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Fuzzy logic-based controller of the bidirectional direct current to direct current converter in microgrid

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ABSTRACT

Microgrids are small-scale power networks that include renewable energy sources, load, energy storage systems, and energy management systems (EMS). Lithium-ion batteries are the most used battery for energy storage in microgrids due to their advantages over other types of batteries. However, to protect the battery from the explosion and to manage to charge and discharge based on state-of-charge (SoC) value, this type of battery requires the use of an energy management system. The main objective of this paper is to propose an intelligent control strategy for energy management in the microgrid to control the charge and discharge of Li-ion batteries to stabilize the system and reduce the cost of electricity due to the high cost of grid electricity. The proposed technique is based on a fuzzy logic controller (FLC) for voltage control. The FLC is based on the measured voltage of the direct current (DC) bus and the fixed reference voltage to generate buck/boost converter signal control. The proposed technique has been simulated and tested using MATLAB/Simulink software which illustrates the tracking of desired power and DC bus voltage regulation. The simulation results confirm that the proposed systems can diminish the deviations of the system's voltage.

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1. INTRODUCTION

A microgrid (MG) system is composed of several renewable energy sources (RES), including photovoltaic (PV) and wind energy, as well as batteries. The deployment of RESs alters the way energy is transmitted through utility power networks, allowing for greater flexibility in energy usage [1]. The intermittent nature of renewable energy has a significant impact on the system's normal operation. It poses a considerable challenge to the stability and balance of the microgrid system [2]. To address this issue, recent research has focused on integrating energy storage systems in the microgrid [3], [4]. Li-ion batteries are the most used electrochemical batteries due to their benefits. However, this form of battery requires a battery management system to guard against an explosion. We have previously witnessed multiple catastrophes using Li-ion battery packs, including the crash of Japan airlines' 787 in Boston due to battery overheating. As a result, battery and energy management systems safeguard the battery while maintaining the microgrid's stability and energy management [5]. Numerous articles [6], [7] focused on bidirectional converter regulation of the direct curent (DC) bus voltage. Conventional controls for bidirectional converters, such as proportional integral derivative (PID) controllers, are frequently utilized [8]. This control approach, however, is only applicable to linear systems [9].

As indicated in [10], nonlinear techniques, such as sliding mode controllers, are more efficient than linear methods. These solutions, however, need exact mathematical modeling and a thorough understanding of the regulated system. However, the intermittent nature of renewable energy sources and their sensitivity to weather factors, unpredictable load demand, and the existence of grid faults complicate system modeling and result in suboptimal control performance. These constraints have encouraged researchers to develop and deploy more sophisticated adaptive control algorithms for highly nonlinear microgrid systems [11].

An artificial intelligence-based approach has been used for energy management systems (EMS) strategies in MG applications to improve the efficiency and performance of MG systems and fulfill load demand with the maximum feasible power output. Energy management systems are frequently described as centered on power balance and system stability [12]. While ordinary generators and other energy storage systems often use dynamic components, the battery energy storage system is comprised of static components. Battery energy storage systems (BESS) can help with both long-term power management and short-term power quality control [13], [14]. Incorporating BESS systems into smart grids and microgrid systems considerably increases the computing complexity of the optimal power flow problem because it is a dynamic optimal power flow problem [15]. The use of the BESS system can be optimized based on factors such as network topology, weather conditions, and battery state of charge (SoC). Overcharging or undercharging can significantly impact the battery's life expectancy [16], [17]. In addition, batteries with low SoC cannot send power to the network because of their lower output voltage. The SoC of the BESS systems will also affect the optimization function after the battery efficiency depends on the SoC [18]. Distributed systems in microgrids or isolated locations may benefit from mixed-coupling, which connects a DC bus with an alternating current (AC) bus [19]. We have included solar panels and batteries that utilize DC electricity in our list of sources and storage units. In contrast, wind turbines employ alternating electricity [20], [21].

The loads may be continuous or intermittent depending on the circumstances. Reversible DC/AC converters enable the connecting of each device to its corresponding bus and the subsequent interchange of power between buses [22], [23]. To assure the autonomous management of produced energy, we aim to establish the potential design for a power system in a remote site [24]. Consequently, two parts are vital to its design: a local and if possible, renewable energy source fed into the structure and a storage unit that can keep excess production and release it to complete the construction [25], [26]. A hierarchical energy management system controller is required to enhance the entire system's economics and resiliency and boost the robustness and adaptability of PV, wind, and battery-based microgrids. The use of internet of things (IoT) in microgrid control offers distributed control, improved data collection, and real-time decision making [27]. IoT sensors and meters monitor energy production and consumption, leading to optimized energy generation and distribution, reducing waste, and increasing efficiency [28]. The real-time data collected allows for a more responsive control system, resulting in a smoother operation and cost savings. IoT technology provides a more sustainable energy solution for microgrids.

