HYBRID WIND/PV/BATTERY ENERGY MANAGEMENT FOR SMART DC MICROGRID USING INTELLIGENT FRACTIONAL ORDER-PID CONTROLLER

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***Abstract*- Hybrid renewable energy sources combine multiple types of renewable sources, such as solar, wind, hydro, or biomass, to maximize energy output and ensure consistent power generation, an intelligent energy management controller is proposed to enhance the power quality of a DC Microgrid. The controller utilizes a combination of fuzzy logic and fractional-order proportional-integral-derivative (FO-PID) methods. The DC Microgrid incorporates a hybrid energy system consisting of a battery bank, wind energy, and photovoltaic (PV) energy sources. To optimize the energy extraction from renewable energy sources (wind and PV), new intelligent fractional-order PID strategies control the source-side converters (SSCs). This ensures the maximum power extraction and improves the power quality supplied to the DC Microgrid. The prioritization of wind and PV energy sources aims to make the microgrid cost-effective. The proposed controller achieves smooth output power and uninterrupted service continuity. The effectiveness of the proposed controller is demonstrated through simulation results using Matlab/Simulink software.**

***Keywords*- Renewable energy sources, DC-microgrid, energy management control, fuzzy logic control, FO-PID controller.**

I. INTRODUCTION

As we know that in older days and present days also, we are generating power by using fuel resources. Thermal power plants, fueled by coal and oil, release harmful emissions during the combustion of fossil fuels, contributing to air pollution and climate change. Nuclear power plants, in while cleaner in terms of air quality, produce radioactive waste, posing challenges for safe storage, processing, and transport [1].

However, renewable energy sources come with their own challenges due to their variable nature. The demand for energy from consumers fluctuates over time, leading to problems in synchronizing energy production with consumption. The stability of the electricity grid depends on maintaining a delicate balance between power generation and usage.

Energy storage plays vital role in the successful integration of renewable energies into the electricity grid. Not only does it provide a technical means for grid operators to achieve real-time balance between energy production and consumption, but it also optimizes the utilization of renewable resources by preventing wasteful load shedding during periods of overproduction. The flexibility and reliability provided by energy storage systems complement the intermittency of renewable resources, creating a synergy that can revolutionize the energy [2][3]. Grid stability relies on maintaining a balance between production and consumption [4]. To increase the penetration of renewable energies, their participation in various grid services is essential [5]. The emerged field of integrating renewable energies with energy storage systems in standalone microgrids. The preference is to combine various renewable sources, such as tidal, wind, and photovoltaic (PV), to maximize the energy storage system's capacity [6][7]. Microgrids are classified as DC, AC, or a combination of both types. DC microgrids offer several advantages, including simpler control, easier integration, and a straightforward structure. In contrast, AC microgrids require more information, such as frequency synchronization and reactive power, making the control design process more challenging. Additionally, DC microgrids offer flexibility, allowing them to operate in various modes, such as AC microgrid operation, standalone operation, or integration with AC microgrids. In certain scenarios where all energy sources and battery storage systems are interconnected, the AC grid is used instead of supercapacitors. Microgrids can be classified into DC, AC, or hybrid types [9]. DC microgrids offer several advantages, including simplified control, seamless integration, and a straightforward structure. On the other hand, AC microgrids require more complex control mechanisms, such as frequency synchronization and reactive power management, making their design more challenging [10].

Various control strategies have been explored in the literature to address DC-link voltage issues. Linear approaches, such as combined fuzzy and voltage control, and dual proportional-integral controllers, have been proposed. However, these linear methods have limitations in regulating the DC-link in wider operating intervals. To overcome this limitation, researchers have investigated nonlinear controls. Nonlinear control strategies, including adaptive droop control, energy management-based optimal control, robust H1 control, robust sliding mode control, adaptive backstepping control, Lyapunov-based control, feedback linearization control, and hybrid backstepping and sliding mode control, have been proposed [11][12]. Despite their potential advantages, these nonlinear controls face performance limitations in certain scenarios, such as the droop control strategy's application and optimal energy management in systems with multiple integrated energy storage units. Additionally, some of these controls suffer from poor stability with the H1 method and chattering issues related to sliding mode control [13][14]. Moreover, many of these controls rely heavily on fixed gains, making them sensitive to parameter uncertainties and external disturbances [15][16].

II.RELATED WORKS

It describes a novel approach to address the challenges of hybrid energy management in a DC-microgrid with multiple stochastic energy sources and essential DC loads. The proposed solution involves a new fractional order PID (IFO-PID) controller combined with a fuzzy logic method. Fractional-order controllers offer advantages over conventional integer controls, such as robustness to oscillations, measurement noise, and increased degree of freedom. The IFO-PID controller is integrated with an energy management unit (EMU) to achieve efficient and stable operation. The EMU serves as a high-level controller, generating appropriate references for the IFO-PID and monitoring the generated and consumed power. The main objectives of this research are twofold: firstly, to control the source-side converters (SSCs) effectively to extract maximum power from renewable energy sources like wind and PV. Secondly, to improve the power quality supplied to the DC-microgrid by regulating reactive power and DC-link voltage.

The proposed controller represents an innovative solution to improve the performance and stability of DC-microgrids with multiple stochastic energy sources. By combining the benefits of fractional-order control and fuzzy logic, the system can efficiently manage energy generation and consumption. This research contributes to develop smart and reliable energy management systems for sustainable power distribution and utilization.

The novel contributions of a research work focused on enhancing the energy management of a DC-microgrid with stochastic multiple energy sources and essential DC loads. The key contributions are as follows:

1. Fractional Order PID (FO-PID) Controller: The researchers developed a new FO-PID controller specifically for the DCmicrogrid integrated with multiple stochastic energy sources and essential DC loads. The FO-PID controller offers advantages over conventional integer controllers, such as robust behaviour in the presence of oscillations and measurement noise, and increased degrees of freedom.
2. Fuzzy Logic Strategy: The FO-PID controller is combined with a fuzzy logic strategy to further enhance its performance. Fuzzy logic is used as a fuzzy gain supervisor to adaptively adjust the gains of the FO-PID controller. This adaptability greatly improves the robustness of the proposed approach against uncertainties and external disturbances.
3. Reduced Number of Fixed Gains: One essential characteristic of this approach is the significantly reduced number of fixed gains used in the proposed strategy. This reduction in fixed gains makes the system less sensitive to parameter uncertainties, leading to improved robustness and global stability of the DC-microgrid.
4. Global Stability Validation: Extensive simulation results were conducted to ensure the global stability of the system. The validation of global stability further confirms the effectiveness and reliability of the proposed energy management approach.

III.PROPOSED SYSTEM

The block diagram of the proposed system is given below. This ensures the maximum power extraction and improves the power quality supplied to the DC Microgrid. The prioritization of wind and PV energy sources aims to make the microgrid costeffective. The proposed controller achieves smooth output power and uninterrupted service continuity.

