# Frequency response of microgrids with PV power generation and energy storage system (battery and supercapacitor)

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**Article Info**

***Article history:***

Received Oct 23, 2022
Revised Jan 29, 2023
Accepted Apr 24, 2023

***Keywords:***

Droop control
Frequency response
Frequency stability
Inertia emulation
Renewable energy resource inertia
System inertia
Virtual inertia

**ABSTRACT**

Since renewable energy sources (RES) have almost little inertia, an increase in their electricity might harm the power system's ability to run steadily and dependably. Numerous solutions to the issue mentioned above are offered. This paper aims to assess the technological possibility of using energy storage system (ESS) devices built from batteries and supercapacitors to enhance the interia response of sources in microgrids with a large amount of PV power penetration. The microgrid's inertia was altered by varying the penetration level of RES. To obtain a rigid microgrid, batteries and supercapacitors are suggested in this study to enhance frequency stability and droop control is utilized to complete this assessment. The model of the on-grid power network was designed using Simulink in MATLAB to evaluate the high level of RES penetration impact on the frequency stability of the system. Results verify that the microgrid stiffness is significantly enhanced when the suggested storage elements are incorporated. The findings show that the rate of change of frequency (RoCoF) is reduced when the size of the ESS increases and vice versa. The supercapacitor energy storage system (SCESS) can increase the stability of the system's frequency more effectively than the battery energy storage systems (BESS) with a slower time response.



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## 1. INTRODUCTION

Decreased system inertia is a crucial obstacle to implementing renewable energy sources (RES) with a large-scale penetration rather than the conventional units [1]. The net system inertia of a traditional generation unit is primarily related to the rotational mass of machines, which preserves frequency stability, and deviation from the rated values during disturbances is smaller than in the RES [2]. However, most RES lack intrinsic inertial supports since they are linked to directing the electrical network via a power electronic converter connection. No rotating machines can store the moment of inertia. Due to the proportion of RES increases, the system's total inertia decreases, making it more susceptible to difficulties with frequency stability [3]. The rate of change of frequency (RoCoF) increases significantly with reduced system inertia, which causes a sharp increase or decrease in frequency and a more considerable frequency deviation. In a worst-case scenario, these circumstances might set off RoCoF and the protective device "under-frequency load shedding" relays, leading to a complete system shutdown [4]. Traditional systems with adequate synchronous generation have not seen a severe issue with low inertia. Still, it has become an increasing concern in RES-integrated systems with decreasing inertia. Therefore, system administrators and power grid managers must accurately forecast the entire power system's accessible inertia. A precise assessment may create suitable defences against frequency stability's difficulties [5].

Techniques for frequency and inertial response (IR) must be used in a system with low inertia. RES may be employed using a few tools or techniques to maintain the network's stability. A few methods that should be used in conjunction with RES to increase the strength of the power network in Figure 1 include quick power reserve, inertia simulation, droop control, concurrent condensers, needed action, and the adjustment of current protection relays [6]. Droop control involves intuitively modifying the voltage's frequency and amplitude to regulate the voltage source inverter (VSI) output. Power system frequency greatly influences its real power. The voltage difference determines reactive power. Therefore, both frequency and voltage differential may regulate active in MW and reactive in millivolt-ampere reactive (MVAR) power, respectively. Due to its advantages over the standard central power grid, the microgrid is an essential development at moderate and reduced voltage levels [7]–[9]. The droop control approach replicates the droop features of traditional electrical units in the microgrid by varying the outputs of act MW and MVAR power to control both the frequency and voltage. Switching ensures the load keeps running normally [10], [11].

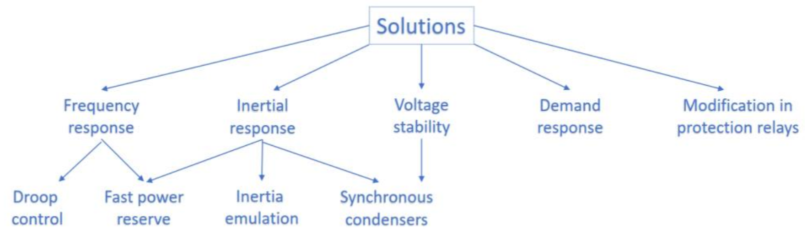



Figure 1. The suggested methods for incorporating RES into the power system stability [6]

Increasing inertia in microgrids through energy storage system (ESS), such as battery energy storage, supercapacitors, and freewheel with RES is a practical and effective option. It can be considered a fast power reserve solution [12]. Electric energy storage is beneficial for improving the performance of renewable energy facilities [13]. The surplus power generated at light load conditions during the nighttime can also be preserved and utilized throughout the daytime. ESS could offer services that include frequency management, reactive power control, voltage control, and operational reserves. Over the past ten years, there have been significant technological and economic advancements in storage facilities. As a result, storage systems are more affordable and dependable [14]. The traditional swing equation-based technique of inertia estimate is frequently employed to calculate the constant of equivalent inertia from measuring the frequency response for a particular power variation.