MG system performance can be improved by using fuzzy logic controllers in distributed control systems to choose the suitable settings for distributed controllers. The artificial intelligence-based EMS model is proposed in [29] to improve the microgrids stability connected to the primary grid by considering RESs and energy storage systems (ESS) units. To ensure a smooth out of the power profile exchange with the grid, the generation and demand forecast considers the expected future behavior of MGs. This paper proposes an effective control strategy based on fuzzy logic control for voltage control in DC bus. The proposed technique is used for voltage stabilization by fixing the voltage and providing load power while also considering battery management through the integration of the state of charge in the control strategy.

This paper's remaining sections are organized as follows: section 2 presents system studies. Section 3 goes over the proposed controller for the energy management system. Section 4 presents the simulation results. This paper concludes with a conclusion and recommendations for future work.

2. MICROGRID SYSTEM

Figure 1 the proposed microgrid system studied. The microgrid system is comprised of two renewable energy sources (photovoltaic and wind turbines), a storage system, and a backup connection to the primary grid. All sources are linked to the DC bus through converters to provide a continuous AC and DC loads supply. Maximum power point tracking (MPPT) controller used to maximize the output power of the solar system, solar photovoltaic panels, are linked to the DC bus through a DC/DC converter regulated by a MPPT [12] block. The battery system is linked to the microgrid through a bidirectional DC-DC converter and is managed via fuzzy logic controller (FLC).

The power generated by the photovoltaic and wind sources represents the total renewable power produced in the microgrid. This power may be greater or less than the load power, resulting in an imbalance in the microgrid power system. The system controller compensates for this imbalance by charging or discharging the battery. The Li-ion battery used in this system has a voltage of 140 V and a capacity of 140 Ah. Furthermore, using bidirectional DC-DC converter (BDC), the voltage can be increased to 400 V. The solar cell type is SPR-300NE-WHT-D used from the Simscapr power system toolbox of MATLAB/Simulink with 15 panels in parallel and 10 in series. The wind system consists of a wind turbine, a permanent magnet synchronous generator (PMSG), AC/DC converter, a DC-DC boost converter, and an MPPT controller. In addition, a 15 kW for DC load and 40 kW for AC load. The electrical grid was also dimensioned to cover the required power via an AC/DC converter.