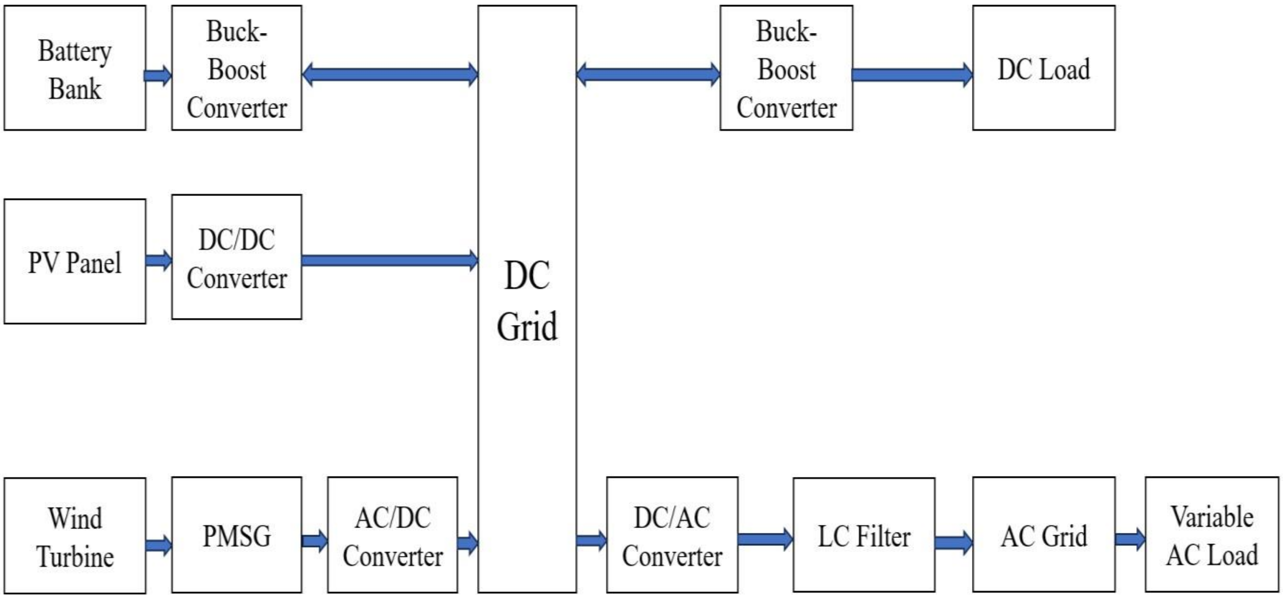


Figure 1 Block Diagram of Proposed system

The above figure shows that the DC microgrid consists of solar PV array, Battery converter and DC loads. We have taken as input, solar, battery and wind. If the PV array input is taken as temperature and irradiance value to generate the voltage and current and connect to the boost converter to boost up the voltage. If the MPPT value is connect to generate the duty cycle of the pulse. The solar energy supply through DC link and then the wind input is taken as wind speed to rotate the shaft to produce the energy is in the AC form. We have to convert the energy in AC to DC by using rectifiers, in this voltage supplied through DC link. Solar and Wind energy voltage are same because, this system will be synchronized. And another condition battery, In case the solar and wind energy supply will be flow, battery will be charged conditions. When the solar and wind will be unavailable conditions, the battery will get discharge to continuous supply through the loads. We have taken as DC load condition and AC load variable conditions. An intelligent energy management controller based on combined fuzzy logic and fractional-orderproportional-integral-derivative (IFO-PID) controllers are used for continuous power quality supplied by the DC microgrid. We will give us different types of inputs like irradiance and wind speed. Hybrid renewable energy sources combine multiple types of renewable sources, such as solar, wind, hydro, or biomass, to maximize energy output and ensure consistent power generation, an intelligent energy management controller is proposed to enhance the power quality of a DC Microgrid. The controller utilizes a combination of fuzzy logic and fractional-order proportional-integral-derivative (FO-PID) methods. The DC Microgrid incorporates a hybrid energy system consisting of a battery bank, wind energy, and photovoltaic (PV) energy sources. To optimize the energy extraction from renewable energy sources (wind and PV), new intelligent fractional-order PID strategies control the source-side converters (SSCs). This ensures the maximum power extraction and improves the power quality supplied to the DC Microgrid.

(A) *Energy conversion system with controller:*

The wind energy conversion system can be operated under MPPT algorithm for maximum power extraction or off-MPPT for power balance as shown below

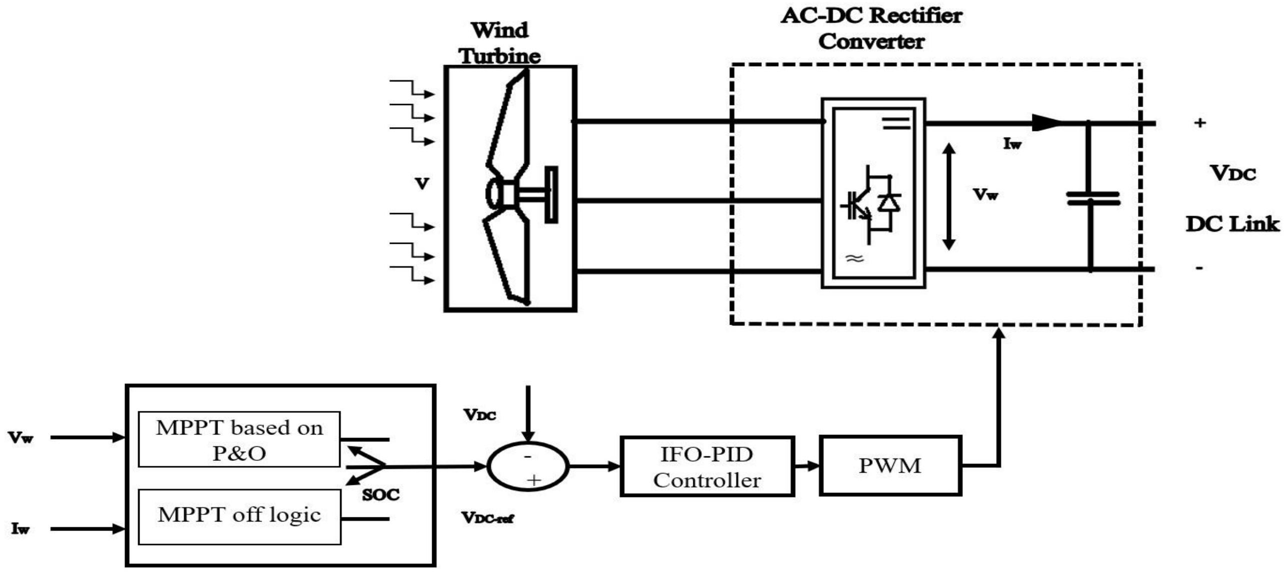


Figure 2 Wind energy conversion system with controller

When the wind energy system generates more power than can be stored in the connected battery system, an issue can arise. Excess power could potentially damage the system components or destabilize the grid. The EMU is a device or system that monitors and controls various aspects of the energy generation and usage in order to optimize efficiency, stability, and balance. MPPT stands for Maximum Power Point Tracking. It's a technique used to optimize the efficiency of power generation systems by dynamically adjusting the load to operate at the point where the system generates the maximum amount of power. In this context, the wind controller is likely adjusting its operation to maximize the power output of the wind energy system. When there is excess power and no battery capacity to store it, switching from MPPT mode to off-MPPT mode is suggested. Off-MPPT mode likely refers to a mode where the wind energy system operates in a way that intentionally reduces its power generation output. This could involve adjusting the system's parameters to limit its power output or to prevent it from operating at its peak efficiency. By switching to off-MPPT mode and deliberately reducing power generation, the EMU aims to maintain a balance between power generation and consumption in the standalone system. This helps prevent issues related to excessive power, voltage instability, or other potential disruptions. The Voltage reference mentioned in the context of off-MPPT likely refers to the target voltage that the wind energy system is aiming to achieve during its reduced power generation operation. This reference voltage might be determined based on the needs of the system and the connected loads.

$$\mathrm{Vref} = \frac{PL-PW}{IW} \qquad (1)$$

Where, PL is the load power and PW is the wind power system.

The solar energy conversion system can be operated under MPPT algorithm for maximum power extraction or off-MPPT for power balance as shown below

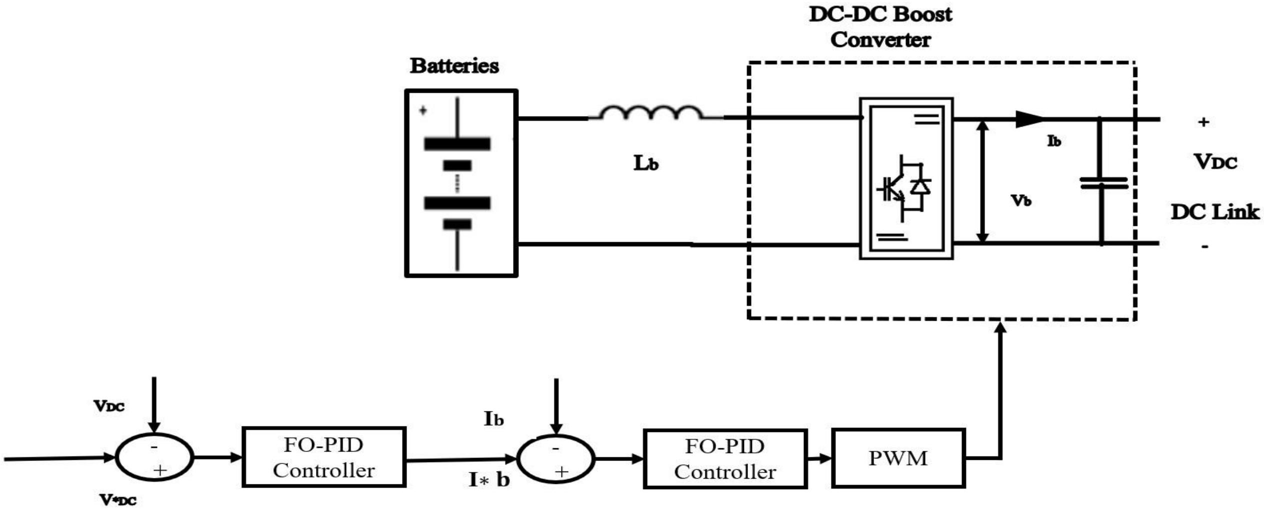


Figure 3 Battery energy conversion system with controller

In this system, there is a standard battery connected to the DC-link of a microgrid. The connection is facilitated by a bidirectional DC-DC back-boost converter. This converter is capable of both boosting and bucking the voltage depending on the requirements of the system. Its bidirectional nature allows energy to flow both from the battery to the microgrid and vice versa. the main purpose of the bidirectional DC-DC back-boost converter is to keep the DC-link voltage stable. This voltage is a critical reference point for the entire system, ensuring that the microgrid operates within desired voltage limits despite changes in power generation sources and load. The Converter regulates the DC-link voltage by adjusting its operation based on the inputs it receives from various sources, such as power generation systems (like wind turbines) and the load demand. This regulation is essential to ensure the stability and efficiency of the microgrid. to manage the battery's charging and discharging, a reference current is calculated based on the desired DC-link voltage. This reference current determines how much energy should be transferred to or from the battery to maintain the voltage within the acceptable range. A voltage controller is designed to control the bidirectional DC-DC back-boost converter's operation in a way that aligns with the calculated reference current and helps maintain the DC-link voltage at the desired level. This controller ensures that the energy flow to and from the battery is managed accurately. the Battery State of Charge (SOC) model is a representation of the battery's current charge level. SOC is a critical parameter as it indicates how much energy is available in the battery. The SOC model likely takes into account factors like the battery's capacity, efficiency, and past charging/discharging history. Accurate SOC modelling is essential for optimizing battery usage and preventing overcharging or over discharging [26].

$$SOC=100\left(1+\frac{\int Ibatdt}{Q}\right) \qquad (3)$$

The coordination between the supervisory system, SOC monitoring, and decision-making is crucial for maintaining the overall stability, efficiency, and longevity of the energy management system, especially in contexts like microgrids or renewable energy systems where battery usage optimization is essential.

$$SOC\ min \leq SOC \leq SOC\ max \qquad (4)$$

Where SOC min and SOC max are the minimum and maximum states for the battery safety. The model of the Battery Storage System converter is given by ref [11].

