

# BESS Assisted Frequency Management for Black Start Process of Microgrid

Mushfiqul Ahmed, Ferdous Irtiaz Khan, and S. M. Ishraquul Huq

**Abstract** — This paper proposes a method for restoring the nominal frequency and improving the system recovery time using battery energy storage system (BESS) for an islanded microgrid (MG) which is operated by a black start unit (BSU). The frequency stability is controlled by varying the apparent power (MVA) rating of the BESS after simultaneously connecting with the BSU during the post fault scenarios. Simulations are performed on the IEEE Std. 399-1997 test MG using DIgSILENT PowerFactory. Results show that the nominal frequency of the system can be retained by connecting the BESS during the transient period and increasing the MVA rating up to a maximum value. Simulation results also show that with a higher distributed connection of the BESS units over the system, the frequency recovery time can be reduced.

**Index Terms** — BESS; black start; frequency stability; microgrid, recovery time.

## I. INTRODUCTION

Frequency stability is a major concern in the power sector as frequency deviation can greatly hamper the system and damage the connected loads. With the continuous growth of the power industry, systems often incorporate a complex structure, and maintaining the frequency becomes a daunting task. The modern power system is often equipped with microgrid (MG) functionality besides operating in grid-connected mode. MG makes the system resilient as it can isolate itself from the grid in the event of major faults in the grid. MG operated by a black start unit (BSU) is a further reliable option where the BSU will provide the backup supply required to power up the section.

It is important that an MG in the islanded mode operation can sustain the transient period and retain its stability, otherwise the whole purpose of reliability is not attained. An MG might fall due to poor infrastructure, inaccurate design, and lack of monitoring [1]. Moreover, the integration of renewable energy sources affects the frequency stability in an MG [2]. Conventional MGs have a power electronic interface installed for optimization purposes [3]. This interface could also bring stability problems in an MG [4]-[5]. A high possibility of system failure also exists when frequency control is performed by automatic means during restoration [6]. Since a black start operation involves the remote connection of

generation units and reconnection of the system step by step, a proper frequency control mechanism is necessary.

Numerous literature and practical works are devoted to obtaining a stable frequency in the MG. The adaptive droop control method utilizes a battery energy storage system (BESS), a supercapacitor and a droop controller to maintain frequency with changes of loads [7]. The model predictive control (MPC) makes changes in input parameters through prediction and measurement to stabilize frequency [8]. A two-layer control scheme is proposed in [9] that enables power exchange between them to control frequency and voltage for a hybrid MG. Frequency stability in an MG was proposed by incorporating dump load and BESS to dissipate the supplementary power [10]. By utilizing a smart load, the frequency can be maintained for variable load and wind power [11]. An algorithm termed as Multiobjective Symbiotic Organism Search along with PI controller can also help to maintain a stable frequency [12].

It has been identified that most of the literature did not consider stabilizing frequency by controlling the transient period. Moreover, the control of frequency for an MG operated by a BSU is new and requires investigation. This paper proposes a frequency management system (FMS) to control the frequency of an MG during the transient period with the help of BESSs. A methodology is proposed that enables system planners to choose the appropriate size of BESS required to obtain nominal frequency after BSU starts operating. Further enhancement of the restoration procedure by distributing the BESS is also observed.

The paper is arranged as follows: Section II describes the effect of real and reactive power on frequency in an MG and section III provides the model of a BESS. The proposed FMS is described in section IV. Section V gives an overview of the results and finally, the conclusion is made in section VI.

## II. EFFECT OF REAL AND REACTIVE POWER IN A MICROGRID

MG generators are often linked to low or medium voltage systems at small scales, from few kilowatts to several

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megawatts, via power electronic devices. Owing to the unavailability of any governor systems to manage the voltage and frequency of MGs comprising power electronic interfaces, the method of regulating MG generators varies considerably from that of traditional power systems. Consequently, a feasible strategy is a requisite to adjust the voltage and frequency in power electronic interfaced MGs [13]. In high voltage (HV) lines, it is well established that active power (P/f) and reactive power (Q/V) control frequency and voltage, respectively. This claim is accurate since the inductive effect (X) predominates in HV lines over the resistive (R) one.