Implementing virtual inertia in inertia emulation, commonly called synthetic inertia, is one way to achieve a stable grid of inverters entirely. Designing a controller linked to the grid side via a feedback mechanism aims to replicate the imbalanced power response of a simultaneous machine, including its inertia and damping properties. This design enables primary frequency reserves (PFR) and allows the system to generate more power on its own a few seconds after disruptions occur to keep the system within a frequency deviation [15].

Equipment called synchronous condensers, sometimes known as synchronous compensators, are already present in modern networks. Except for the fact that their shaft is rotating freely, they behave exactly like synchronous machines. As a result, they are primarily used to help regulate voltage in electric transmission power networks by generating or consuming reactive energies as required [16]. Therefore, they are unable to generate any meaningful power independently. As a result, their knowledge of inertia and voltage control may be used to maintain a stable power system and compensate for the inertia lost when synchronous generators (SG) are replaced by RES, respectively. Synchronous condensers, like synchronous machines, have inertia varying from 1 to 6.5 s. Demand-side solutions are also put out as a way to address system imbalances and participate in frequency regulation. It is the ability to regulate demand-side workloads so that they continually switch off and on or modify how much energy they use in response to the network operators' application of power performance, voltage, frequency, technology, security of power, and economic limitations. Although comparable to load shedding, used in emergencies and irregular power system operations, this approach cannot be identical. Loads that respond to frequency and have an automated control, such as induction motors, can help with frequency regulation in demand response.

Furthermore, frequency-sensitive relays that serve as load disconnectors when frequency thresholds are exceeded can be added to the grid [17]. High-frequency fluctuation will come from the decreased system inertia, as was already indicated, which might also cause relays that protect the system's components from tripping. The protective devices should be adjusted while working toward a low inertia network if the RoCoF is still more significant than it is right now. RoCoF relays are commonly configured at from 0.1 and 1 Hertz/s for fifty-hertz systems today, depending on the network's inertia [18]. In this paper, the implementation of a microgrid using MATLAB/Simulink that consists of a PV generation system with variable irradiation, boost converter, and ESS (battery and supercapacitor) with the bidirectional converter is present. It is suggested that a three-phase changeable AC load be connected to the inverter's output; the inverter control is droop control, which significantly improves the frequency response as possible. This work will apply many scenarios regarding the RoCoF and frequency response, with/without ESS, with different penetration levels of PV, and with/without droop control strategies. The following is how this paper is organized: the problem is described in this part, while the introduction section contains the aims and methods of the suggested system. Section 2 will define the frequency response control steps. Section 3 includes the inertia emulation and the virtual synchronous generator (VSG) in RES. The inverter wills' droop control approach is demonstrated in section 4. The specific example will discuss in section 5 and suggest MATLAB/Simulink microgrid implementation along with the findings. Section 6 will provide the conclusion.

## 2. STAGES OF FREQUENCY RESPONSE CONTROL

The standard SG based on conventional power systems has three frequency regulation or control phases. The IR of such devices is represented by the first stage. The second stage includes the primary and secondary controls for SG. In comparison, the third stage, tertiary frequency control, is manual. Figure 1 depicts these control stages according to the ENTSO-E platform [13]. The machine's IR, which stands for the synchronous machinery's natural energy release (inherent inertia), is connected to the first level. The frequency is then stabilized to a stable level in just an allowable deviation of its desired voltage by the PFR. Figure 2 shows how the size and timing of the installation of these two systems affect the lowest frequency position. For the stability of grid frequency, this is crucial. Lastly, the tertiary frequency reserve (TFR), which will replace the PFR, is planned for the previous generation units [19], [20].