During the charging phase of the battery system, the maximum power allowed is set at 6525 Watts. This means that the battery can be charged at a rate of up to 6525 Watts without exceeding its defined limits. The charging power is typically determined by the battery's characteristics, efficiency, and thermal constraints. During the discharging phase of the battery system, the maximum power allowed is set at 10440 Watts. This indicates that the battery can release energy to the load or system at a rate of up to 10440 Watts without surpassing its predefined limits. The discharging power limit is usually determined by factors such as the battery's chemistry, design, and cooling capabilities. According to the parameters of the battery storage system given by ref [27].

(B) *Proposed Controller Design Process*

The Fuzzy Optimization-Proportional-Integral-Derivative (FO-PID) is a control technique that combines fuzzy logic and PID control. It aims to achieve better control performance by incorporating fuzzy logic's ability to handle nonlinearities and uncertainty along with the well-established Proportional-Integral-Derivative (PID) control structure. in this approach, the controller laws are initially calculated using the FO-PID technique. This involves determining the appropriate control gains for the PID components (Proportional, Integral, and Derivative) using fuzzy logic to handle uncertainties and variations in the system. the proposed approach uses a Fuzzy gain supervisor to make the controller adaptive and robust against parameter uncertainties. This means that the control gains can be adjusted based on the current operating conditions and variations in the system. the control gains computed by the FO-PID are adopted as fixed gains in the initial step. However, since fixed gains can be challenging to calculate accurately when dealing with uncertain parameters or variations, the fuzzy gain supervisor intervenes to modify these fixed gains based on real-time conditions. In a previous work ref [26], a proportional-integral (PI) control approach was used to design the controllers for the source-side converters and load-side converters. However, PI control often struggles with adapting to parameter uncertainties or variations, as mentioned in your text ref [27]. to address the challenges faced by the fixed gains of PI control under uncertainties, the IFO-PID controller is introduced. The IFO-PID controller enhances robustness and performance by incorporating fuzzy logic-based adjustments to the PID gains.

(i) Source Side Controllers Design

The general structure of Source Side Converters controller with Intelligent Fractional-Ordre PID Controller is shown given below

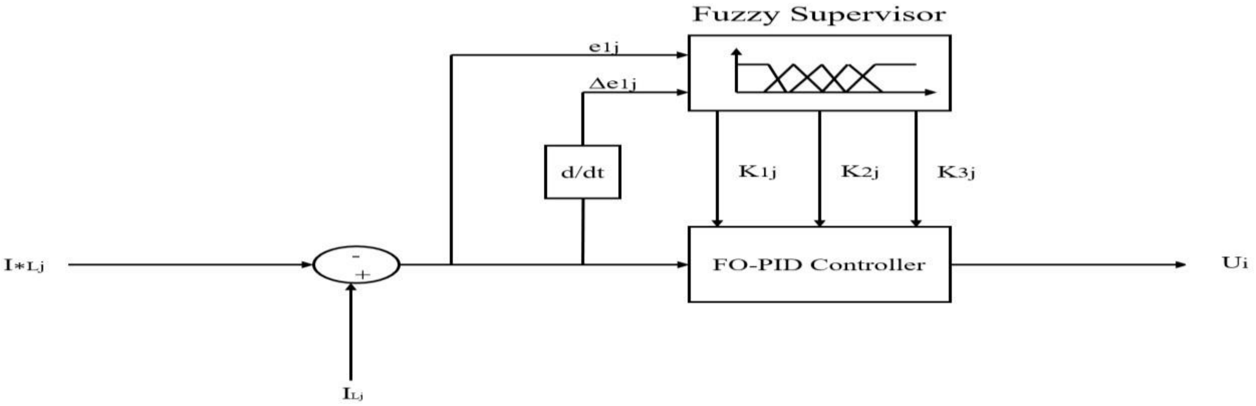


Fig 4 SSCs controller with IFO-PID

The equation of the controller law $U_i = K1je1j + K2je1jDt^{-\alpha} + K3je1jDt^{\beta}$ (5)

Where K1j, K2j and K3j is the gain matrix,

$Dt^{-\alpha}$ represents order α of fractional integration Dt^{β} represents order β of differentiation and e1j denotes the current error expressed as

$$e1j = (I_{Lj} - I_{Lj}^{*}) \quad (6)$$

Where the desired current I_{Lj}^{*} in eqn (6) is expressed by using the FO-PID as below

$$I_{Lj}^{*} = K1je2j + K2je2jDt^{-\alpha} + K3je2jDt^{\beta} \quad (7)$$

Where e2j is the DC-link voltage error expressed as

$$e2j = (V_{dc} - V_{dc}^{*}) \quad (8)$$

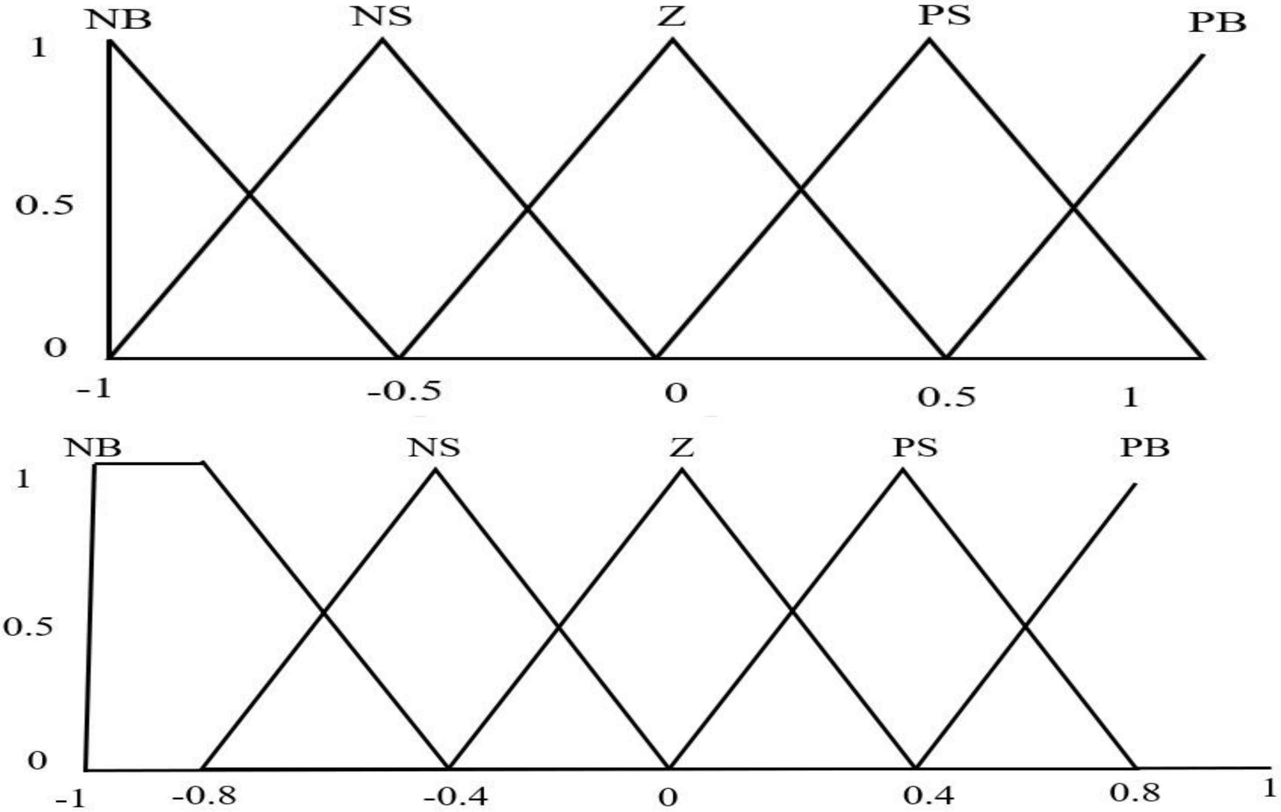


Fig 5 The fuzzy controller configuration (a) Input membership functions (b) Output membership functions TABLE 1 Fuzzy logic rules of the both SSCs and LSCs

$\Delta e_{j,p}$ $e_{j,p}$	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NB	NB	NB	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PB	PB
PB	Z	PS	PS	PB	PB

It have mainly three components: Input fuzzification, Inference system and Defuzzification, the fuzzy will converts the normal values to crisp values, it will gives to the rule system. In this rule base system, we will have many tools we have error and change in error two input and getting one output. These are the rules we have obtained 25 rules, error is negative big and change in error also negative big so we have obtained negative big as a output. We have implemented the fuzzy based FO-PID controller so this rules after obtaining, it will give the rules to the defuzzification block, it will convert the crisp sets to normal sets. We can implement the fuzzy based FO-PID controller. The fractional order PID controller will calculates reduce the event fractional. We may obtain the fractional disturbances, so that can also to overcome the reduced by this fractional order PID controller. We have tuning factors like Kp, Ki, Kd in the PID controllers.

