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Impact of Spinning Reserve on Frequency Control in a Hybrid Power Plant Including Renewable Energy

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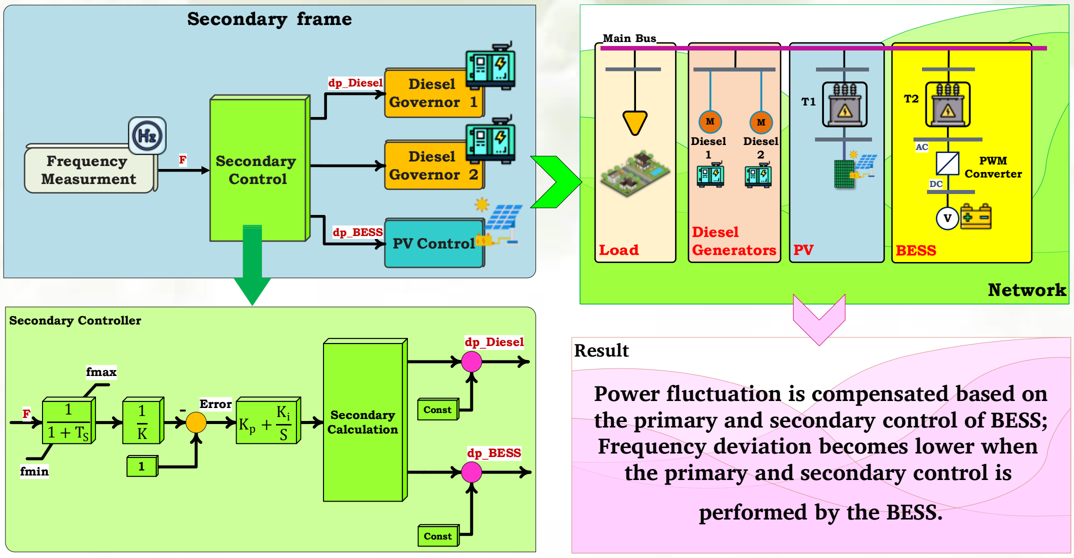
Highlight

- **Designing a secondary control for several diesel generators and BESS to participate in frequency control.**
- **Considering the effect of a BESS as a spinning reserve to control a microgrid's frequency**
- **Proposing the secondary control to deal with frequency deviation and accelerate the operation of spinning reserve.**

Graphical Abstract



Power fluctuation is compensated based on the primary and secondary control of BESS; Frequency deviation becomes lower when the primary and secondary control is performed by the BESS.

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Impact of Spinning Reserve on Frequency Control in a Hybrid Power Plant Including Renewable Energy

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ABSTRACT

In this paper, the effect of a battery energy storage system (BESS) as a spinning reserve is considered to control the frequency of a microgrid consisting of a diesel generator, photovoltaic, BESS, and electrical loads. In this stand-alone microgrid, the output power of diesel generators and the BESS are subject to variations to compensate for power fluctuations caused by the load and output power of photovoltaic. Therefore, secondary control, in addition to the primary control, has been proposed to deal with frequency deviation and accelerate the operation of spinning reserve. The scheme is simulated in a hybrid power plant, where results show the effectiveness of the secondary control on frequency deviation damping of the microgrid, thus improving dynamic stability.