Conversely, if the MG is built in a distribution system with a high R/X value, the resistive element of the interconnected line impedance cannot be ignored [14], [5]. Fig. 1 illustrates a power electronic configured low voltage (LV) or medium (MV) MG where the apparent power is flowing from MG sources via the interconnected line and its corresponding phasor plot is shown. The source voltage,  $V_S$ , for the system can be demonstrated by:

$$V_S = V_R + I_L R \cos \theta + I_L X \sin \theta + j(I_L X \cos \theta - I_L R \sin \theta) \quad (1)$$

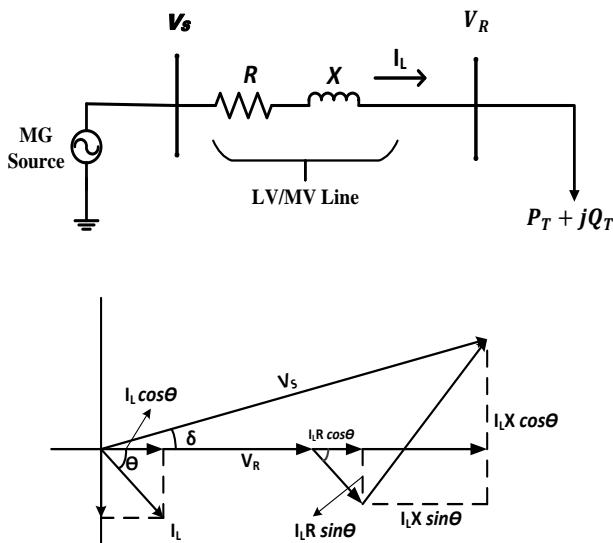


Fig. 1. Equivalent model and phasor plot of LV/MV MG.

As the in-phase component are large compared to the quadrature component, the equation can be written as:

$$V_S \approx V_R + I_L R \cos \theta + I_L X \sin \theta \quad (2)$$

$$V_S \approx V_R + \frac{P_T R}{V_R} + \frac{Q_T X}{V_R} \quad (3)$$

If the bus voltage,  $V_R$ , is approximated for 1 per-unit (p.u.), then the voltage drop is given by:

$$\Delta V = V_S - V_R \approx P_T R + Q_T X \quad (4)$$

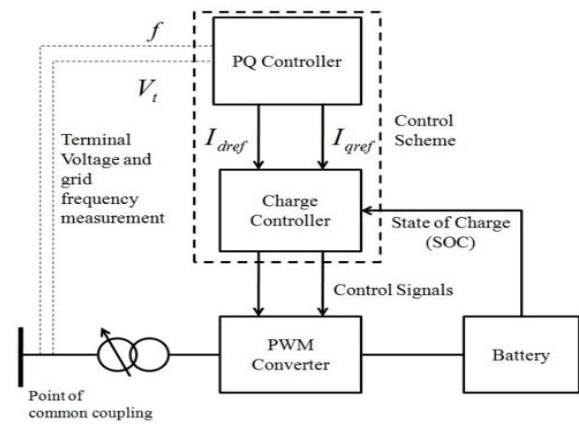


Fig. 2. Equivalent model of BESS.

Similarly, the power angle,  $\delta$ , between  $V_S$  and  $V_R$  can be derived as:

$$\delta \approx P_T R - Q_T X \quad (5)$$

where,  $P_T$  is the real power and  $Q_T$  is the reactive power of the system. Solving (4) and (5),  $P_T$  and  $Q_T$  tends to become:

$$P_T \approx \frac{\delta X + \Delta V R}{X^2 + R^2} \quad (6)$$

$$Q_T \approx \frac{\Delta V X - \delta R}{X^2 + R^2} \quad (7)$$

Thus, in LV/MV MG, both the active power and reactive power might depend on voltage and frequency and they are said to be coupled. Depending on the controlling method, type of generator, the structure of the distribution system and other factors, real and reactive power could be coupled in an LV and MV MG [16]-[18]. Thus, the overall size of generators and controllers can affect the frequency.