(ii) Load Side Controllers Design

The general structure of Load Side Converters controller with Intelligent Fractional-Ordre PID Controller is shown given below

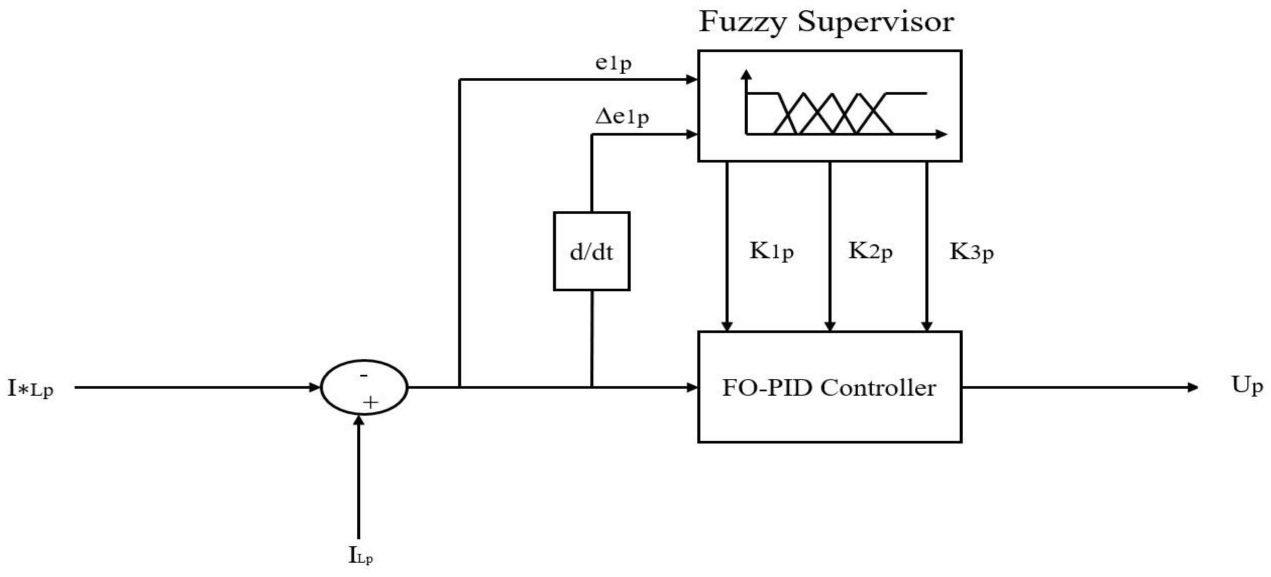


Fig 6 LSCs controller with IFO-PID

The equation of the controller law $Up=K1pe1p+K2pe1pDt^{-\alpha}+K3pe1pDt^{\beta}$ (9)

Where K1p, K2p and K3p is the gain matrix,

$Dt^{-\alpha}$ represents order α of fractional integration

Dt^{β} represents order β of differentiation and e1p denotes the current error expressed as

$$e1p = (I_{Lp}\text{-}I_{Lp}{}^{*}) \quad (10)$$

Where the desired current $I_{Lj}{}^{*}$ in eqn (6) is expressed by using the FO-PID as below

$$I_{Lp}{}^{*} = K1pe2p+K2pe2pDt^{-\alpha}+K3pe2pDt^{\beta} \quad (11)$$

Where e2j is the DC-link voltage error expressed as

$$e2p = (V_{Loadp}\text{-}V_{Loadp}{}^{*}) \quad (12)$$

(A) *Energy Management Unit:*

This is the flow chart for a Maximum Power Point Tracking (MPPT) algorithm. MPPT is used in photovoltaic systems to optimize the power output by tracking the point on the current-voltage (I-V) curve of a solar panel where the maximum power is obtained.

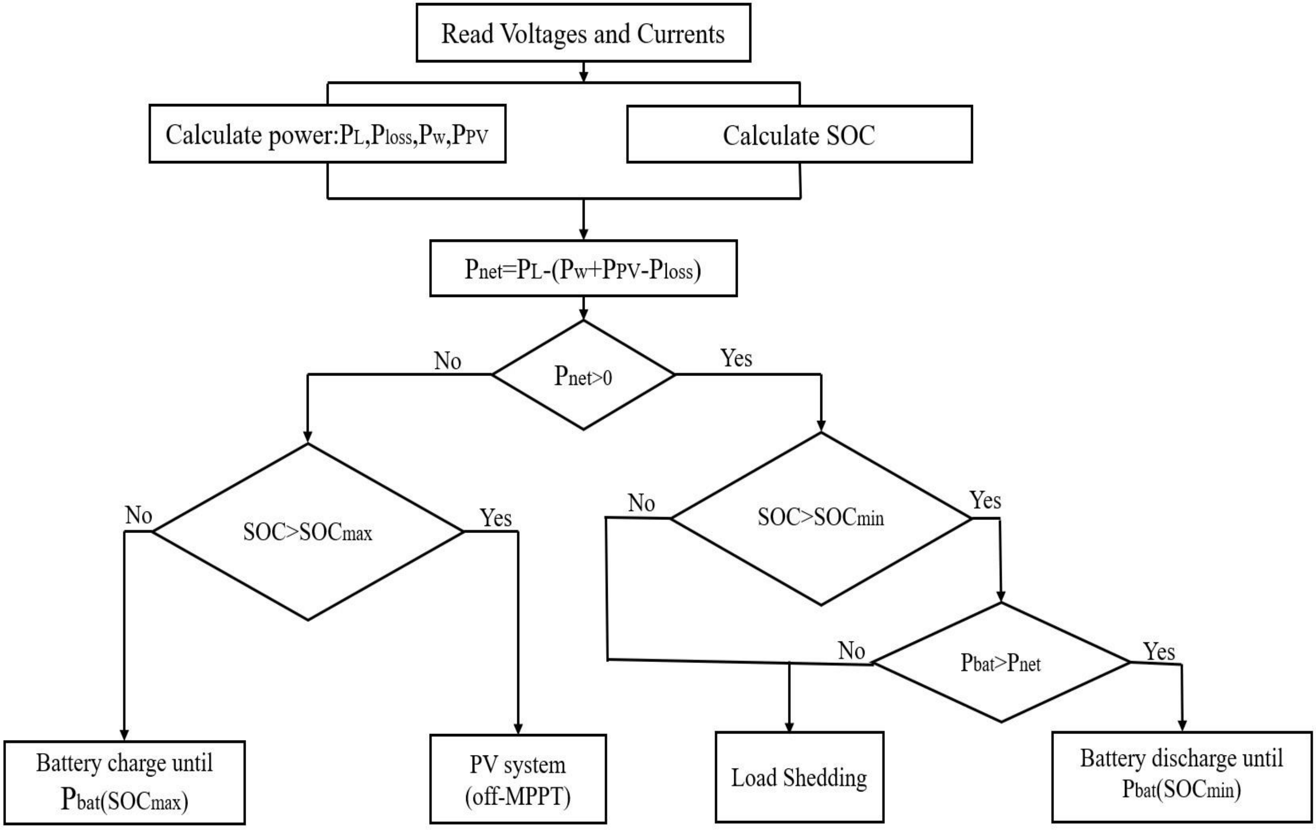


Fig 7 Flow chart of Energy Management Unit

According to figure 7, it has four modes of the energy management unit can be represented and each modes have an two conditions: SOC state and the generating power. It seems to implement a control strategy that takes into account the generated power from renewable sources, load demand, and battery state of charge to manage the operation of a photovoltaic system with energy storage. The code decides whether to activate or deactivate the Maximum Power Point Tracking (MPPT) functionality based on the system conditions. the code attempts to optimize the operation of the photovoltaic system by deciding when to engage the MPPT function and when to rely on battery energy storage or external sources to meet the load demand. The specific values of on-mppt, off-mppt, soc_max, and soc_min will determine the thresholds for switching between different operational modes.