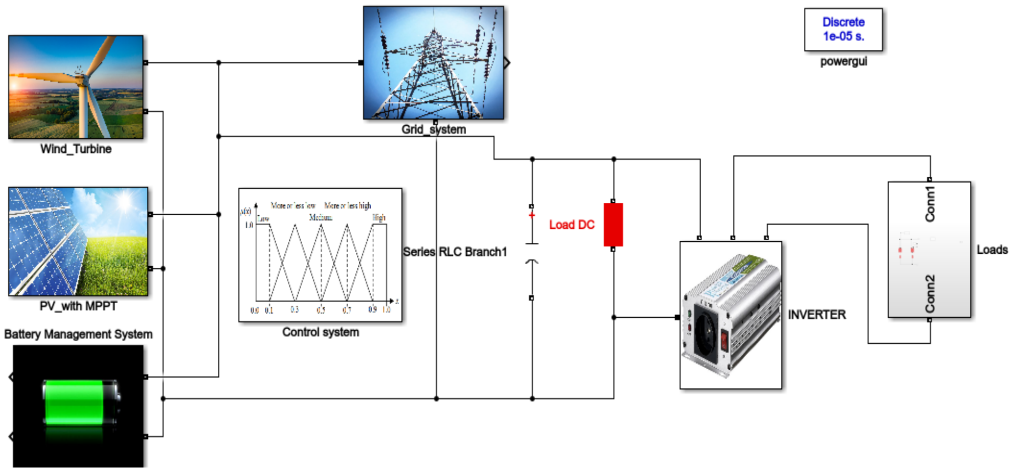

Figure 1. Microgrid proposed system

3. PROPOSED CONTROLLER FOR ENERGY MANAGEMENT SYSTEM

The energy management system's purpose is to meet load demand in various weather conditions while controlling power flow and ensuring the system operates efficiently. The EMS should primarily rely on solar and wind energy to meet the load demand. The concept of energy transfer is realized with an efficient control algorithm that includes the bus power, voltage, and battery SoC. The proposed control strategy achieves good regulation capability. The EMS meets load demand under all weather conditions (solar irradiation and wind fluctuation). Additionally, maintain the DC bus voltage near the 400 V reference voltage. The battery system is then responsible for maintaining the required voltage value by charging and discharging the battery throughout the bidirectional DC-DC converter. The first component is converter control, ensuring that the power system remains balanced; and The second is for regulating the DC bus voltage.

The main part of the energy management system is the bidirectional DC-DC converter, which can be seen in Figure 2. By charging or draining the battery, the bidirectional converter is employed to maintain the energy balance of the microgrid. When power is being transferred from the battery to the bus, and the DC bus voltage is less than 400 V, it also functions as a boost converter. The converter operates as a buck converter and charges the battery when the bus voltage in the opposite direction exceeds 400 V.

The converter parameters used in this simulation are shown in Table 1. The main object of the EMS is to keep the balance at the microgrid, which means at the DC bus: voltage stability on 400 V; and the power balances (PRES=Ploads). At the AC bus: frequency stable on 60 Hz; and the power balances (PRES=Ploads).

Figure 3 illustrates the control approach employed in this system. The bidirectional converter operates on a voltage-regulated basis. As a result, the voltage on the DC bus was measured and compared to a reference value. The difference between these voltage readings is analyzed using fuzzy function blocks to determine the duty cycle for each direction.

The control of the bidirectional converter is the critical factor of power management. To manage the energy exchanges between the DC bus, the power production, consumption, and the storage system. Three operating modes of battery are employed: charging, discharging, and stop mode.

The DC bus voltage was measured and compared to the fixed 400 V reference value. The duty cycle of buck and boost converters is determined by the difference between these voltage levels analyzed in fuzzy function blocks. The function of the funnel controller (FC) controller is depicted in Figure 4.

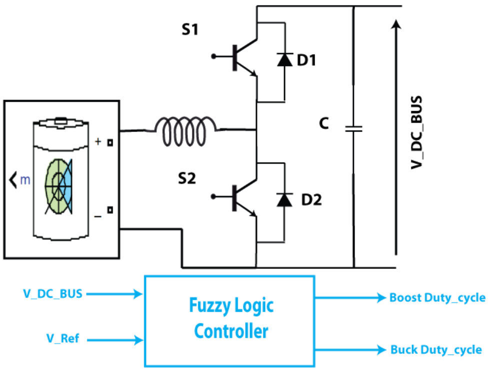

Figure 2. Bidirectional DC-DC converter

Table 1. Parameters of the bidirectional converter

Parameter	Value
Converter inductance	2.4 mH
Converter capacitance	0.8 uF
Semi-conductor type	IGBT*

*Note: insulated gate bipolar transistor (IGBT)

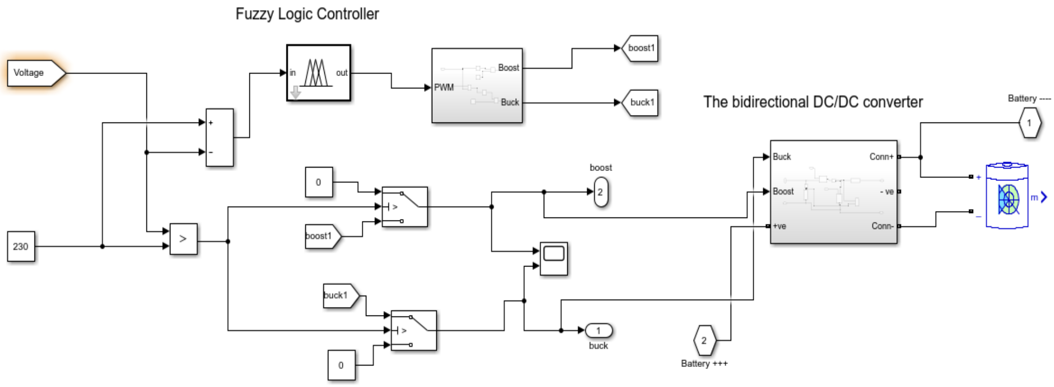

Figure 3. Bidirectional DC-DC converter control technique using fuzzy logic (FL)