### III. MODELING OF BESS

Frequency regulation is critical for maintaining power generation balanced in electrical grids. There are two ways of controlling frequencies: primary frequency control (PFC) and secondary frequency control (SFC). PFC operates dynamically by means of a regulatory feedback system. It responds to frequency variations in the grid within seconds. By controlling all the generators linked to the frequency control network, SFC regulates the grid frequency near its nominal value. The response times for SFCs are higher than for PFC, usually minutes. BESS is becoming a prominent energy storage method for both PFC and SFC due to its quick ramping time, operating expenses, and comparatively cheap capital expenditure. Therefore, BESS is better suited for frequency control than most other types of the energy storage system (ESS). The equivalent model of BESS with associated control scheme is shown in Fig. 2.

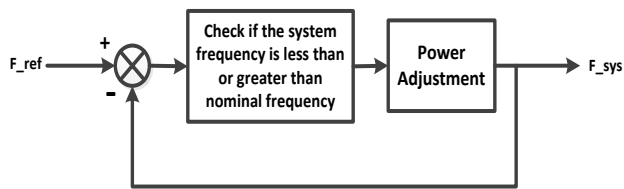


Fig. 3. Frequency management process.

The storage portion of the battery models a static generator with additional variables allowing it to imitate a BESS. The framework incorporates a DC-AC/AC-DC converter which enables direct connection to the grid. The control strategy of BESS as shown in the PQ controller block in Fig. 2 is comprised of the BESS active power controller (P controller) and the BESS reactive power controller (Q controller). The active power signal is transmitted to the P controller circuit and the reactive power signal is forwarded to the Q controller circuit. The PQ controller block output signals are active ( $I_{dref}$ ) current reference and reactive ( $I_{qref}$ ) current references that will be sent to the current controller block fully integrated for the aim of accomplishing the desired operational requisites. For most frequency control applications, the active current ( $I_{dref}$ ) often has a higher priority than the reactive current ( $I_{qref}$ ) when implementing BESS. The output signal of the charging controller is transferred to the converter and eventually sent back to the MG to mitigate the deviations in frequency and voltage. As disturbances occur in the MG, this may lead to variations in active and reactive power and contribute to differences in frequency and voltage. Thus, such variations can be eradicated by regulating the equilibrium between supplying power and demanding power using the BESS control scheme.

#### IV. FREQUENCY MANAGEMENT SYSTEM

MG provides the advantage of self-isolation to allow itself to disconnect from the main grid in the event of a fault in the main grid. It helps to stop the fault from cascading to the MG section. Although MG is considered a reliable option, under certain circumstances it might fail to operate. To tackle such a situation, the use of an emergency supply such as BSU can help the system to mitigate the problems. Among the different challenges when using a BSU, the fluctuation of frequency is a vital one. The proposed frequency management system (FMS) can help the system planners to maintain system frequency for an MG operating under BSU. BESS is utilized as a restoring parameter of frequency. Two steps are proposed in the FMS:

- a) Restoring frequency to the nominal value.
- b) Reduction of restoration time through distribution method.

##### A. Restoring Frequency to the Nominal Value

When using a BSU in an MG operating in an isolated mode, the frequency might not reach the nominal value, or it might exceed the nominal value. In either case, a control scheme is necessary. Through the supply or consumption of power, system operators can obtain the nominal frequency value.

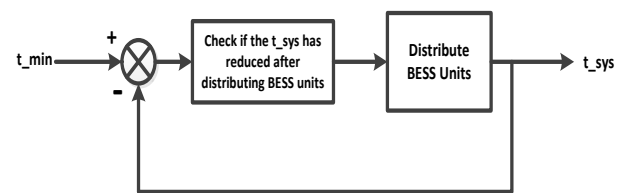


Fig. 4. Time management process.