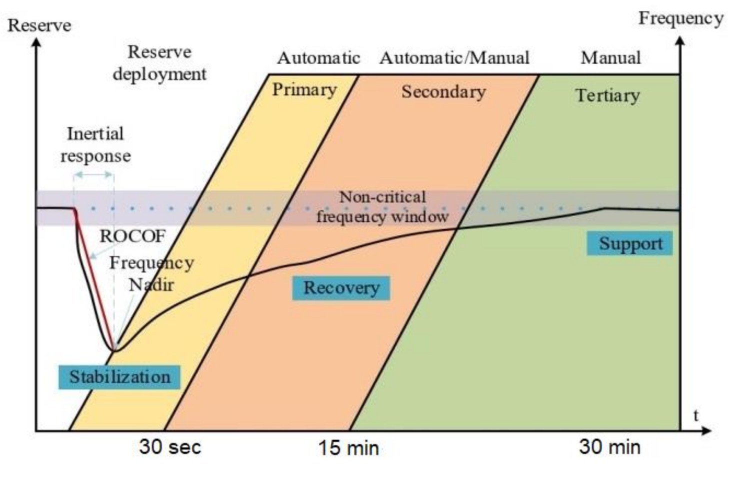



Figure 2. Levels of frequency response according to the ENTSO-E platform [13]

### 2.1. System inertia

Traditional generators can store kinetic energy in their rotating parts [17]. After a disturbance, the stored energy is quickly let out or consumed, which enhances the system's initial frequency performance. When there is a generation-demand mismatch, there will be an imbalance in the torques acting on the generators' rotors, resulting in acceleration or slowing [21], [22]. By dividing the generator's VA rating by the inertia constant (H), the kinetic energy stored in the device is frequently represented. It can be defined as the time, in seconds, required for a machine to regain its kinetic energy while operating at the output power and speed specified in its specifications. The swing equation, given in (1), describes how the power dynamic, inertia constant, and RoCoF are related.

$$\frac{2H}{w_0}\frac{dw}{dt} = P_m - P_e - K_d\,\Delta w \quad (1)$$

The damper factor $K_d$ is typically ignored for investigations of short periods, such as the period following disturbances. Consequently, we have the simple form of (1).

$$\frac{2H}{w_0}\frac{dw}{dt} = P_m - P_e = \Delta P \quad (2)$$

$P_m$ stands for the mechanical power and $P_e$ stands for the machines' electrical power, expressed in p. u., where $w_0$ and wm stand for the rated and automatic speeds in rad/sec. The kinetic energy held over the designated machine rating in VA equals the inertia constant (H), expressed in a sec.

### 2.2. Primary and secondary control systems

Conventional generating units have two autonomous management systems: the initial and second frequency control. Each unit has an immediate control system. However, a few do not have a secondary control system. The governor's direct response to any variations in system frequency is called the primary control, represented by the governor's reaction. The governor lowers the frequency deviation and provides stability shortly after diversity, often within 30 s. So long as the second control mechanism is not operating, the frequency remains within reasonable boundaries. Only in the region of the disturbance is a secondary frequency control system that uses a proportional integral controller. The intention is to reset the system to its nominal frequency [23]–[25]. It begins following the deviation for around 30 s and lasts a few minutes.

### 2.3. Tertiary frequency control

As mentioned before, the governor's fast reaction to system frequency alterations acts as central control. The governor lowers the frequency deviation and guarantees stability shortly after the variation, typically within 30 s. It only uses a secondary frequency control mechanism in the disturbance zone. During the tertiary frequency control phase, the produced units' delivered power is manually altered within dozens of seconds and several hours after a disruption. Restoring the primary and secondary resources is the goal of the meticulously monitored process [18], [24].

## 3. VIRTUAL INERTIA EMULATION

Virtual inertia is the inertial support provided by non-synchronous generating units, load demands, or energy storage technologies that simulate a typical power plant's inertial reaction when combined with the proper control strategy and power electronic interface. Several control topologies have been described in the literature. The more well-known ones include the synchronizer design, VSG, swing-equation-based structure, and droop control approach [2]. The purpose of virtual inertia emulation serves to replicate the impact of conventional synchronous machines' rotating inertia on the electrical grid. Various ways have been developed to mimic rotational inertia from non-synchronous sources.

