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Hybrid Industrial Microgrid with Fractional Order Controller for Improved Frequency Stability

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Abstract- Increasing the integration of renewable energy sources into electrical power systems reduces overall inertia, leading to potential frequency instability. Effective control strategies are crucial to maintain frequency stability in hybrid industrial micro grids. This research proposes a fractional sliding mode control strategy for frequency stabilization in hybrid industrial micro grids. Explicit state-space model of a multisource hybrid industrial micro grid, includes load, energy storage systems, photovoltaic and wind farms, electric vehicles and batteries with state-of-charge control. This research investigates the effectiveness of the proposed controller based on fractional order to improve the frequency stability and micro grid performance. The proposed controller effectively damps frequency oscillations and maintains frequency stability under diverse scenarios. The controller demonstrates robustness, fast response, and reliability in managing frequency deviations.

Keywords Energy storage Systems (ESS), Fractional Sliding mode controller (FSMC), Fuel cell, Hybrid Industrial Micro grid (HIMG), Photovoltaic cell (PVs), Wind Turbine (WT).

1. Introduction

The idea of a microgrid (MG) made it easier to include DG and various important ESS technologies into a distribution network so that they could function independently under the current load configuration. Reducing the erratic energy swings in the distribution network caused by fluctuations in both generation and demand is thought to be possible with the concept of a microgrid. Any application of local demand generation can be accommodated by microgrid.

Through the provision of an improved control approach, this study delves deeper into improved microgrid functioning. The structure of the microgrid can be divided into two categories: hybrid and classic types. Classic type MGs are produced by conventional sources like distributed generator combined with a static switch and a standard network structure. The microgrid is made up of distributed storage units, loads, and DG units. It can function both independently and autonomously and be connected to the utility grid. However, Regarding the necessity of integrating DG sources into the energy market and advocating for high levels of DG penetration, typical MGs and the traditional network topology are inadequate. Additional issues with the traditional MG paradigm include the hierarchical structure that underpins a centralized controller [1]. The majority of HMGs blend conventional and renewable energy sources. Due to its integration of many technologies, including gas, electric vehicles (EVs), hydropower, solar, wind, and fossil fuel, As backup systems, HMGs frequently rely on a variety of regional renewable energy sources. In the context of industrial and rural electrification, more coordinated control processes are especially necessary for HIMG systems. An HMG design replaces the traditional static transfer switch with a bidirectional power controller, in order to meet the different power quality requirements of the different MG components and the various types of loads. Numerous energy and electrical issues can be resolved with HMGs [2].

2. Structure of HIMG System

This part describes the structure of HIMG, its functioning, and the accompanying he test system and control approach used in the simulation model. The schematic diagram of a HIMG is displayed in Figure 1.

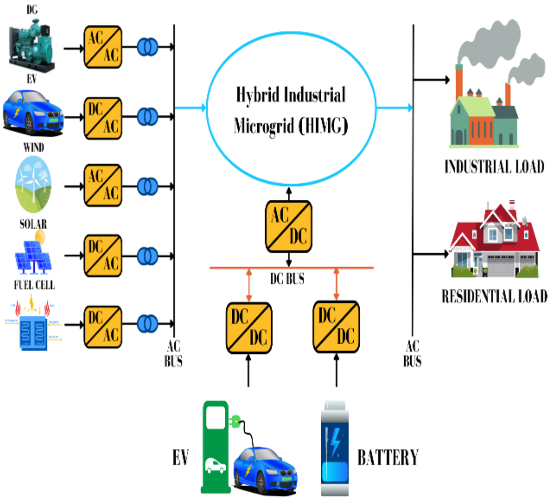

Fig. 1 Structure of HIMG.

This work simulates a microgrid including source like Distributed generator, WT, FC, battery, PV system, and EV aggregator in order to examine the dynamic frequency responses of the system. To enable energy transfer in both directions between the AC and DC buses of the sub-grids, interlinking converters are used, contingent upon the existing internal supply-demand scenario. Voltage and frequency issues arise from a HIMG's difficulty in setup and maintenance, which is attributed to the differences in operation between AC and DC components.