Fig. 3 shows the block model representation of frequency adjustment. Here the term  $F_{ref}$  denotes the nominal frequency of the system and the term  $F_{sys}$  denotes the actual frequency of the system. After the connection of BSU to the MG, the system operator could find the frequency to reside at a value less than the nominal frequency or greater than it. If the frequency settles at a value less than nominal frequency, then the BESS equipped with PWM will need to supply power. If the system frequency exceeds the nominal frequency, then the BESS will need to consume excess power. So, after the connection of BESS to the MG at certain intervals, it is checked whether the system reaches the nominal value with BESS of that rating. BESS rating is increased or decreased so on until the system frequency and nominal frequency are at marginal values. The BESS is disconnected from the system after frequency stability is attained. This way system planners can identify the size of the BESS unit required for a particular MG to retain its frequency when operated by BSU.

##### B. Reduction of Restoration Time through Distribution Method

For any system operators, it is desired that the nominal frequency is reached as quickly as possible. In other words, the transient period should be minimum. This can be achieved through a technique that is proposed using the distribution method.

It is necessary to minimize the transient period so that system becomes stable quicker and also the BESS can be disconnected from the system at a faster pace. Fig. 4 shows the block model representation of time management. When the BSU is connected to the MG the frequency shoots up for a moment and with the help of the frequency management process, the nominal value could be reached ultimately. Transient period can be reduced by distributing multiple BESS units across the system while keeping the overall power of BESS units same. It is true that at one-point saturation level will be reached and further increment of BESS units will have no impact on transient period reduction.

In Fig. 4, the  $t_{min}$  is the minimum possible time of transient period that can be obtained, or it can also be the desired time of the system operator and  $t_{sys}$  is the actual transient period of system after BESS is used. So, by keeping the overall size of BESS same, multiple units of BESSs are used and distributed in the system until the minimum time or the desired time is reached.

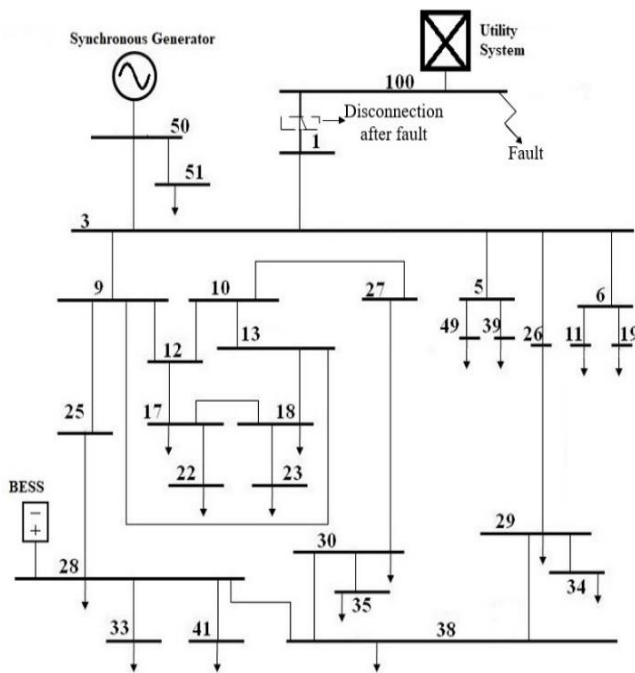


Fig. 5. Considered portion of IEEE Std. 399-1997 test system.

## V. RESULTS AND ANALYSIS

### A. Test System and Simulation Platform

The proposed FMS is tested in IEEE Std. 399-1997 test MG using DiGSILENT PowerFactory 15.1.7. The section of the test system that is considered for simulation is shown in Fig. 5. It consists of 30 buses, 22 induction motors and 3 normal loads. The synchronous generator (SG) connected to bus 50 is the BSU of the MG. The MG is connected to the main grid via bus 1. When a fault takes place at the main grid (i.e., bus 100), bus 1 is disconnected and the MG goes to islanded mode. The BSU is then activated to power up the islanded MG. To improve the frequency stability, BESS is initially connected at bus 28 and its apparent power is varied to see the impact it has on frequency. To test the time management process, BESSs are distributed across the system and the results are analyzed.