IV. SIMULATION RESULT AND DISCUSSION

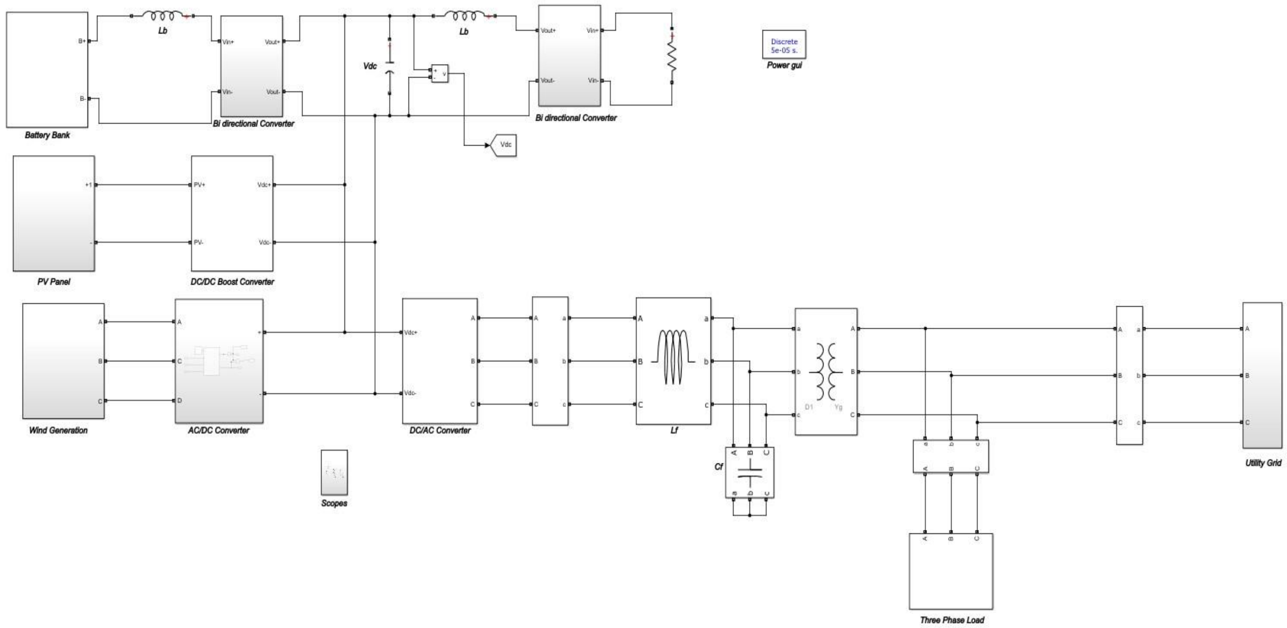


Fig 8 Simulation circuit diagram

The second part of the proposed system, which focuses on prioritizing the expected load for smart cities, such as companies, factories and other applications, maximum power point tracking algorithms are utilized for wind and solar (PV) conversion system to operate them at their maximum output power. The energy management unit calculates the total energy consumed and generated to determine the appropriate control mode for the system.

The simulation results of the proposed system in Matlab/Simulink are based on certain parameters.

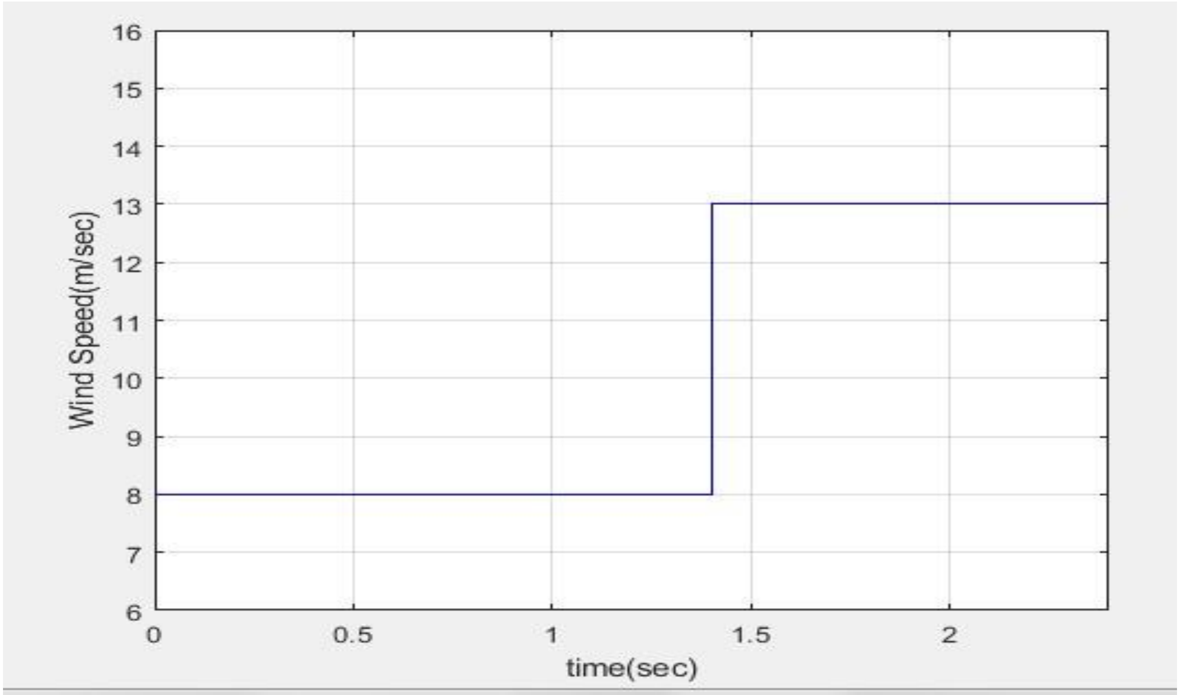


Fig 9 Wind speed

It shows the wind profile between 8 and 13m/s, generating power ranging from 4000 to 10,000 watts, depending on the wind speed.

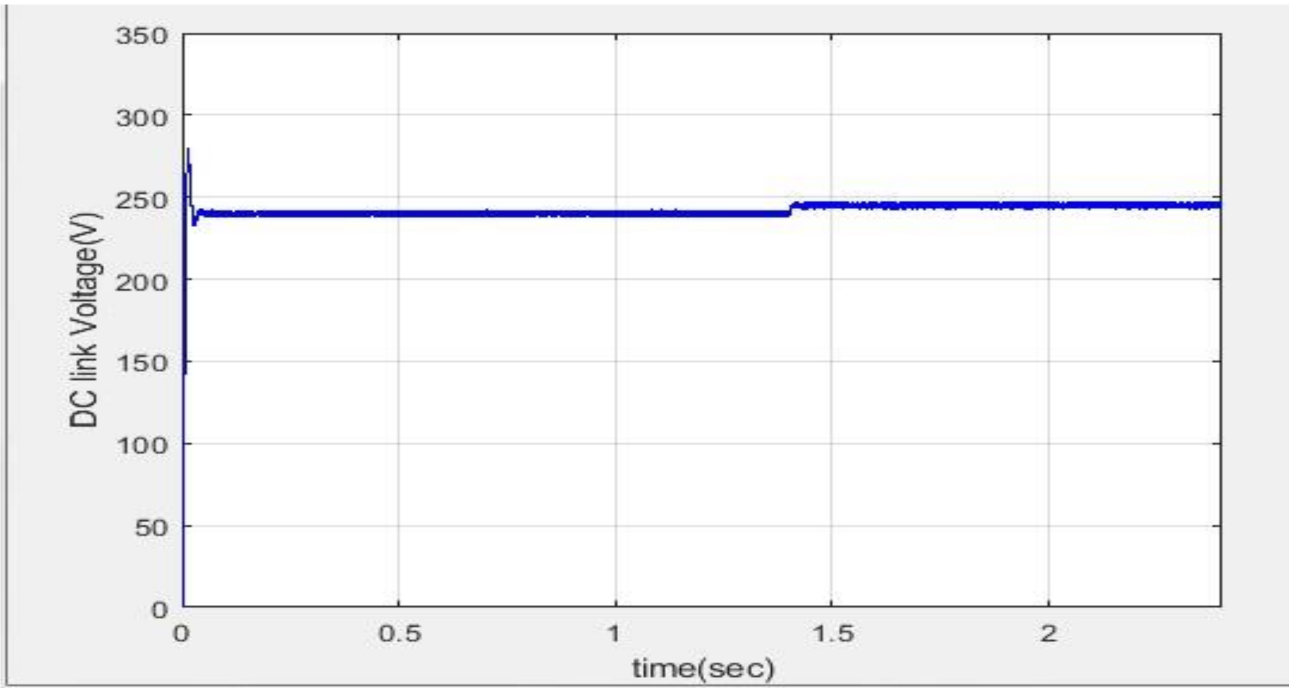


Fig 10 DC link voltage

The fixed DC link reference value is approximately 240V. The simulation results focus on energy management unit as shown