The AC and DC components of the microgrid are connected via a bidirectional interlinking converter. The microgrid's DC side is connected to an ESS and an electric vehicle charging station, while The synchronous generator, fuel cell, AC loads, wind energy, solar energy system source are all connected to the AC side. A system that integrates an AC and a DC component is known as an AC/DC microgrid. The AC/DC power source has the ability to receive and supply both AC and DC power. An FC, an EV, and a grid-connected DC-AC photovoltaic panel was used in this work, as seen in Figure 1 [3].

This distributed design provides clear benefits:

Sustainability of the environment: The use of renewable energy lessens reliance on fossil fuels, therefore reducing greenhouse gas emissions and their effects.

Increased Efficiency: By encouraging power generation on-site, microgrids reduce transmission losses and maximise energy use inside the industrial complex.

Increased Resiliency: By operating in island mode during main grid failures, important industrial operations are protected from interruptions and operational continuity is ensured.

The Main Concern of Frequency Stability Though there are many advantages, one major problem is keeping the frequency stability inside the microgrid because renewable sources are intermittent. Production operations might be jeopardized and significant expenses can result from frequency fluctuations that upset sensitive industrial equipment and cause cascade outages [4].

3. Modelling of Solar Photovoltaic System

The burgeoning integration of renewable energy sources, particularly solar photovoltaic (PV) systems, into industrial microgrids presents a significant challenge: maintaining frequency stability. Unlike traditional power plants with large rotating masses that contribute inertia to the system, solar PV systems lack this inherent characteristic. This reduced inertia makes industrial microgrids with high solar penetration more susceptible to frequency fluctuations caused by changes in power demand or solar irradiance. These fluctuations can disrupt critical industrial processes and damage equipment [5].

3.1 PV Cell Model

The model has a solar photovoltaic array that uses photovoltaic cells to convert sunlight into electrical energy. In order to mimic realistic solar power generation, parameters like temperature, solar irradiation, and PV panel properties are taken into account. The amount of power that a solar farm could produce was determined by measuring the amount of irradiance generated and by considering area covered by the panel.

The temperature – 25° C and irradiance 1 kW/m^2 will be the input variables utilized for compute the output factors of voltage, current and Power. The output current of a solar cell is directly influenced by the amount of light shining on it.

The single diode model is the most widely used type of solar array, Figure 2 shows the corresponding circuit for this model. It is made up of a series resistor (R1) acting as the inner resistance to the current flow, one diode in parallel with a current source, and a parallel resistor (R2) that denotes a leakage current (I_p). Because PV energy is inexpensive and doesn't require any machine-driven components, it is growing in popularity across all RESs[5].

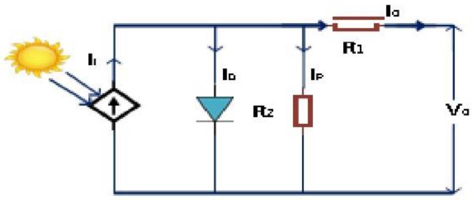

Fig. 2 Equivalent circuit diagram of a Solar cell.

The complete PV array is modeled by connecting numerous single-diode or two-diode models in series and parallel, reflecting the actual configuration. Additional factors such as inverter efficiency and non-linear characteristics can be incorporated for enhanced precision. The inverter dynamics that interface the PV system with the microgrid need to be incorporated into the overall model for comprehensive analysis. These dynamics can introduce delays and introduce additional complexities into the system behavior [7].