### B. BSU Performance without BESS

After the occurrence of a short circuit fault at 5 s at bus 100, the line connecting bus 1 to 100 is disconnected at 5.2 s. Fig. 6 represents the voltage in p.u. and frequency in Hz of bus 50. As observed from the Fig. 6, voltage and frequency of bus 50 drops as MG go to islanded mode. The system is then recovered by connecting SG acting as BSU at around 120s. From Fig. 6, it is clearly visible that although the BSU was able to recover the voltage (0.91 PU) close to the nominal value, the frequency took approximately 190 s to get settled at 52.98 Hz.

### C. BSU Performance with Centralized Located BESS

This time for a similar scenario, along with SG as BSU, BESSs equipped with PWM are connected at bus 28 and the impact on frequency is checked. Fig. 7-9 show the frequency plot of bus 50 as BESSs with size 8.8 MVA, 10.6 MVA and 12.5 MVA are used respectively. Every time the BESSs are

connected for a duration to improve the frequency and then disconnected. In all the simulations, the BESSs are connected at 120 s along with the BSU but their disconnection time is varied.

At first, two BESSs, each of size 4.4 MVA, are connected on bus 28. From Fig. 7 it can be observed that after the disconnection of the BESSs at 800s, the frequency finally settles at 56.02 Hz. Although the frequency improved, it did not reach the nominal value. To improve the frequency further, the simulation is repeated by changing the size of each BESS to 5.3 MVA, making a total capacity of 10.6 MVA. It can be observed from Fig. 8 that after the disconnection of BESSs at 800s the frequency settles at 57.50 Hz. The simulation is repeated for a total BESS capacity of 12.5 MVA. Fig. 9 shows that the frequency finally reached and settled at the nominal value of 60 Hz, after the disconnection at 800 s.

The previous simulation is repeated keeping all parameters fixed except the disconnection time of BESSs, which is made at 700 s instead of 800 s. Fig. 10 shows the plot for the corresponding scenario. It can be observed that the frequency becomes unstable. The reason behind such anomalies is that the BESSs are disconnected during the transient period of the frequency i.e., before the frequency value settles down.

The overall analysis of the results gives a clear picture that since the frequency value without BESSs was lower than the nominal value, a supply of extra power from BESS was necessary. As the size of BESS was gradually increased the frequency finally reached its nominal value. The duration of supply by BESS is also an important aspect. If it is disconnected within the transient region then frequency might never reach the nominal value.

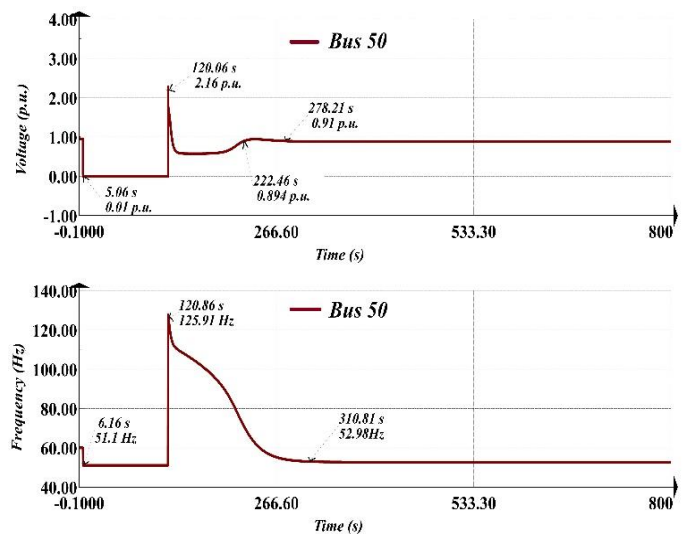


Fig. 6. Voltage and frequency plot of Bus 50 without BESSs.