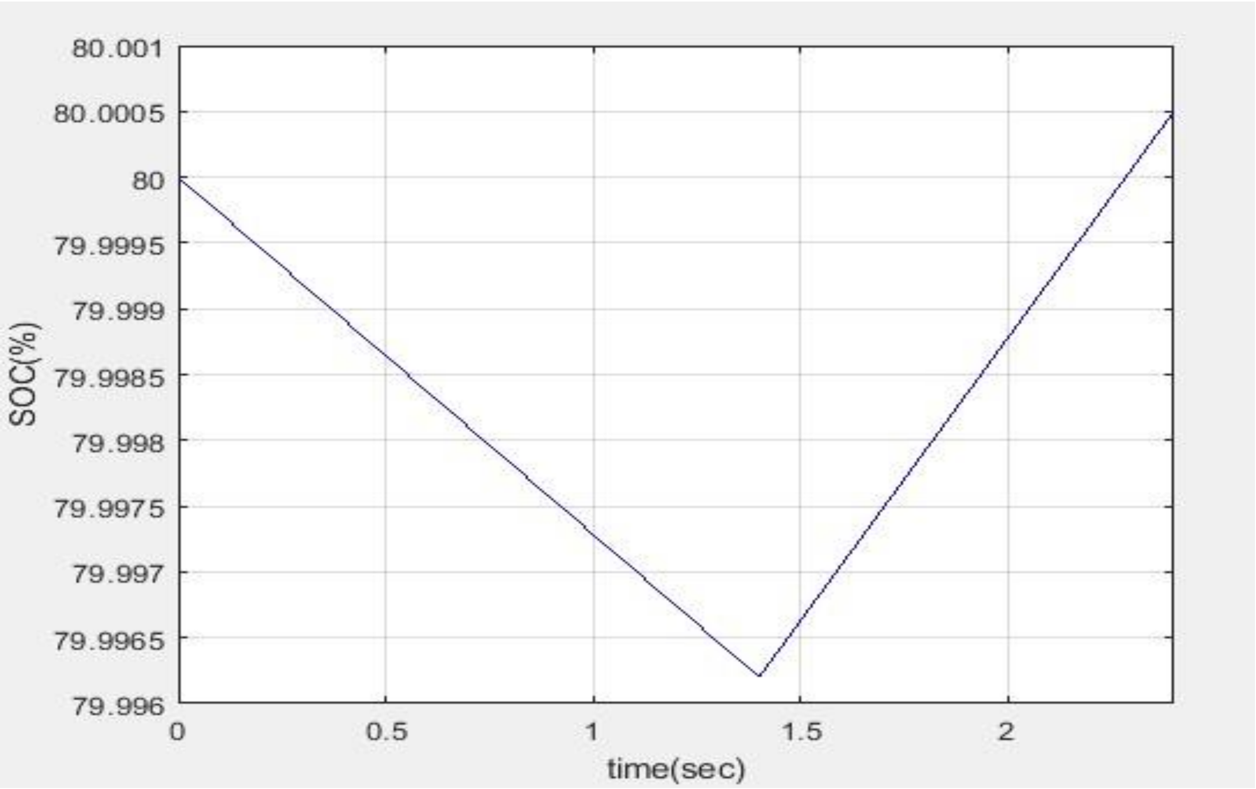


Fig 11 State of Charge

The initial state of charge (SOC) of the battery is 80% as depicted in figure 13. It displays the battery's performance and its SOC

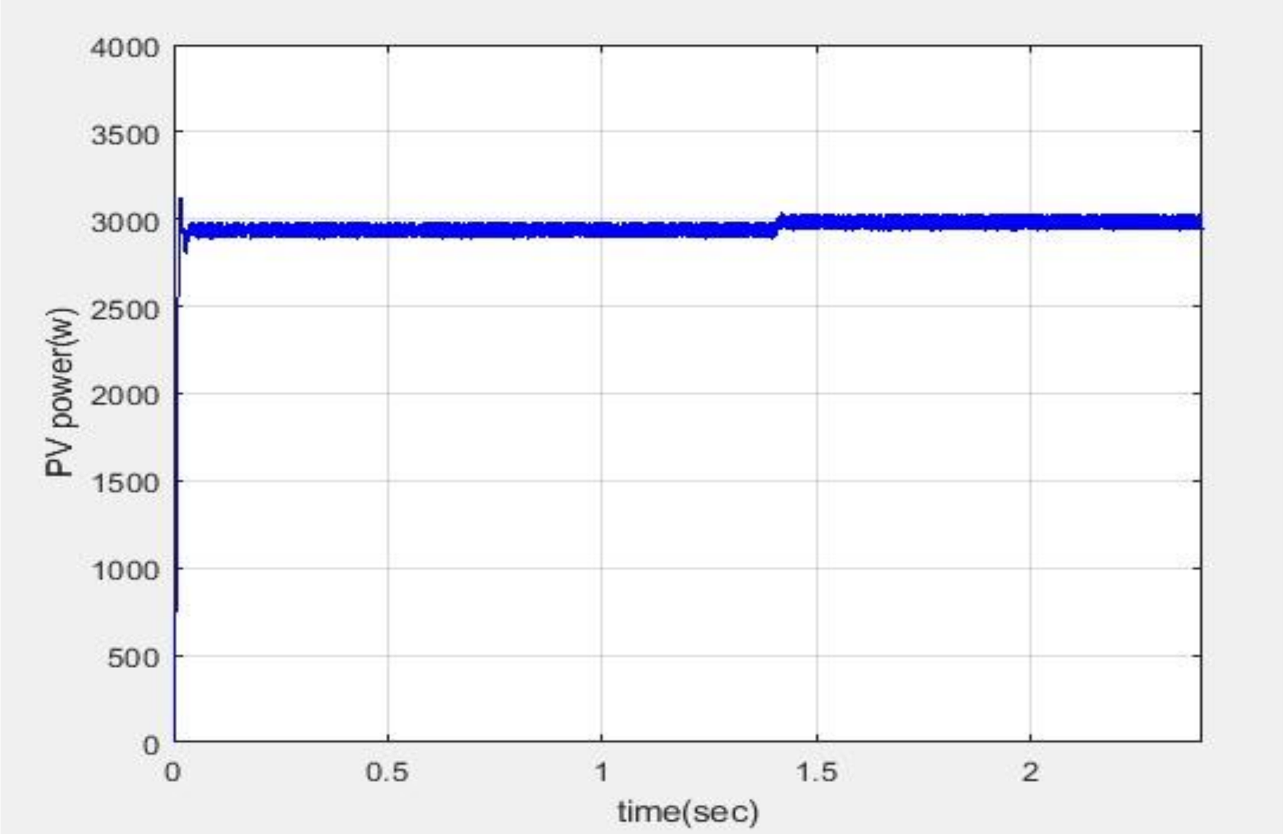


Fig 12 Solar Power

It shows 3000 watts of solar photovoltaic (PV) energy generation under a radiation level of 600W/m^2 and at a temperature of 25 degree Celsius.

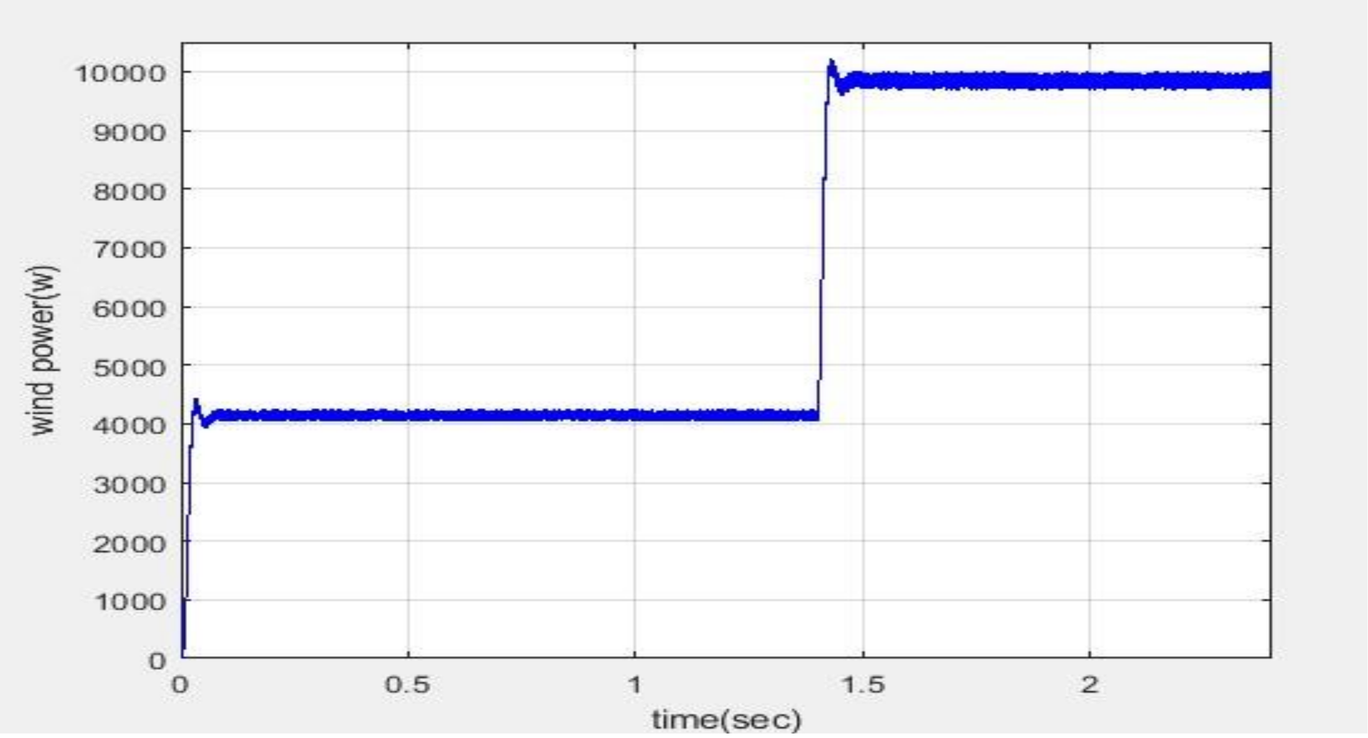


Fig 13 wind power

Wind power utilized in the system. The generating wind power ranging from 4000 to 10,000 watts, it depends on the wind speed.