The following represents the nonlinear V-I characteristic equation of a PV cell:

$$I_o = I_I - I_D - I_P \tag{1}$$

$$I_o = I_I - I_s\left(\exp\left[\frac{V_o+I_oR_1}{\varepsilon\times V_t}\right]\right) - \frac{V_o+I_oR_1}{R_2} \tag{2}$$

where

II=input current

IP=parallel current

ID=diode saturation current

Io=current flowing across PV cells

Is=saturation curve of the diode

When a PV farm output is connected to the microgrid, an inverter is utilized to transform the DC electricity from the PV system into AC power on the microgrid side. The first-order lag approximation model is considered as follows:

$$G_{pv} = \frac{\Delta P_{pv}}{P_{pv}} = \frac{1}{1+sT_{pv}} \tag{3}$$

The PV system has been designed by considering following parameter as shown in Table 1.

Table 1: PV System Parameter

Sr. No.	Parameter	Value
1	Input1= Sun irradiance	800 Wb/m^2
2	Input2= Cell Temperature	25^{0}C
3	Maximum Power	200.143 Watt
4	Cell/module	54
5	Short circuit current (Isc)	8.21 A
6	Open circuit voltage (Voc)	32.9 V
7	Voltage at maximum Power point (Vmp)	26.3 V
8	Current at Maximum Power Point (Imp)	7.61A
9	Temperature coefficient	-0.35502 %/^{0}C
10	Temperature coefficient of Isc	0.06 %/^{0}C
11	Shunt Resistance Rsh	150.6921 Ω
12	Series Resistance Rs	0.34483 Ω

4. Modelling of Wind Turbine System

An increasing penetration of wind turbines (WTs) in hybrid industrial microgrids requires the development of robust control strategies to maintain frequency stability. Wind speed variability presents a significant challenge in this regard. Fractional sliding mode control (FSMC) offers a promising approach due to its inherent robustness to uncertainties and external disturbances. This work outlines a professional approach to modeling a wind turbine system for frequency stability analysis within a fractional sliding mode control framework for hybrid industrial microgrid. Most MGs acknowledge the WT as an essential renewable energy system. Due to the unpredictable nature of wind speed, the generation of mechanical power is extremely variable [8] [10].

$$P_{wt} = \frac{\rho\times A_s\times K\times V_w}{2} \tag{4}$$

where

ρ=air density

As=swept area of the turbine blades

K=coefficient of power

Vw=wind velocity

The essential RESs generated by solar and wind power plants result in an unstable and erratic supply of electrical power. As a result, these negative effects on non-ESS industrial consumers have been appropriately sized and fitted in accordance with technical specifications. In this work, It is investigated how the nonlinear dynamics of the WT are approximated using the first-order lag model.

$$G_{wt} = \frac{\Delta P_{wt}}{P_{wt}} = \frac{K_{wt}}{1+sT_{wt}} \tag{5}$$

The Wind Turbine modelling is based on parameters as shown in Table 2.

Table 2: Wind turbine Generator Parameter

Sr. No.	Parameter	Value
1	Generator speed	0.98
2	Pitch angle	30^0
3	Nominal mechanical output power (W)	1.5 MW
4	Base wind speed(m/s)	12
5	Maximum power at base wind speed	0.73
6	Base rotational speed	1.2
7	Asynchronous Generator	480V, 275KVA

5. Modelling of Fuel Cell System

The increasing deployment of fuel cells (FCs) in hybrid industrial microgrids requires the development of accurate dynamic models for frequency stability analysis. This is particularly crucial when implementing Fractional Sliding Mode Control (FSMC) due to its dependence on system dynamics. This work outlines an approach to modelling a fuel cell system for frequency stability analysis within a fractional sliding-mode control framework for hybrid industrial microgrids. To mitigate the risk of failure resulting from the sporadic nature of the PV and WT systems, the ESSs are equipped with a fuel cell. Fig. 3 shows how the FC block is a part of distributed generation power source of HIMG. Hydrogen serves as an energy producing input. The fuel cell functions as a backup generator for power and as a production controller. Fuel cells are able to supply electricity at peak hours, per the necessity [11].

