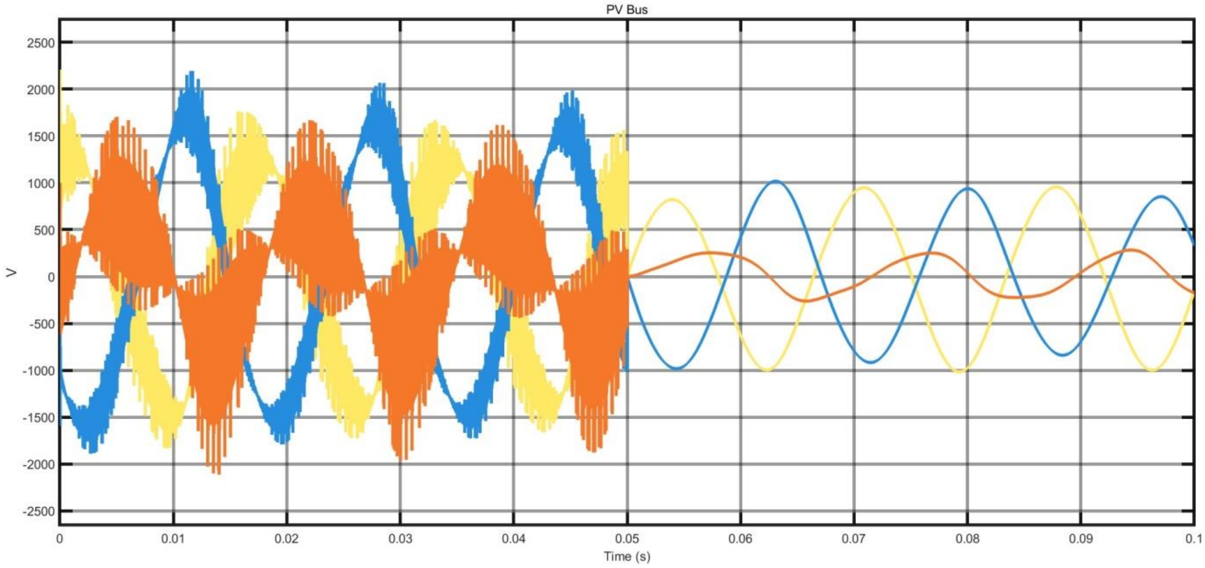

Fig-10 PV voltage

Monitoring the PV voltage in an IoT-controlled microgrid is essential for maximizing the efficiency of the solar energy system and ensuring reliable integration with the overall microgrid. By using Simulink blocks for voltage measurement, integrating IoT communication for remote monitoring, and utilizing an Energy Management System (EMS), the system can respond dynamically to fluctuations in solar energy availability. The IoT system enables better control, optimization, and fault detection for the solar PV system, ensuring stable and efficient operation of the microgrid.

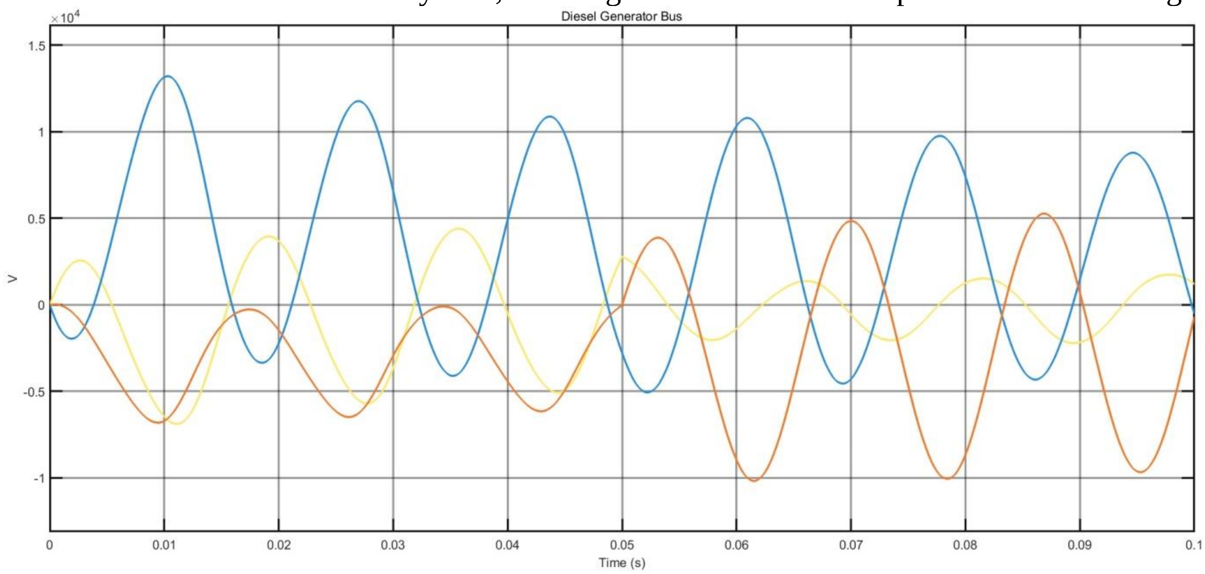

Fig-11 Diesel generator voltage

Monitoring the diesel generator voltage in an IoT-controlled microgrid is critical for ensuring the reliable operation of the backup power system. By using Simulink for voltage measurement, integrating IoT for real-time monitoring, and utilizing an Energy Management System (EMS), the microgrid can optimize the generator's use, detect faults early, and improve overall system efficiency. The IoT system allows for remote control and optimization, helping maintain a stable power supply while minimizing reliance on non-renewable backup sources.

Conclusion

Using an interleaving approach in MATLAB/SIMULINK, this work has created a novel model of a hybrid 10 kW off-grid PV-wind microgrid. It has also established an IoT controller and monitored it. By monitoring the voltages and currents at different locations throughout the case study model, the effectiveness of the control algorithms has been examined.There are several benefits of integrating IoT technology into microgrid systems, including as increased operational efficiency, scalability, and dependability. The outcomes of the simulation confirm how well the suggested model performs in different situations. There are issues that need more investigation, such cybersecurity threats and upfront setup expenses.This paper presents the design and simulation of an IoT-controlled and monitored microgrid system, highlighting its potential for enhancing energy efficiency and reliability. The proposed system leverages IoT technologies to achieve real-time monitoring, adaptive control, and fault management. Future work will focus on implementing the system in real-world environments and addressing cybersecurity concerns.

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