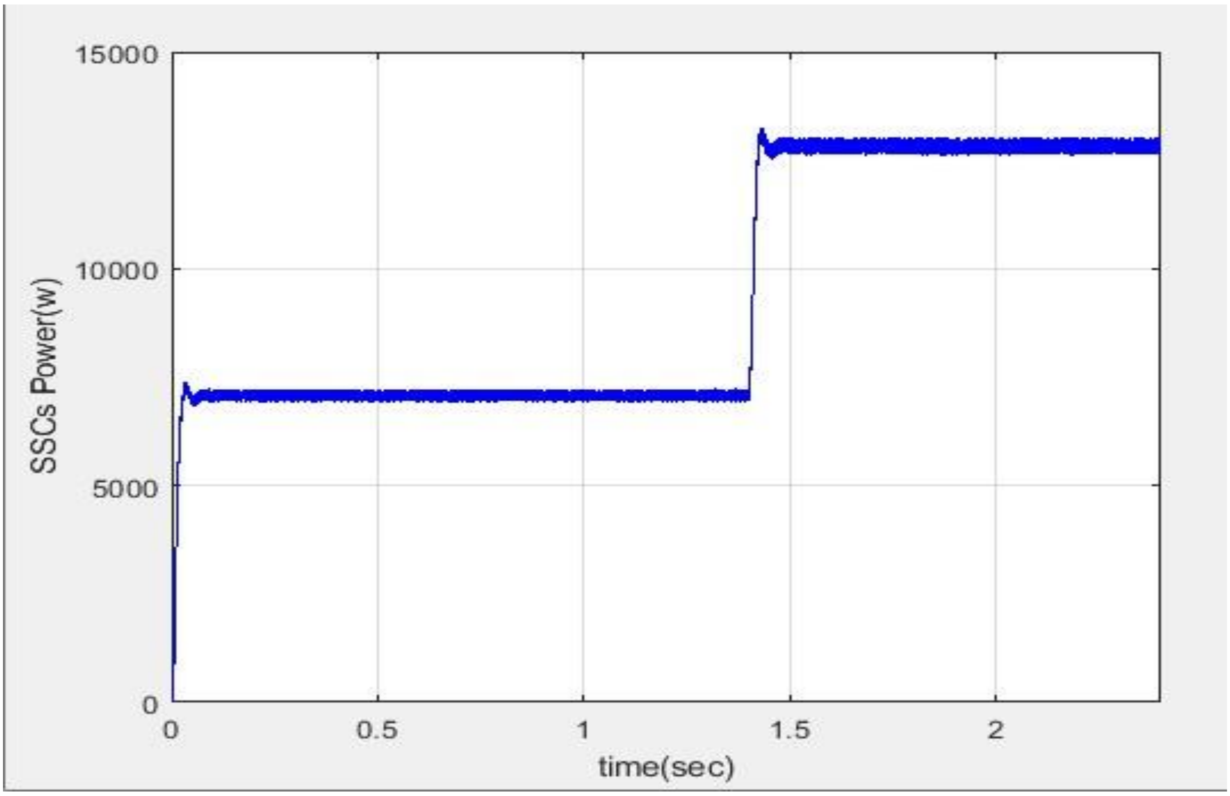


Fig 14 Source Side Converter's Power

It represents the power (Pdg) generated from both the PV and wind sources, varying between 7000 and 13000 watts according to the current conditions.

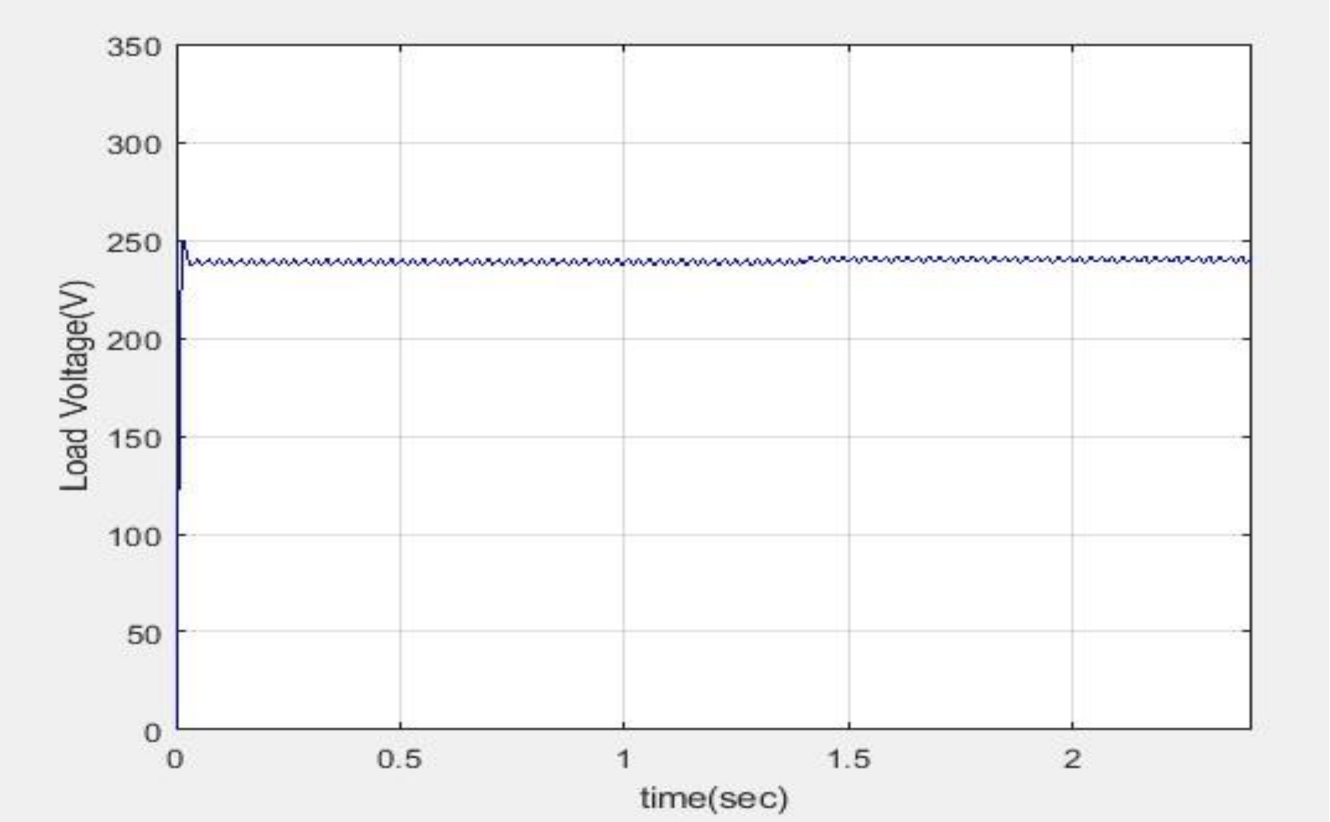


Fig 15 The wave form of Load voltage

It regulates the output voltage at it reference as 220V.

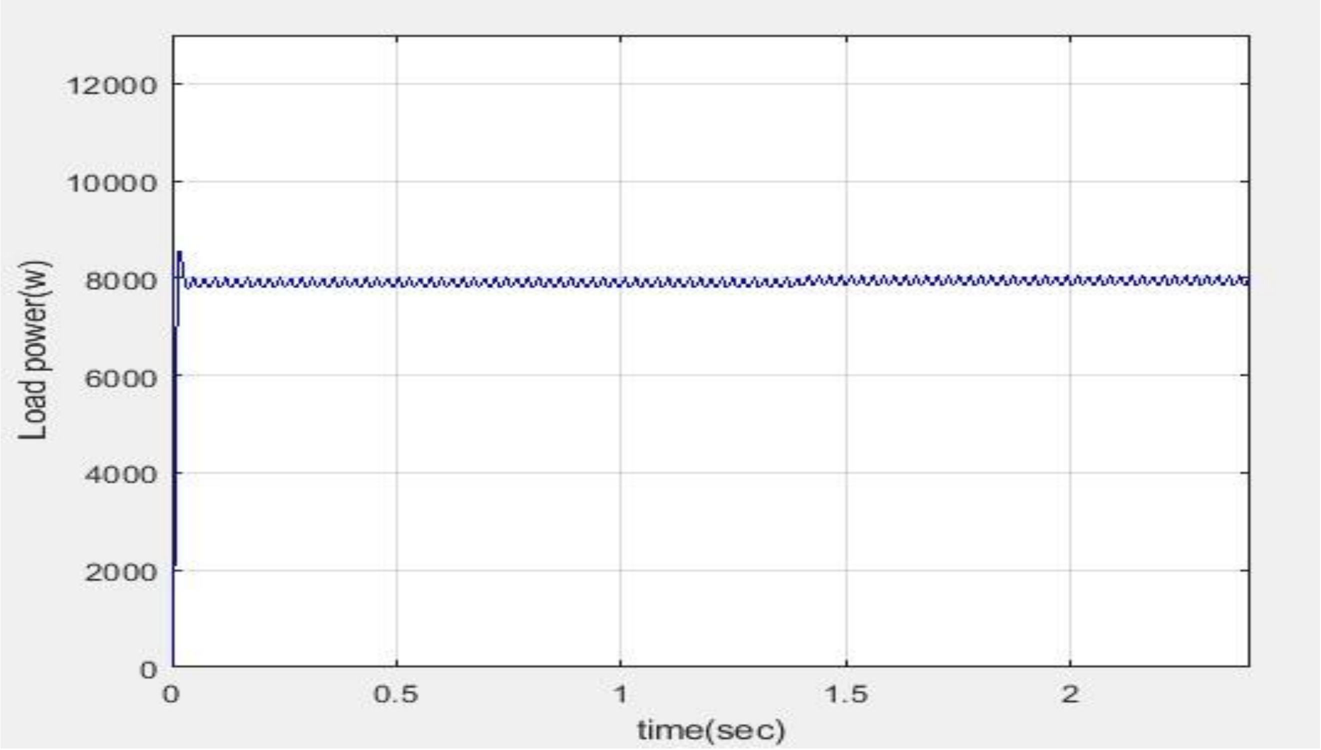


Fig 16 Load power

In this system, 8000 watts of DC load is connected to the DC link via two load-side converters for battery storage.