1. Introduction

In the past, frequency has not been a major problem for most power systems due to low electricity demand in comparison to power resources. Recently, for economic and environmental reasons, power systems have operated at their maximum capacity and near their boundaries, which may affect frequency stability. Therefore, in addition to providing a reliable power supply, the technologies of new power generation controllers should be more efficient and upgraded to control the basic parameters of the network, such as frequency [1-3]. Due to the need to supply remote areas, smaller stand-alone power grids have no access to interconnected networks to deliver electricity and feed the load. Connecting these areas to the main grid is a time-consuming and costly project, or in some cases physically impossible, where sensitive protection devices need to be devised to prevent devastating faults [4]. These grids usually supply their energy through a distributed generation system, called a microgrid. Electricity in microgrids is traditionally generated using diesel fuel. The high cost of such generation of electrical energy and its environmental problem have encouraged the utilization of renewable energy resources [5-7]. These resources have many advantages for power systems, but their output power is uncertain and probabilistic. Therefore, the widespread integration of power systems faces some challenges. On the other hand, spinning reserve (SR) is one of the most important ancillary services to maintain system reliability during hazardous events. In microgrids, due to the presence of renewable sources with uncertain output, the frequency of the system experiences more oscillation than usual; so, they should be controlled so that network frequency and stability are kept within acceptable boundaries. A developing network is divided into primary, secondary, and tertiary control hierarchy, which focuses on power delivery and frequency control by balancing generation and load. Increased penetration of renewable energy to 50% of the total energy requires new solutions to maintain the stability of such a system [8].

Power systems integrated with intermittent renewable power generation require more advanced control, as well as an SR to maintain the stability of basic parameters such as voltage and frequency. This SR can be supplied by generation on the demand side [9]. Another solution is to use optimal control for power resources in microgrids. This method is becoming more important today due to the lack of SR [10]. Hybrid power plants are an optimal approach for remote networks [11]. Increasing the penetration of renewable energy such as photovoltaic is leading to more fluctuations in the grid frequency. Storage systems with a combined heat pump can participate in frequency treatment [12]. Other cases of energy storage technologies e.g. batteries [13], and flywheels [14], can also help frequency control in a microgrid. However, these technologies are complex and costly, and their effects on operating and maintenance costs have not yet been entirely evaluated [15]. In the case of events such as load failure or generation shortage, system stability will be affected and may lead to a critical situation. As a result, energy storage devices help the enhancement of the stability of microgrids. Among the main energy storage devices are battery energy storage systems (BESS), flywheels, and capacitive units [16-18]. The benefits of installing renewable energy resources are reduced if the SR is fully allocated to them. One solution is adopting inverters for storage systems and applying proper control. Therefore, a combination of renewables and storage systems performs the roles of primary and secondary frequency control and shares the total SR [19]. A frequency control method using the fuzzy PI controller is proposed in [20] to ensure active power balance and frequency fluctuations damping in a microgrid power system. The integration of BESS with such a system compensates for the fluctuations of renewable energy output to have an acceptable frequency response. Reference [21] provides a multitasking program for a large-scale BESS that stores excess PV energy and provides a secondary control strategy. In [22], during high fluctuation power, the BESS adjusts the output of PV to ensure that the net power injected from the PV/BESS system into the grid is smooth. For this purpose, an improved dynamic BESS model with charge controller feedback is proposed. Additional BESS capacity may be available to improve the efficiency of the energy storage system. This means that the frequency correction reserves by this approach are more economical [23]. The frequency control service is given significant importance, and a concise overview of the interconnections between energy storage, energy production, and energy consumption components may be found in reference [24]. Furthermore, a comprehensive evaluation of BESS grid applications in the last decade is employed to gauge advancements in technological and economic research, as well as the health condition and charge level. This work introduces a novel approach to examining the duty cycle of BESS applications. It enhances the understanding of BESS operations and facilitates their integration with technical and economic operations [24]. This is achieved by performing a comprehensive evaluation of the grid application and integrating the BESS. The review study [25] encompasses comprehensive and impactful research that specifically examines the current advancements in hybrid PV-BESS systems. This report additionally encompasses a meticulous evaluation of the research projects that were carried out with hybrid PV-BESS systems. The review examines the merits and limitations of these investigations, together with the limitations they may encounter, and the possibility for further enhancement. The study [26] investigates, evaluates, and classifies the uses of BESSs based on the time constants associated with each application. The literature [27] aims to investigate the power quality problems arising from wind turbines in the electrical system, and how BESS can mitigate or minimize these disruptions in the network. Wind power, thermal power, and hydropower all contribute to system frequency regulation. The technique described in [28] allocates reserve capacity among these three power sources. In multi-objective chance constraint programming, the optimization goals of the economics and frequency stability are considered. The research presented in [29] proposes the integration of an energy storage system (ESS) into the control loop to regulate the frequency in cases of network instability or when the average frequency between connected areas deviates from zero.