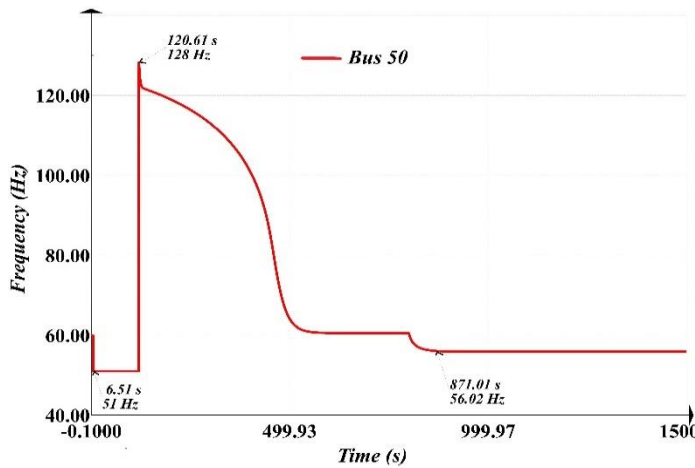


Fig. 7. Frequency plot of bus 50 with BESSs of 8.8 MVA.

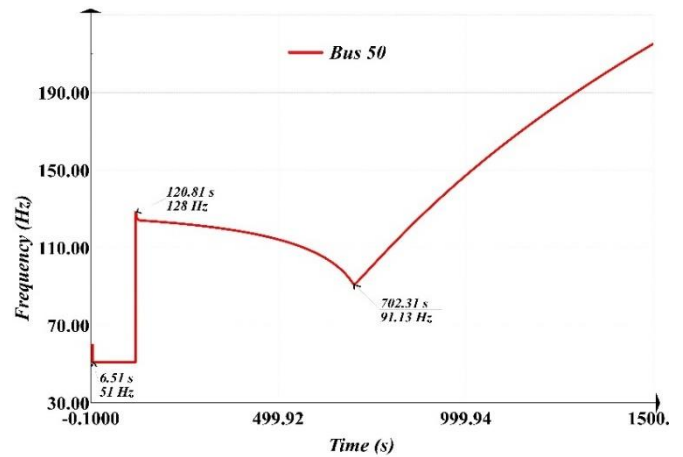


Fig. 10. Frequency plot of bus 50 with BESSs of 12.5 MVA disconnected at 700s.

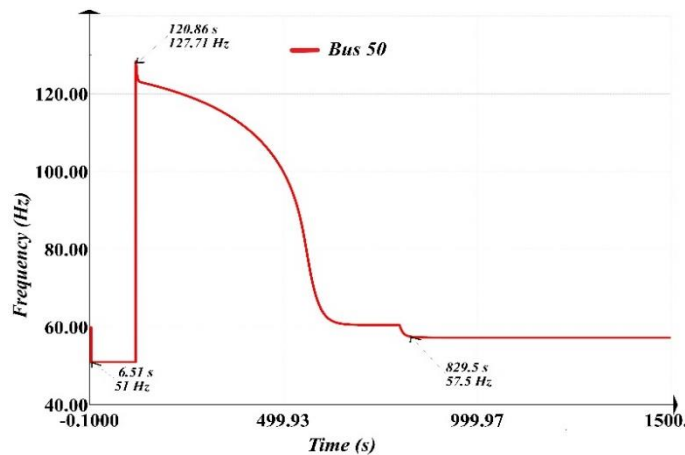


Fig. 8. Frequency plot of bus 50 with BESSs of 10.6 MVA.