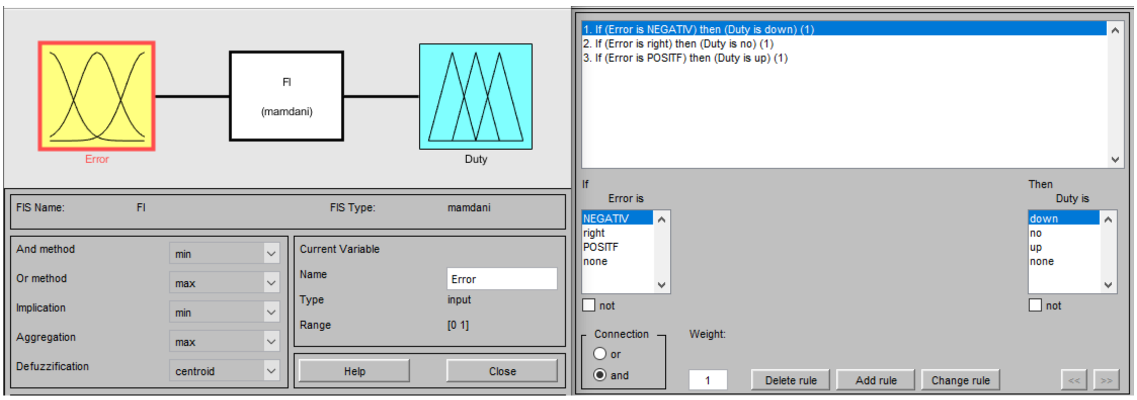

Figure 4. Fuzzy logic control function

4. SIMULATION AND RESULTS

The simulation runs for 1.2 seconds with a 1e-5s sampling time. To show the robustness of the fuzzy logic controller against the brutal change of meteorological conditions, we choose a scenario containing multiple changes in solar irradiation to represent all possible scenarios, as shown in Figures 5 and 6. The renewable energy elements are the primary power source in the proposed microgrid. Due to the variation in renewables power production, as shown in Figures 7 and 8, the variable loads demand. A backup system is needed to keep the balance of the microgrid all the time.

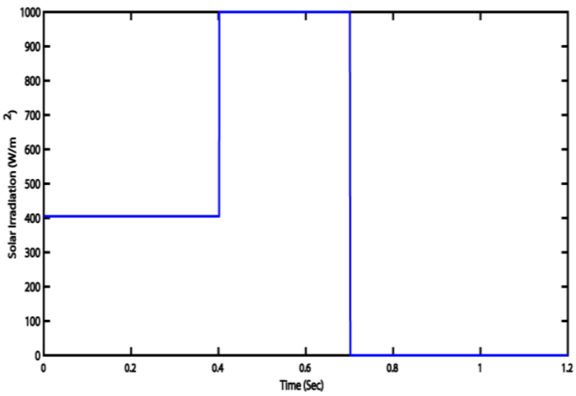

Figure 5. Solar irradiation (W/m^2)

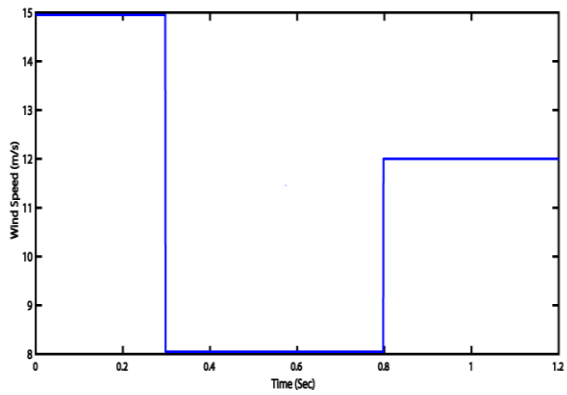

Figure 6. Wind speed (m/s)

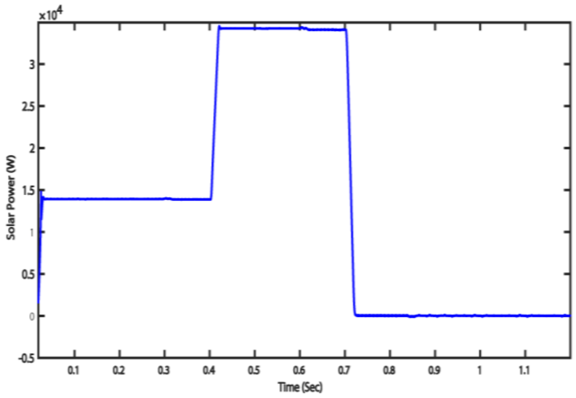

Figure 7. Solar power (W)