According to the literature, frequency control is one of the most important issues in power systems especially in microgrids including renewable resources. Considering the advantages and disadvantages of frequency control methods, this paper proposes a hybrid control system including BESS and secondary control for SR in a microgrid.

Due to frequency deviation, the secondary control decides how much the diesel generator and BESS output will change. The effect of secondary control on the diesel generator due to mechanical parts increases response time, fuel consumption, and cost, but there is no problem with reducing inertia. On the other hand, the effect of secondary control on the battery is very effective in improving the frequency but low inertia may cause some problems. Thus, the proposed method considers these two resources for SR with the following features:

- The secondary control for several diesel generators and BESS is designed to participate in frequency control.
- In this paper, the BESS acts as a spinning reserve, in which:
  A. Daily load profile is more realistic and peak load day is considered (summer day load profile).
  B. Diesel generators have less fluctuation and do not have a high peak at outage time.

C. The frequency fluctuations are decreased as a result of applying the proposed control system.

2. Modeling and formulation

2.1. Primary control and governor

The governor is the primary control of a generator that controls the active power output of a generator. After a load change, the governor immediately changes the diesel torque and its generation to supply the load. It causes an imbalance between mechanical torque and electrical torque in the generator shaft. So, the rotor velocity and the frequency are changed. On the other hand, the primary controller of BESS is integrated with its controller to regulate the output power and the frequency. The primary controller regulates the frequency around the nominal value after a short time by changing the load which has been shown in Figure 1. The frequency deviation is proportionate to the amount of load increase/decrease and the control parameters of primary control which was configured in the governor of diesel generators or BESS frequency controller.

As indicated in Figure 2, the modified output power of a diesel generator or BESS can be computed due to Equation (1):

$$P_i' = P_i + \Delta P_i \tag{1}$$

P_i': is the modified active power of the power source *i*.

P_i: is the initial active power value of power source *i*.

ΔP_i: is the active power change in the power source according to primary control.

ΔP_i: is determined by the total frequency deviation and the corresponding primary control gain K_{pf_i} (i.e. the inverse of the droop value)

$$\Delta P_i = \Delta f * K_{pf\_i} \tag{2}$$

K_{pf_i} : is the primary control gain of generator i: [MW/HZ];

Δf: is the total frequency deviation.

Δf can be calculated as follows:

$$\Delta f = \frac{\Delta P_{Tot}}{\sum K_{pf}} \tag{3}$$

$\sum \mathrm{K_{pf}}$: is the summation of the primary control gain of all generators and BESS;

ΔP_{Tot}: is the total active power change by the primary control.

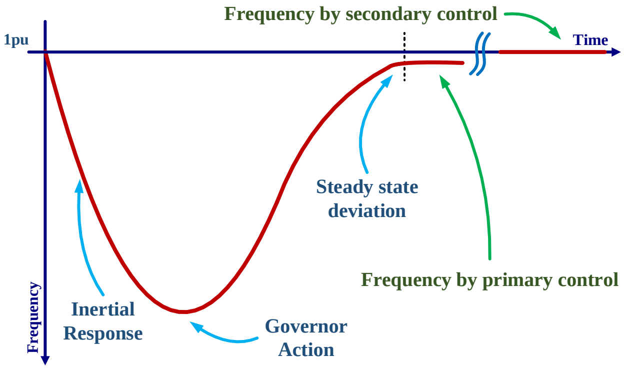


Figure 1. Frequency deviation followed by load increase [6].