### 3.1. Inertia emulation from photovoltaic system

PV systems lack rotating parts and so cannot generate inertia immediately. The DC-link capacitor has a modest energy storage capacity, which will employ at the power electronic connection of the grid. PV systems, on the other hand, can provide inertia by lowering the load. With this strategy, the PV system operates at a suboptimal level to preserve the power reserve required to give an inertial reaction. The DC-DC converter's control loop is engaged if the system's frequency changes, causing the PV unit to inject or absorb more power. Technically, it is not an especially attractive solution due to the inefficient use of generating units. A considerable quantity of electricity is wasted since the system must always run below its maximum capacity to maintain the availability of adequate energy reserves during fault occurrences. Additional power electronic components required to complete the control loops typically push this solution to the rear of the line due to their high price. In addition to all of these disadvantages, the method has specific benefits [26].

### 3.2. Inertia emulation from wind turbine system

Despite wind turbines having rotor inertia, they are regarded as having no inertia because of their minimal dynamic response and connection to the remains of the electrical network. Many frequency support systems have been suggested to increase the inertia support of wind turbines. Using the wind turbine's rotating kinetic energy, rotor side converter (RSC), regulation strategies are proposed to give short-term frequency support [27]. Similarly, the DC-link's stored energy is put to use by the grid side converter's (GSC's) control.

### 3.3. Inertia emulation from energy storage system

The globe is trying to use more significant amounts of renewable power to reduce its dependence on petroleum and oil. But the availability of renewable sources, like solar energy, is sporadic. As a result, ESS is crucial to a future energy system that significantly relies on RES. ESSs are used in microgrids to provide a power balance between generation and demand. Most often, ESSs have two primary uses in microgrids [28]:

- Short-term power management aims to maintain the microgrid's voltage and frequency by equating the microgrid's power consumption with its power generation. For this purpose, the ESS is charged or discharged rapidly (within seconds to minutes), making it an example of a power application involving the ESS.
- Long-term power management aims to match the microgrid's load profile with the generation profile of intermittent energy sources as an example of an ESS application requiring prolonged charging or discharging of the ESS to achieve the desired effect.

The following benefits apply to the power grid with virtual inertia [29]: i) a decrease in the frequency's nadir and its divergence from its nominal frequency (fn), ii) faster transient or response times and less overshoot, iii) a less steep gradient and RoCoF, and iv) a shorter time is needed to return to the standard frequency.

## 4. DROOP CONTROL

A VSG is an inverter that mimics the control of the SG. The inverter control must integrate SG features and modify the output of different parameters similarly to an SG to provide excellent output characteristics. In typical functioning, the excitation controller and prime mover governor control and regulate the frequency and voltage output of an SG. The generator control system could handle the generator's output frequency and mechanical power output, while the excitation regulation system manages the generator's reactive power and output voltage [30]. The main difference between the VSG and SG is that the excitation controllers and mechanical or electro-hydraulic governors are unnecessary. The voltage and power frequency adjustment units are added to the VSG, and the excitation controller and generator governor are used to modifying the inverter's output characteristics.

The power-frequency (P-f) controller is based on the design of the generator governor. The output frequency of an SG is managed by a supervisor based on the P-f characteristics of the conventional unit. The frequency and rotational speed of the generator are interrelated. The management can adjust the input power of the prime mover to influence SG speed [25]. If the energy used for armature induction and the mechanic input power used by the load are equal, the generator's output power and speed will remain constant. The curve for the P-f characteristic is shown in Figure 3(a). Curves are avoided in favour of straight lines to simplify the analysis. Figure 3(b) illustrates the schematic diagram of the P-f droop control.

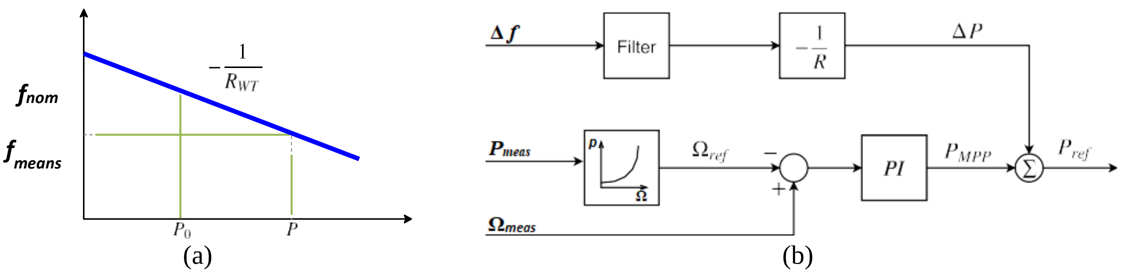



Figure 3. Droop control where; (a) refers to the P-f droop relationship curve and (b) refers to the P-f droop control schematic diagram [30]