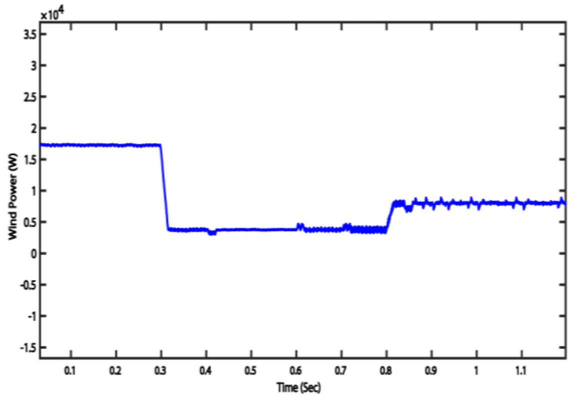

Figure 8. Wind power (W)

The battery is responsible for keeping the balance of the system by charging when the produced power is more than loads demand (between t=0.4 s and t=0.6 s) and by discharging when it is less than requested load power (between t=0 s and t=0.4 s). Figures 9 and 10 show the variation of the state of charge and the battery power during the proposed scenario. The measured power and voltage at the DC bus show the proposed EMS's effectiveness in stabilizing voltage and power at the DC bus, as shown in Figures 11 and 12. Figures 13 and 14 show the measured voltage and power at the AC bus. We can conclude the effectiveness of the proposed EMS in the stabilization of the AC bus in terms of voltage form and load power requested.

At t=0.8, the power produced from the renewable sources is equal (0 kW from solar +7 kW from the wind system), so the battery discharge provides the requested power. Still, at t=0.85, the battery arrives at $SOC < 0$, the minimum value of the battery state of charge. Therefore, the battery cannot be used anymore. To keep the balance at the microgrid bus, the electrical grid connected to the microgrid and provided the requested power, as shown in Figure 15. The variation of measured frequency at the AC bus is shown in Figure 16. The simulation results show the efficiency of the fuzzy logic controller in the balancing of AC and DC, the voltage of the DC bus is stable at 400 V, the frequency for AC voltage on limits marge, and the power consumed by loads is precisely equal to the requested load. Therefore, the energy management system grantee the balance in microgrid AC and DC buses.

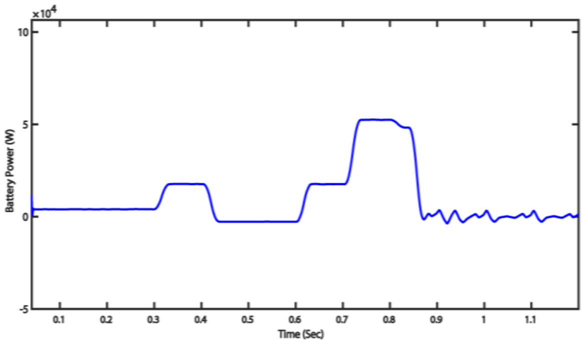

Figure 9. Battery power (W)

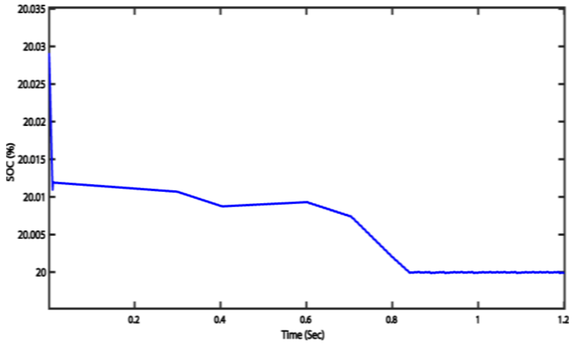

Figure 10. Battery state of charge (%)

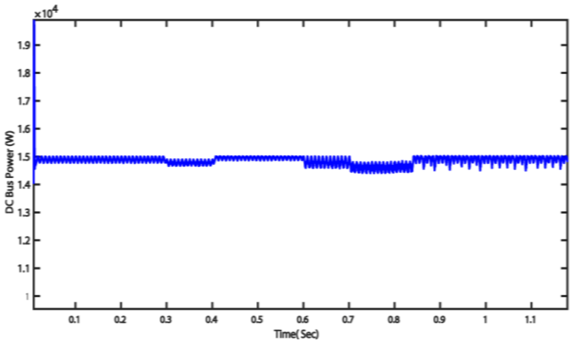

Figure 11. DC bus power (W)