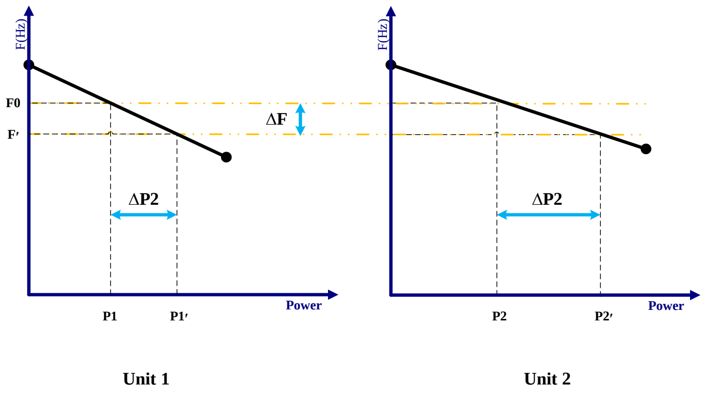


Figure 2. Dividing the power by units parallel to specific droop.

2.2. Secondary control

As a result, at the primary control, a change in the load of the grid causes the steady-state frequency deviation. Restoring the frequency value to the nominal value and eliminating the error requires supplementary control action. Secondary control adjusts power supply set points to keep the frequency at the nominal value. The secondary control operates much slower than the primary control and compensates for the frequency deviation after the operation of the primary control. The secondary control can be considered as an SR that can deliver the required active power to the grid for frequency error correction [2].

3. Case study and its components

The understudy network is an islanded microgrid that consists of two diesel generators that supply the network load, BESS, and a PV power plant. Diesel generators have similar settings and their active power generation values at nominal power are 0.85 (MW) on average. Output power for PV and BESS are 2.84 and 3 MVA respectively [2]. Table 1 tabulates the list of generation units adopted in the system, and provides their capacity. Single-line diagram of these units and configuration of the main bus, load, diesel generators, PV, and BESS are illustrated in Figure 3.

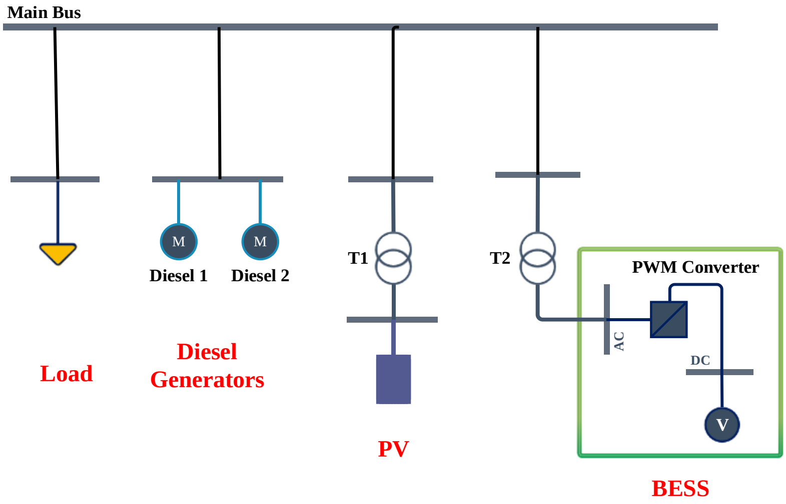


Figure 3. Single-line diagram of a hybrid power plant.

Table 1. Generation units of the system.

5- Main components	4- Capacity	3- Unit
8- Diesel generator × 2	7- 1.02	6- [MVA]
11- PV	10- 2.8	9- [MWp]
14- BESS	13- 23	12- [MWh]

3.1. Secondary controller model

The secondary controller includes five slots which are shown in Figure 4. The first left slot is the frequency measurement, which provides the frequency in the reference bus and sends the signal to the secondary controllers. The second left slot is the secondary controller which receives the measured frequency and sends the control signals to keep the frequency at the nominal value. The third slot is the controller of the BESS. And the last two slots are the diesel governor models [2].

The control signal (dp_sec) as an active power is added to the initial set point of the control models. The model of diesel governors and BESS controller need to be adjusted by adding one input of (dp_sec) to each one, and its value has been used utilizing new summation points to the original power set point of each model.