The slope of the P-f characteristics (m) for the power and frequency can be calculated in (3) [25], [31]:

$$m = -\frac{f_2 - f_1}{P_2 - P_1} = -\frac{\Delta f}{\Delta P} \quad (3)$$

In which the terminal and starting frequencies, f1 and f2, respectively. Final and starting powers decrease when P1 and P2. According to the negative sign in (3), the control deviation is proportional to the frequency variation in the opposite direction. The adjustment coefficient is kf, and it represents the reciprocal of the slop of the frequency-power droop, hence the Kf=1/m it and also can be called a static characteristic coefficient [32]:

$$P2 - P1 = \Delta P = Kf(f2 - f1) \quad (4)$$

It's important to note that the same method is used in this research to construct a controller for preventing voltage drops due to reactive power. Still, this paper focuses on accurate P-f droop control. Figure 4 illustrates the droop control design used for this study. The electricity grid must keep the voltage within the legal limits when operating correctly. For the power system voltage to remain stable, there must be a dynamic balance between MVAR produced and MVAR absorbed in the system. The majority of the reactive power in the power system comes from SG. Reactive power in the system is balanced by the excitation regulator, which regulates its output and distributes it among the parallel-operating generator sets [32]. The disturbance value is strongly associated with the frequency nadir quantity; during minor load change conditions, the frequency nadir is slightly changed, while when the disturbance occurs due to the loss of generation units or power lines, the frequency nadir is changed significantly. In this research, a method called droop control is developed to improve the consistency of frequency. This research's primary objective is to illustrate the RoCoF in various operational situations with and without battery energy storage systems (BESS). Eliminating output power oscillations from solar PV systems is an everyday use case for BESS [33]. RoCoF will be used in this experiment since it responds faster than the BESS supercapacitor.

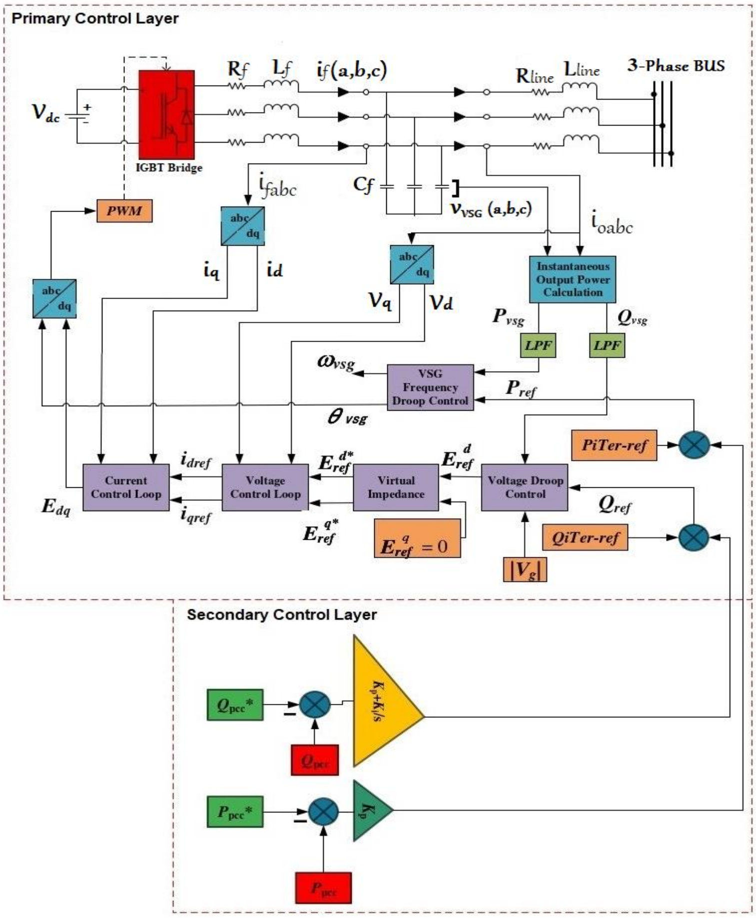
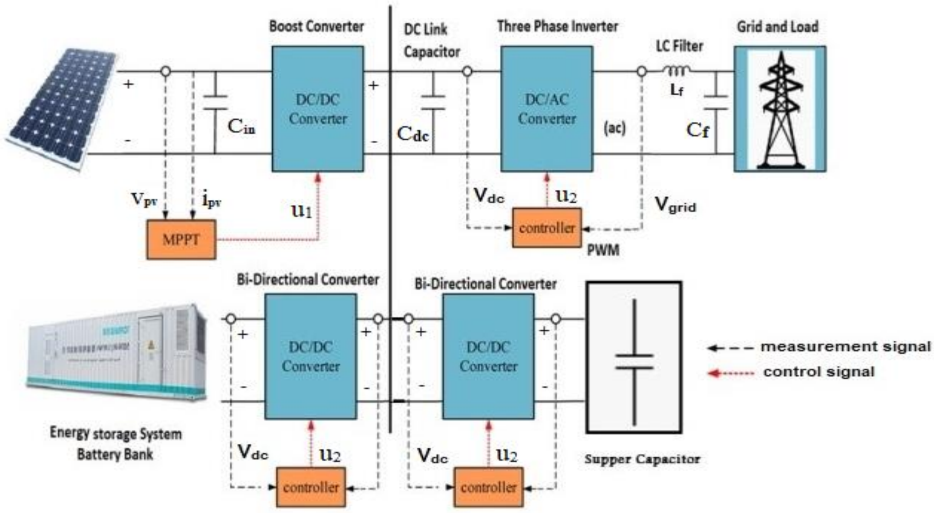