The first order model of Fuel Cell system is considered as follows.

$$G_{fc} = \frac{\Delta P_{fc}}{\Delta U_{fc}} \times \frac{1}{1+sT_{fc}} \times \frac{1}{1+ST_i} \times \frac{1}{1+ST_c} \tag{6}$$

6. Modelling of Diesel Generator System

The integration of renewable energy sources such as wind and solar in industrial microgrids presents challenge to maintain frequency stability. Diesel generators (DGs) play a vital role in mitigating these challenges by providing fast-responding power reserves. Accurate modelling of the DG system dynamics is crucial for the design of robust control strategies, particularly when employing advanced techniques like Fractional Sliding-Mode Control (FSMC).

This work outlines a professional approach to modelling a diesel generator system for frequency stability analysis within an FSMC framework for hybrid industrial microgrids. Owing to the unstable power outputs among the PV and WT systems, the Distributed generator is seen to be the most reliable option for providing consistent, high-quality power to the important loads in a hybrid integrated generation system. Figure 2 depicts the mathematical model of a DG system with a turbine and regulator. The engine's time regulator mechanism keeps it operating at a certain speed, and the AC signal has a frequency of 50 Hz. It is planned to have a primary power generator with a 15 MW capacity [13]. It can improve system reliability by adjusting voltage and frequency. The diesel generators power equation is

7. Modelling of Electric vehicle Battery

The burgeoning adoption of electric vehicles (EVs) necessitates the exploration of their potential to enhancing frequency stability within hybrid industrial microgrids. Their on-board battery energy storage systems (ESS) present a valuable resource for grid operators. However, for effective control design, particularly when employing advanced techniques like fractional sliding mode Control (FSMC), meticulous modelling of the EV battery system dynamics becomes paramount. This work focused on modelling an EV battery system for frequency stability analysis with FSMC in hybrid industrial microgrids [14].

Numerous technological challenges, such as those related to power quality, reliability, safety, grid operation, and economics, have been brought about by solar PV and wind energy systems. DGs can't always provide the power system with enough support because solar PV and wind energies are highly unpredictable due to the meteorological factors that greatly affect power generation. The battery is one of the most important parts of free-standing microgrid systems. By giving the system electricity fast, this makes a significant contribution to preserving system stability. In order to stabilize the frequency deviation response, the battery energy storage functions as a local active power source by trading power with the MG.