The secondary controller is the sub-system, which is attached to the secondary slot model. The input of this sub-system is the frequency, which is provided by the frequency measurement device. The output is active power change, which is sent to the governors

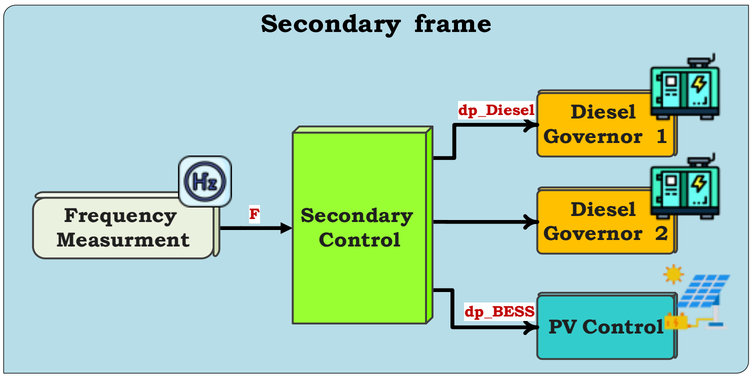


Figure 4. Composite frame model of the secondary controller.

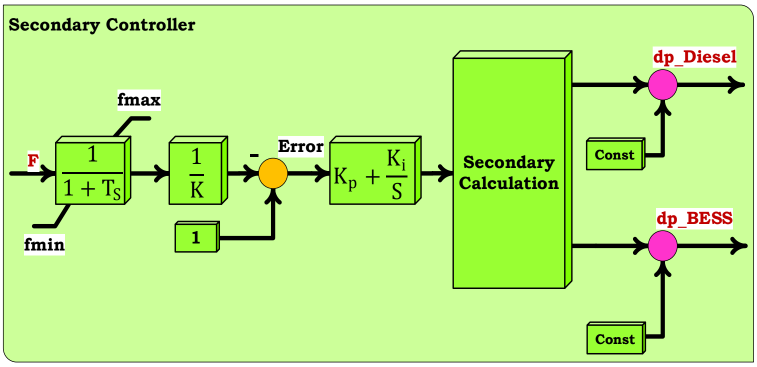


Figure 5. The secondary controller designed with seven blocks.

of the diesel generators (dp_Diesel), and the power controller of the BESS (dp_BESS). The secondary controller is designed by seven blocks (Figure 5) and described as follows:

1. Time delay: represents the reaction of the secondary control compared to the primary control.
2. Gain 1/f: returns the value of the frequency from Hz to per unit value.
3. Constant signal: the set value of the frequency which is 1 [pu].
4. Primitive controller type PT1: has been obtained from the global library of PowerFactory, which has the transfer function of 1/(K+sT).
5. Signal divider: it divides the control signal between the attached blocks to determine their contribution to the secondary control. This block has a main role in secondary control.
6. Constant signal: changes per unit to (MW) value.
7. Constant signal: changes per unit to (MW) value.

The secondary control for active power is distributed between the diesel generators and BESS according to Equation (4) [5]:

$$Kp_j = P_{disp,j} / \sum_{i=0}^{i=n} P_{disp,i} \tag{4}$$

K_{pj}: is the power-sharing factor of the secondary control for the power source (j).

$P_{(disp,\,j)}$: is the dispatch power of the power source to be applied in secondary control.

n: is the number of the attached power sources in the secondary controller.

$$P_j = P_{primary,j} + Kp_j . dP_{secondary} \tag{5}$$

P_j: is the output power of the power source.

$P_{(primary,\,j)}$: is the output power of the power source, which is defined by the primary controller.

$dP_{secondary}$: is the total power change demanded by the secondary controller.

3.2. Load and PV profile

The load profile is an estimation of the total energy required by the power system or subsystem over a given period (hours, days, and so on). In this simulation, the load profile is daily (24 hours) and depicted in Figure 6.