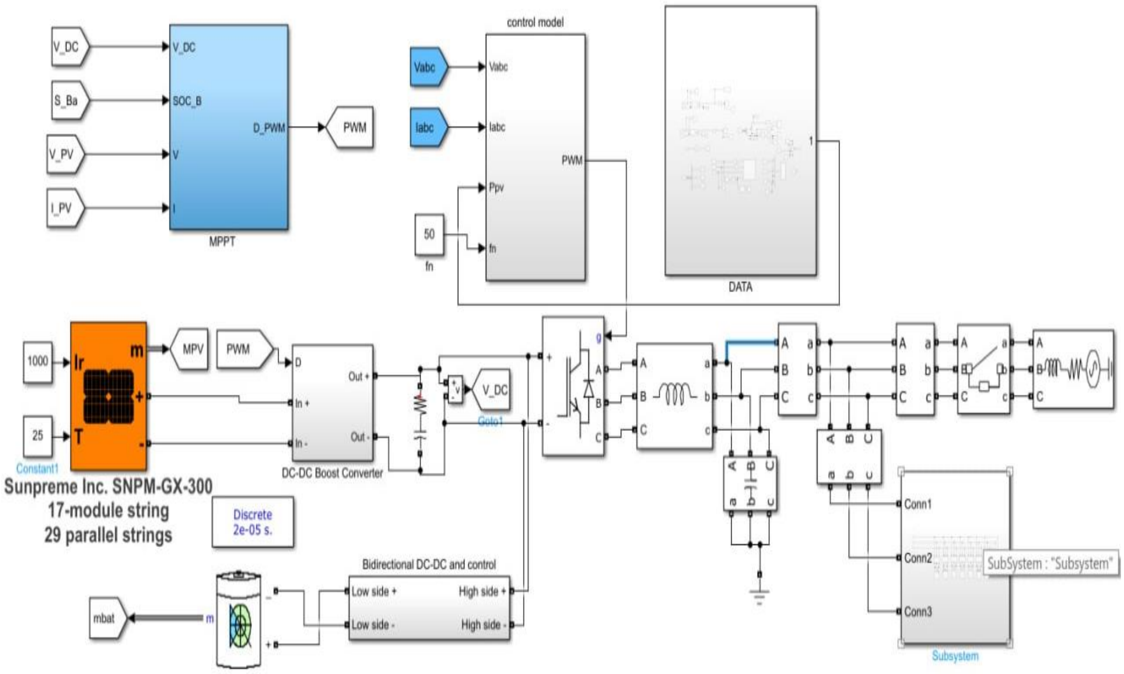

Figure 4. Primary and secondary control layer based on VSG inverter [32]

## 5. RESULTS AND DISCUSSION

Figure 5(a) explains the suggested system in this paper. This system comprises a PV system, ESS (battery and supercapacitor), a three-phase inverter, a boost converter device to increase the DC bus voltage from the PV voltage, and a bidirectional inverter used with ESS. The three-phase inverter is controlled via a droop control strategy, illustrated in Figure 4, based on VSI control. Figure 5(b) refers to our suggested system implementation by using the MATLAB/Simulink program. The load balance according to the suggested load profile and constant irradiation is shown in Figure 6 for the battery storage energy system.