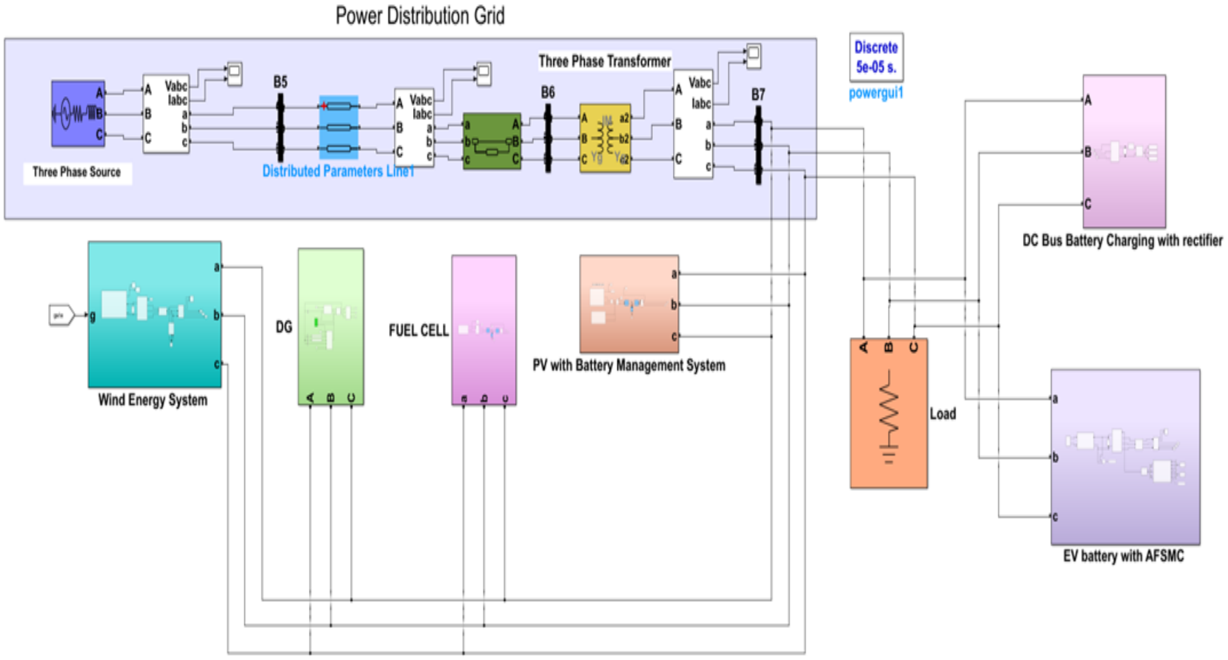

Fig. 3. Simulation Model of FSMC Based Hybrid Industrial Microgrid.

8. Simulation Result

The Hybrid Industrial Microgrid has been modeled and simulated in the MATLAB/SIMULINK environment as shown in Figure 3. The fractional sliding mode controller (FSMC) works effective on frequency deviation and rate of change of frequency and accordingly adjust fractional orders for better stability. With its robust stabilizer, this search process may function well in a variety of operating environments.

A Fractional Order Controller (FOC) offers a powerful and flexible control solution for industrial microgrids, which are characterized by nonlinear dynamics, variable operating conditions, and high levels of renewable energy integration. By employing fractional calculus, the controller extends conventional integer-order control by allowing non-integer orders of integration and differentiation [6][9][15], thereby providing additional tuning parameters to more accurately capture the inherent dynamics of distributed generation units, energy storage systems, and industrial loads. This results in improved robustness, stability margins, and dynamic performance, particularly during load variations, grid disturbances, and mode transitions between grid-connected and islanded operation. Owing to its superior disturbance rejection capability and enhanced power quality regulation, the fractional order controller is well suited for ensuring reliable and efficient operation of industrial microgrids [12].

A Fractional Order Sliding Mode Controller (FOSMC) is an advanced control strategy well suited for industrial microgrids, where high penetration of renewable energy sources, nonlinear loads, and frequent operating disturbances demand robust and flexible control. By integrating fractional calculus with conventional sliding mode control, FOSMC introduces additional degrees of freedom through non-integer order derivatives, enabling more accurate modeling of microgrid dynamics and improved dynamic response. This approach enhances robustness against parameter uncertainties, reduces chattering effects commonly associated with classical sliding mode controllers, and ensures stable voltage and frequency regulation under grid-connected and islanded modes. Consequently, FOSMC provides superior disturbance rejection, faster convergence, and improved power quality, making it an effective and reliable control solution for modern industrial microgrids [17].

The components of a HIMG system include an energy storage system (ESS), an industrial load, diesel generator, and renewable energy sources (such as solar PV and wind turbines). Dynamic disturbances that the HIMG system is subjected to include abrupt changes in wind speed (for wind turbines), variations in solar irradiance (for photovoltaic systems) and a notable rise or fall in power consumption at the industrial load [18].

In order to govern the microgrid's power flow and preserve frequency stability, an FSMC controller is employed.

Fig. 4. Waveforms shows performance of various parts of scheme under consideration which includes, a) PV power output b) Wind Turbine output (Power) c) Distributed Generator output (Power) d) Fuel cell output (Power) e) EV Battery power output f) HIMG Frequency.

In order to examine the system's behavior under FSMC management, the results in Fig. 5. proves the efficacy of changing fractional order to maintain stability of frequency for appreciable frequency disturbance.