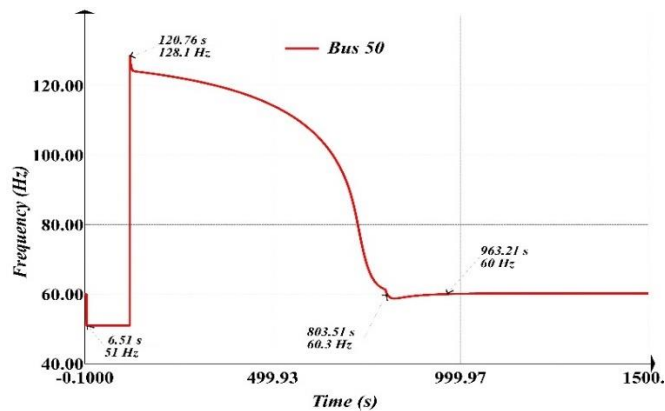


Fig. 9. Frequency plot of bus 50 with BESSs of 12.5 MVA.

#### D. BSU Performance by Distribution of BESS

After frequency has been restored to nominal values with the help of BESSs, system planners have an idea of the size of the BESSs required. In order to reduce the time of recovery of frequency, BESS units are distributed to other buses. In Fig. 9 it is seen that with the use of centralized BESSs, it required around 684 s (804 s-120 s) for the frequency to return to its nominal value. To test the proposed time management process, the BESS units are distributed keeping the total size of the BESS same. The previous simulation is repeated in distribution mode. One BESS with a size of 6.25 MVA is connected to bus 50 (highest voltage bus) and another of the same size connected to bus 28 (lowest voltage bus). Fig. 11 is the frequency plot of bus 50 showing the impact of distributed BESS on it. It can be seen that the transient period has dropped and disconnecting the BESSs at 686 s still enables the system to remain healthy. Hence, the recovery time reduced to 566 s (686 s-120 s). Table I shows the effect of distributing the BESSs across the network while maintaining the same total size on recovery time. It can be seen that as BESSs are distributed, the recovery time drops.

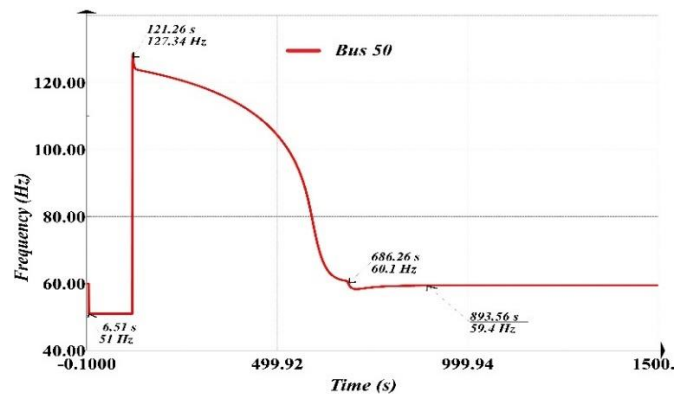


Fig. 11. Frequency plot of bus 50 with distributed BESSs of 12.5 MVA.

TABLE I: IMPACT OF DISTRIBUTED BESS ON RECOVERY TIME

BESSs at bus no.	Recovery time(s)
28	684
50 & 28	566
50, 49 & 28	506
50, 49, 29 & 28	484

## VI. CONCLUSIONS

In this paper, a new frequency control method is proposed which uses BESSs to restore the nominal frequency and reduce the system recovery time of an islanded MG with BSU. Simulation results show that the system without BESS does not retain the nominal frequency. After the BESS is simultaneously connected with the BSU during the transient period, the nominal frequency of 60 Hz is achieved for a BESS rating of 12.5 MVA. A further increase in the rating, however, causes the frequency to collapse. Meanwhile, if the BESS is disconnected before the end of the transient period, the system becomes unstable. Moreover, the distributed connection of the BESS units provides a further advantage by improving the recovery time of the frequency. Distribution of the 12.5 MVA BESS units across 4 buses provided a total recovery time improvement of 200 s. Thus, upon analysis of the results, a proper FMS can be established by the system planners. Through simulation and practical experience, system planners can determine beforehand the size of BESS(s) required to retain nominal frequency when the MG is under the operation of a BSU. If required, they can also minimize the restoration time through the distribution method.

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