(a)




(b)

Figure 5. The model of the on-grid power network where; (a) refers to the proposed system and (b) refers to its implementation using the MATLAB/Simulink program

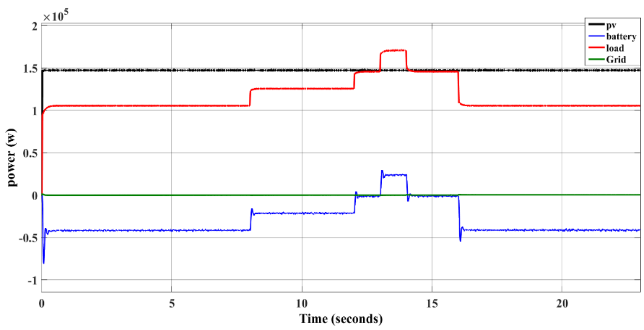
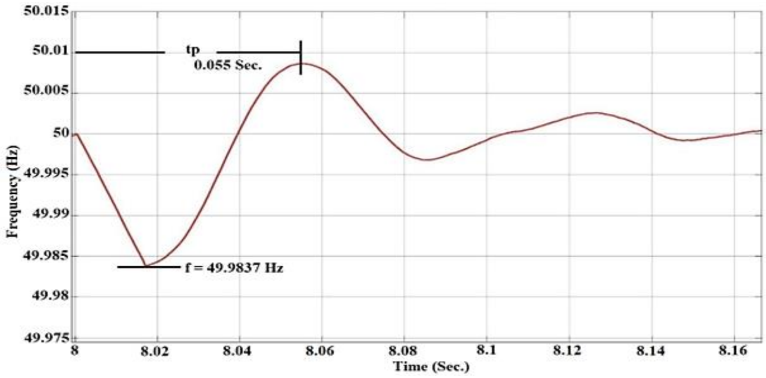


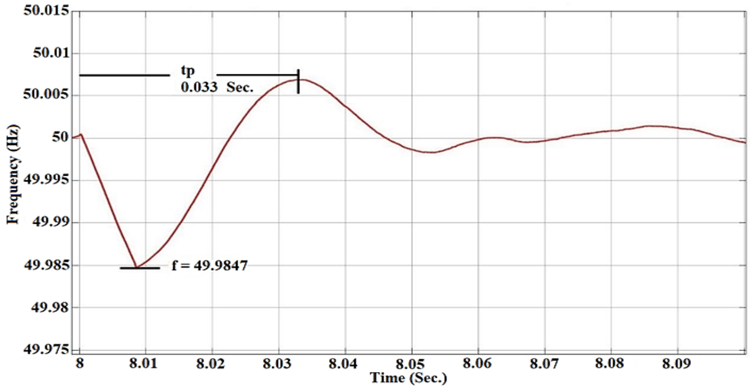

Figure 6. The suggested load profiles

### 5.1. Scenario 1

When the PV system is connected with BESS with different values of BESS (50% and 100%) of the PV-generated power, the frequency response in each case can be shown in Figures 7(a) and (b). The nadir frequency when the BESS is 50% of the PV is about 49.9837 Hz, the peak is about 50.009 Hz, and the peak time is 0.055 s, as shown in Figure 7(a). The nadir frequency when the BESS is 100% of the PV power is about 49.9847 Hz, and the peak is about 50.007 Hz, while the peak time is 0.033 s, as shown in Figure 7(b). These findings demonstrate that raising the ESS's capacity enhances its frequency response and stability.