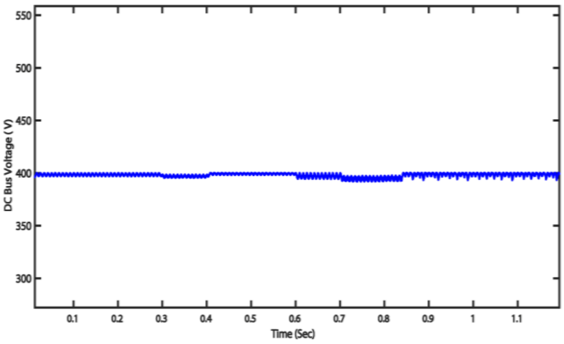

Figure 12. DC bus voltage (V)

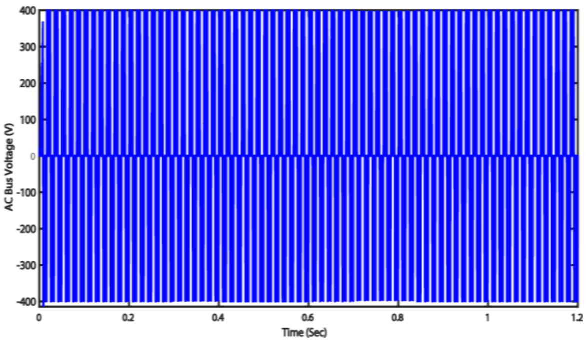

Figure 13. AC bus voltage (V)

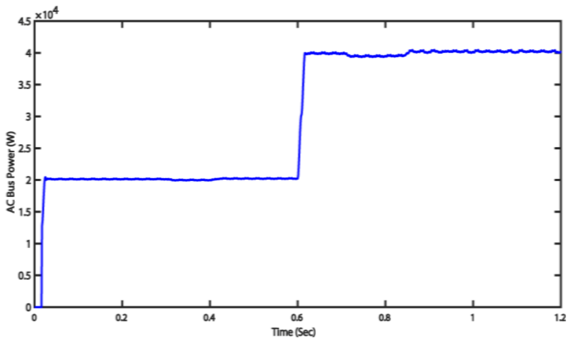

Figure 14. AC bus power (W)

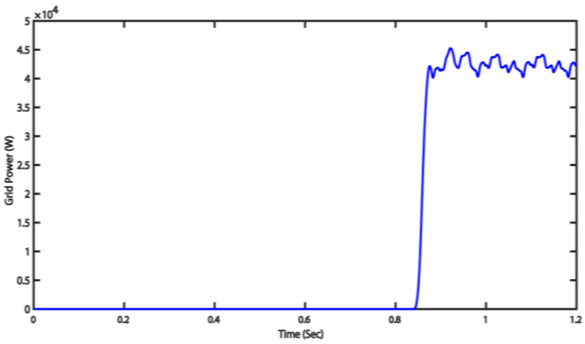

Figure 15. Measured connected grid power (W)

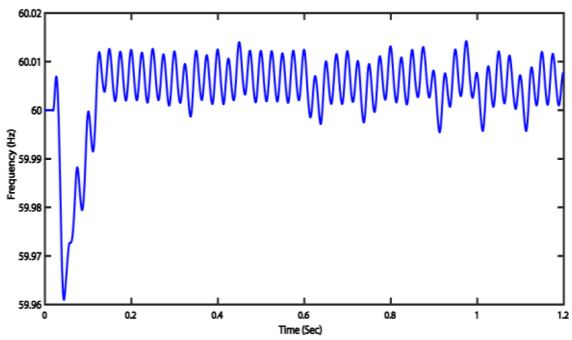

Figure 16. Frequency at AC bus (Hz)

5. CONCLUSION

This paper proposed a fuzzy logic controller for energy management in the microgrid and the power balance challenger in both islanded and connected modes. The proposed technique is tested under various metrology conditions to validate that the PV panel and battery energy storage system are working correctly and the microgrid stability is good. As shown in the simulation results, the fuzzy logic technique is a definitive way to regulate the voltage and frequency in the microgrid bus, taking into account numerous characteristics like SoC, solar power, wind power, and load request.

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