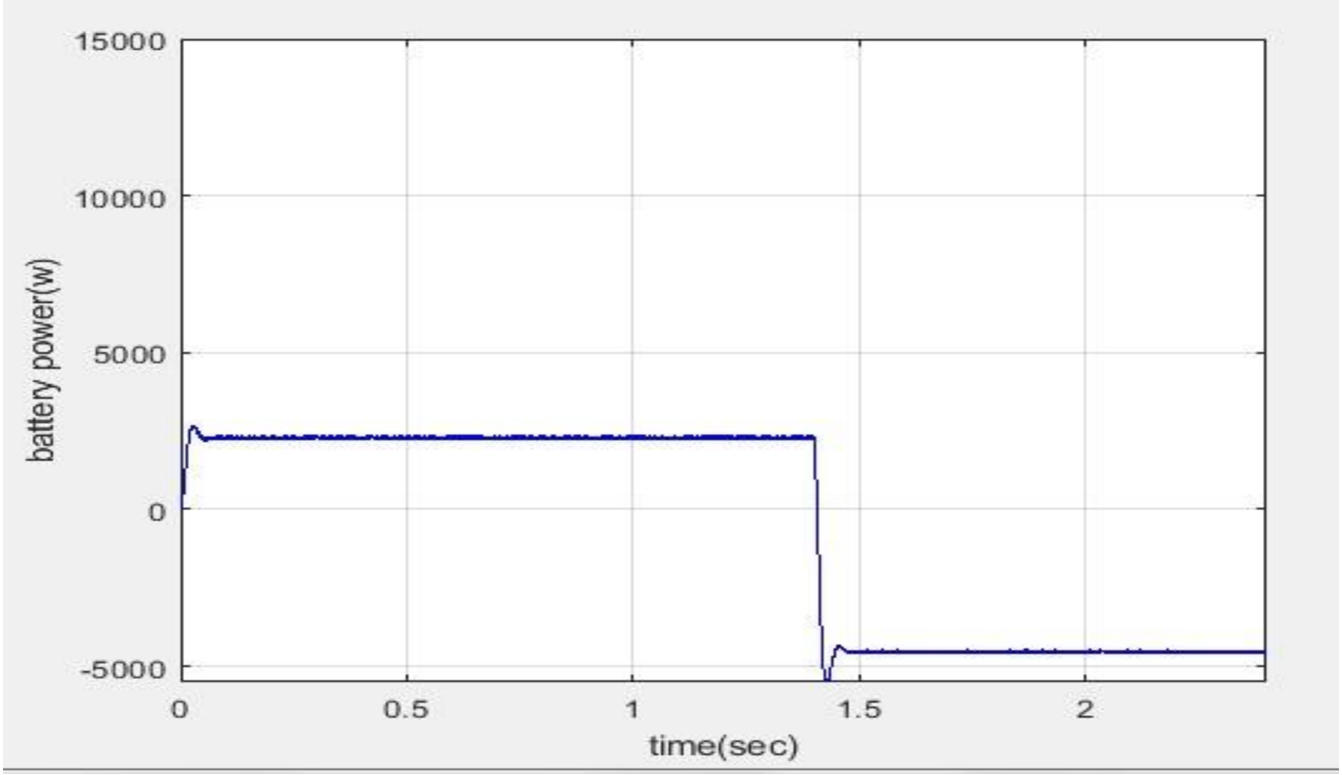
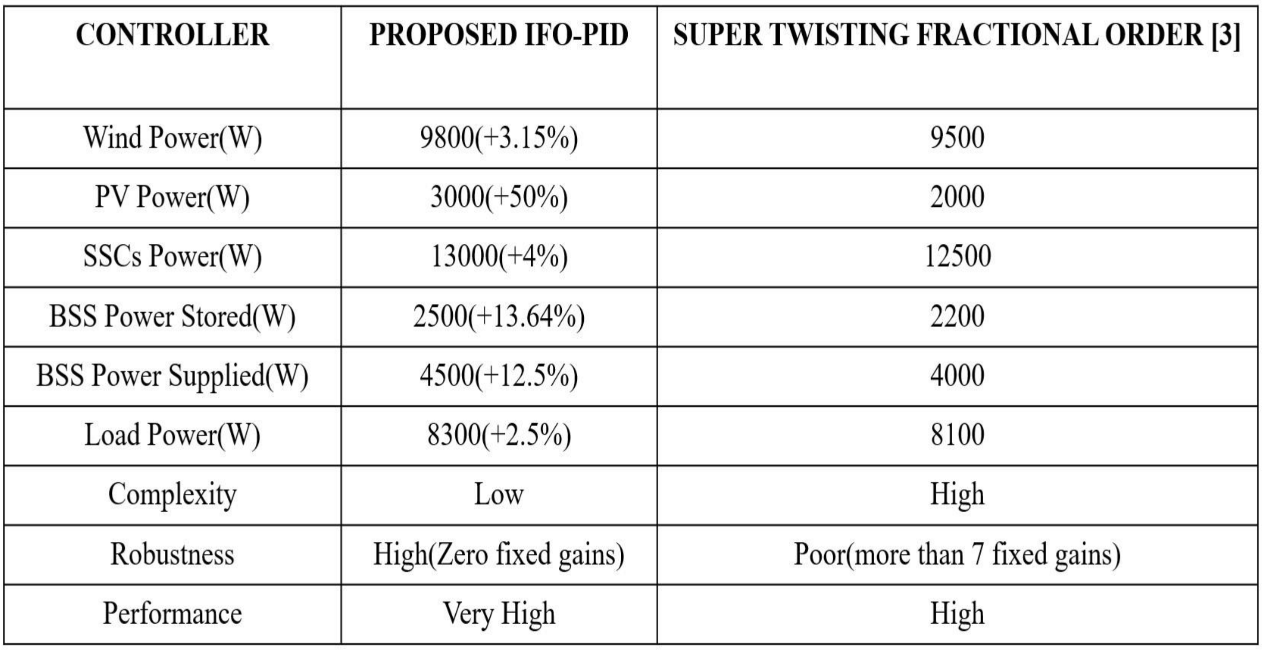


Fig 17 Battery Power

The battery powers the microgrid with approximately 2300 watts when SOC is greater than 20% at time intervals [01.4] seconds. When the generated Pdg exceeds the load power at time interval [1.42.3], the battery is charged from the microgrid at approximately 4500 watts, as shown in Figure 19
The simulation also involved adjusting the intermediate circuit voltage for both SSC (Source Side Converter) and LSC (Load Side Converter) using PI (Proportional Integral) and suggested IFO-PID (Intelligent Fractional-Order Proportional-Integral Derivative) controllers. Both controllers successfully adjusted the intermediate circuit to its set value. Excellent performance in terms of steady-state error and convergence criteria. However, the proposed IFO-PID controller demonstrated excellent performance in terms of steady state error and convergence criteria.

Overall, the simulation results suggest that the proposed system, which combines wind and solar energy sources with a battery storage unit, is capable of generating and managing power effectively. The combination of wind and solar power allows for a reliable and sustainable energy supply, and the battery storage system ensures efficient energy management. Moreover, the proposed IFO-PID controller exhibits superior performance compared to the traditional PI controller in regulating the intermediate circuit voltage. The results of this simulation provide valuable insights into the performance and viability of the proposed system in a microgrid setup. The successful integration of renewable energy sources and battery storage can lead to a more stable and sustainable power supply, contributing to the overall development and adoption of clean energy technologies. Further research and realworld testing will be essential to validate and optimize the proposed system's performance in various scenarios and grid conditions.

TABLE 2 Comparative Analysis



CONTROLLER	PROPOSED IFO-PID	SUPER TWISTING FRACTIONAL ORDER [3]
Wind Power(W)	9800(+3.15%)	9500
PV Power(W)	3000(+50%)	2000
SSCs Power(W)	13000(+4%)	12500
BSS Power Stored(W)	2500(+13.64%)	2200
BSS Power Supplied(W)	4500(+12.5%)	4000
Load Power(W)	8300(+2.5%)	8100
Complexity	Low	High
Robustness	High(Zero fixed gains)	Poor(more than 7 fixed gains)
Performance	Very High	High

It shows comparative analysis of Proposed IFO-PID controller and Super Twisting Fractional Order [3]

V CONCLUSION

The integration of hybrid energy sources, including a battery bank, wind energy, and photovoltaic (PV) energy, in a DCmicrogrid. Maximum power point tracking techniques are implemented to extract the maximum power from these renewable energy sources. A new Intelligent Fractional Order PID controller ensures smooth output power and service continuity. An energy management algorithm coordinates and controls the DC microgrid's operation, managing battery charging and discharging for DC loads. The simulation results using MATLAB/SIMULATION confirm the successful control of output voltage, current, and power in the system.

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