Fig. 5. graph shows that for one percent sudden change in frequency causes the system frequency to respond differently to different fractional orders. It is quite evident that integer order is not adequate for stable frequency due to overshoots and undershoots in frequency and settling with higher steady state error. While choice of fractional order improves frequency profile with almost no overshoot and better settled stable frequency response of overall interconnected system.

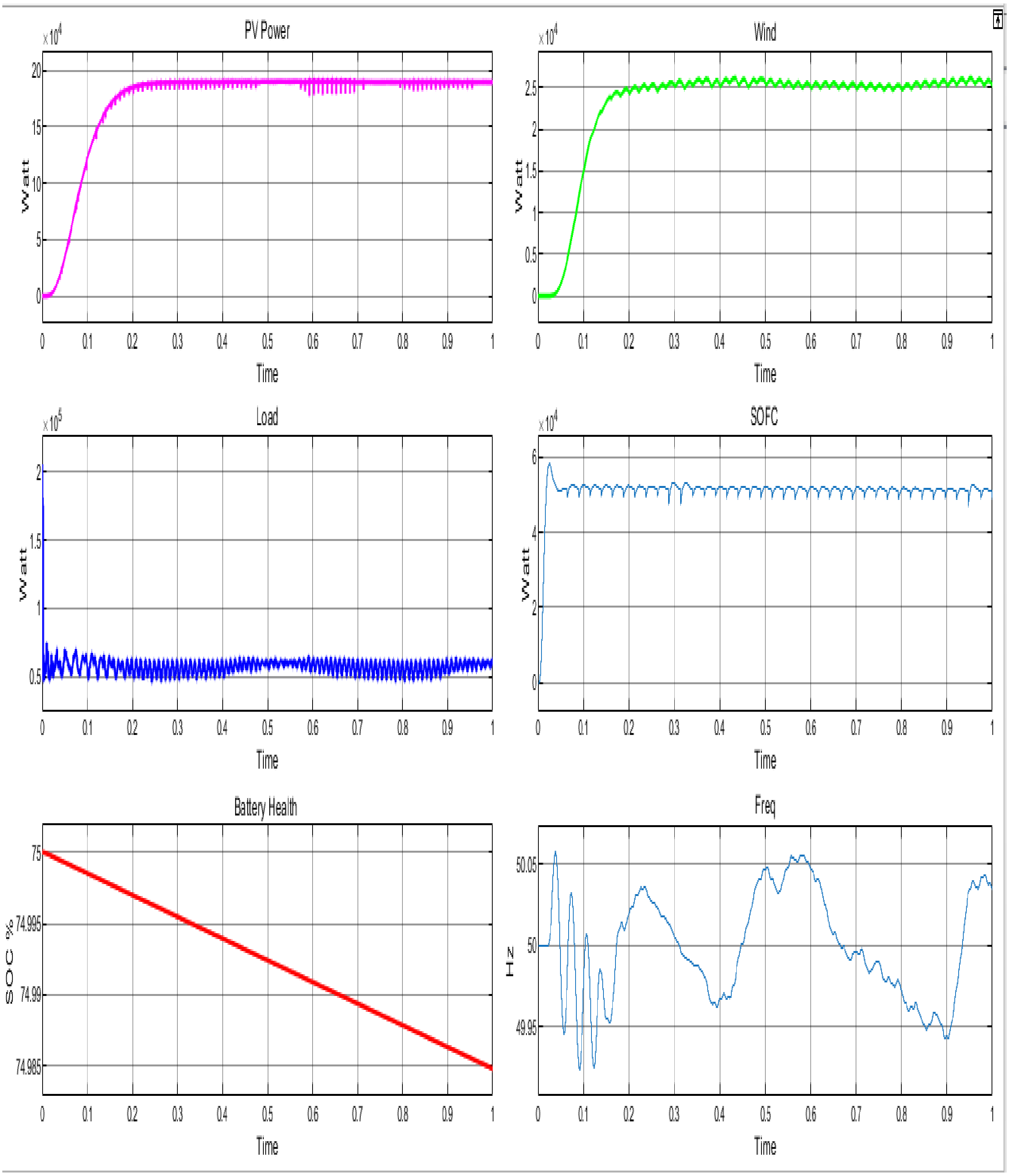

Fig. 4. a) PV power output b) WT output (Power) c) Distributed Generator output (Power) d) Fuel cell output (Power) e) EV Battery power output f) HIMG Frequency.