(a)




(b)

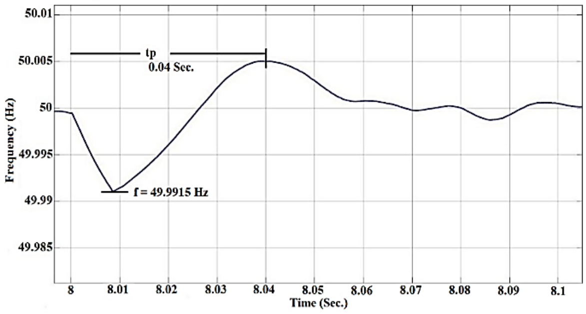
Figure 7. Frequency response with different BESS sizes; (a) refers to BESS 50% of PV-generated power and (b) refers to BESS 100% of PV-generated power

### 5.2. Scenario 2

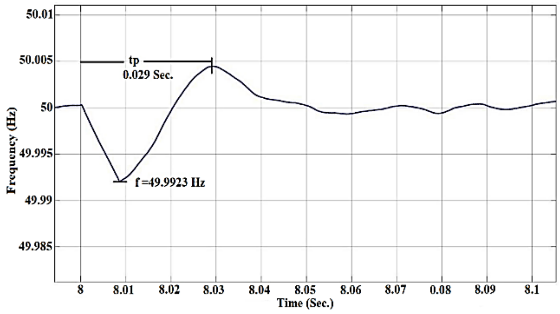
In this scenario, the PV system is connected with supercapacitor energy storage system (SCESS) with different values SCESS of (50% and 100%) of the PV-generated power; the frequency response in each case can be shown in Figures 8(a) and (b), fast time response of the supercapacitor will improve the microgrid frequency response. The peak time is 0.04 s, as seen in Figure 8(a), and the peak frequency is around 50.005 Hz when the SCESS is 50% of the PV power. The nadir frequency is approximately 49.9915 Hz. The nadir frequency when the SCESS is about 100% of the PV is about 49.9923 Hz, and the peak is about 50.0042 Hz, while the peak time is 0.029 s, as shown in Figure 8(b). The findings demonstrate that the frequency response or frequency stability is enhanced when a supercapacitor storage system is used instead of a battery storage system. In addition, the results confirmed that the size of the ESS significantly impacts the improvement of frequency stability.

### 5.3. Scenario 3

The results of this scenario will show the importance of using ESS with RES to improve the frequency stability. Figure 9(a) shows the frequency response of the proposed microgrid without ESS. Figure 9(b) shows how the frequency response becomes stable when using ESS.

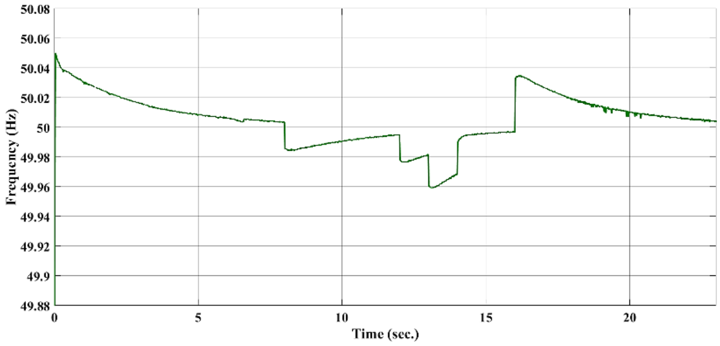



(a)

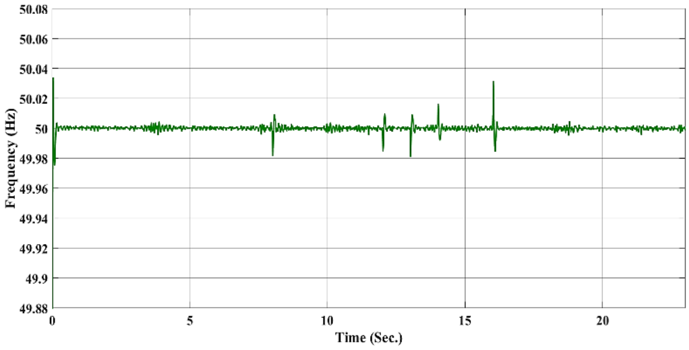



(b)

Figure 8. Frequency response with different SCESS sizes; (a) refers to SCESS 50% of PV generated power and (b) refers to SCSS 100% of PV generated power




(a)




(b)

Figure 9. The frequency response where; (a) refers to frequency response without ESS and (b) to frequency response with ESS

## 6. CONCLUSION

The power system's ability to operate consistently and dependably may be adversely affected by the increased amount of electricity generated by RES, which has very little inertia. This study addressed two solutions to the problem, based on battery and supercapacitors storage. With two values of ESS, the frequency response was examined. It is concluded that the RoCoF is reduced when the size of the ESS increases and vice versa. The SCESS can increase frequency stability more effectively than the BESS and has a slower time response.

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