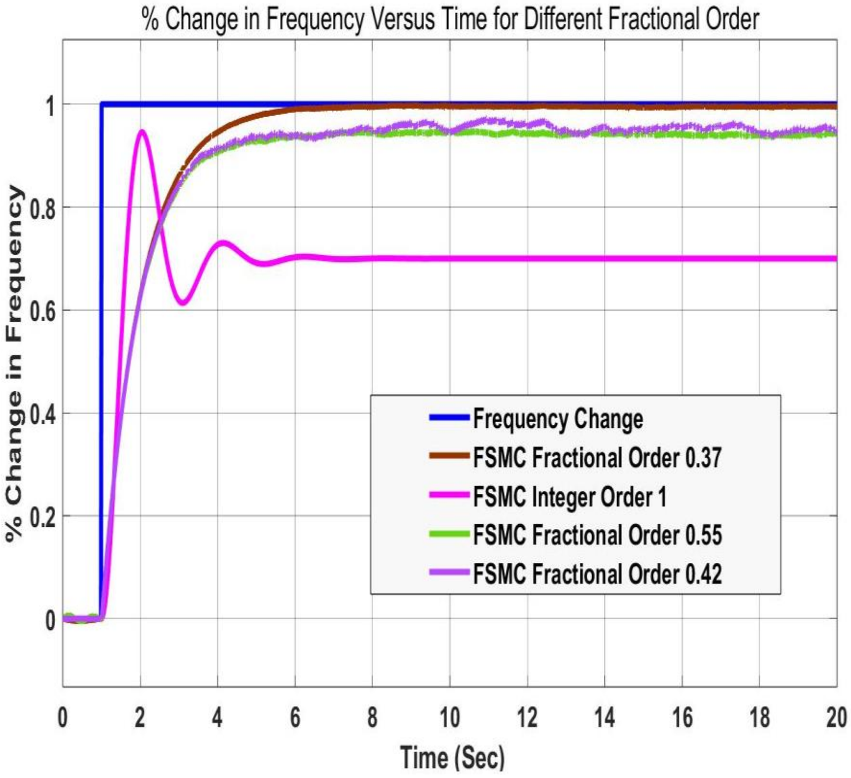

Fig. 5. Frequency stability.

9. Conclusion

Hybrid FSMC system to enhance the frequency stability of microgrid have been examined in this paper. A reliable solar and wind power supply reduces microgrid renewable source uncertainty. The hybrid system provided more energy security and demand management than a single renewable source. A hybrid system with FSMC management improved microgrid stability, voltage regulation, and power sharing accuracy. Successful use of hybrid systems with FSMC control presents chances for the reliable and reasonably priced integration of renewable energy sources into industrial settings. This strategy helps to create a more robust and sustainable energy infrastructure, lowers reliance on fossil fuels, and improves microgrid stability. The results of the simulation indicate that the suggested controller outperforms the controller used to obtain higher values of the performance index appropriate for each scenario. In addition, the suggested control strategy offers a reduced overshoot and settling time. Reliability of generated output, low internal resistance, and unbalanced system circumstances are the main challenges that MGs have faced lately.

The simulation results indicate that the suggested controller outperforms the one used in the past, achieving superior performance index values across various scenarios. In addition, it ensures minimal overshoot and quicker settling times. Despite these advancements, microgrids (MGs) continue to grapple with significant issues such as parameter uncertainty which can affect controller choice of fractional order.

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