The output power of PV modules is a function of solar radiation. PV is simulated as a negative charge. Therefore, it is similar to the load in the system, but the parameters have negative values. The PV output power characteristics are modeled for a sunny day and shown in Figure 7.

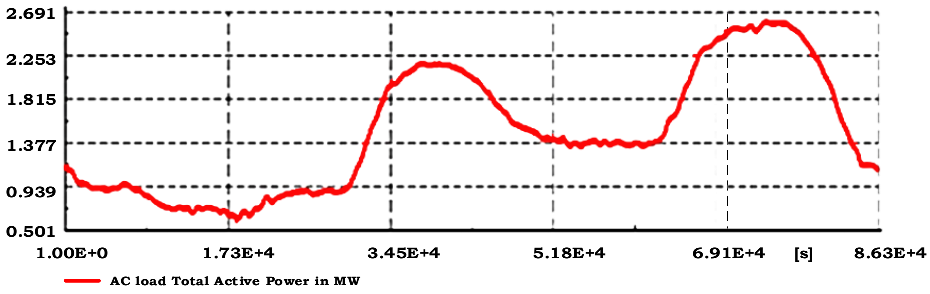


Figure 6. Load profile for the simulated day.

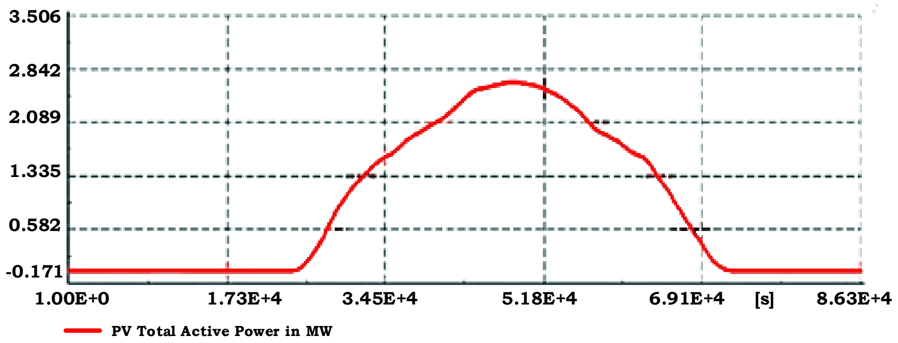


Figure 7. PV power profile for the simulated day.

4. Simulation

Primary and secondary controls in this paper are used to control active power and frequency. in the studied microgrid BESS, diesel generators, and PV are considered as energy resources. PV plant injects all accessible energy into the network by solar radiation, thus the primary and secondary control on the PV plant control section cannot be applied. In this study, the first diesel generator is disconnected from the network when the PV plant is operated at 6:30 a.m. and reconnects at 8 p.m. The total operating time is 10.5 hours. On the other hand, the second diesel generator disconnected at 7 am and reconnected to the network at 7:30 pm. The total operating time for the second is 11.5 hours. The network frequency fluctuates during the disconnection and connection of diesel as well as the connection time of the PV plant. To control the frequency, three strategies are introduced in this study:

Strategy 1: In the first strategy, primary control is applied to diesel generators and BESS.

Strategy 2: In the second strategy, primary and secondary control are applied to diesel generators and BESS.

Strategy 3: In the third strategy diesel generators and BESS perform primary control, but BESS participation is more for secondary control.

4.1. Output power of diesel generators

Figure 8 shows the output power for each diesel generator for all strategies. In the first strategy, because diesel generators do not participate in the secondary control, the amount of diesel output is constant, Figure 8(a). In the second strategy due to secondary control of the diesels, the output power fluctuations are visible in Figure 8(b). In this strategy, network reliability is decreased because of continuous changes in diesel generators output which reduces their lifetime. In the third strategy, due to more BESS participation, diesel generators experience fewer fluctuations, as shown in Figure 8(c). Therefore, the issue of repair and maintenance and its costs is varied due to the operation of diesel generators. This combination of secondary control consisting of BESS and diesel has better results in power and frequency fluctuations and it is more reliable and efficient.

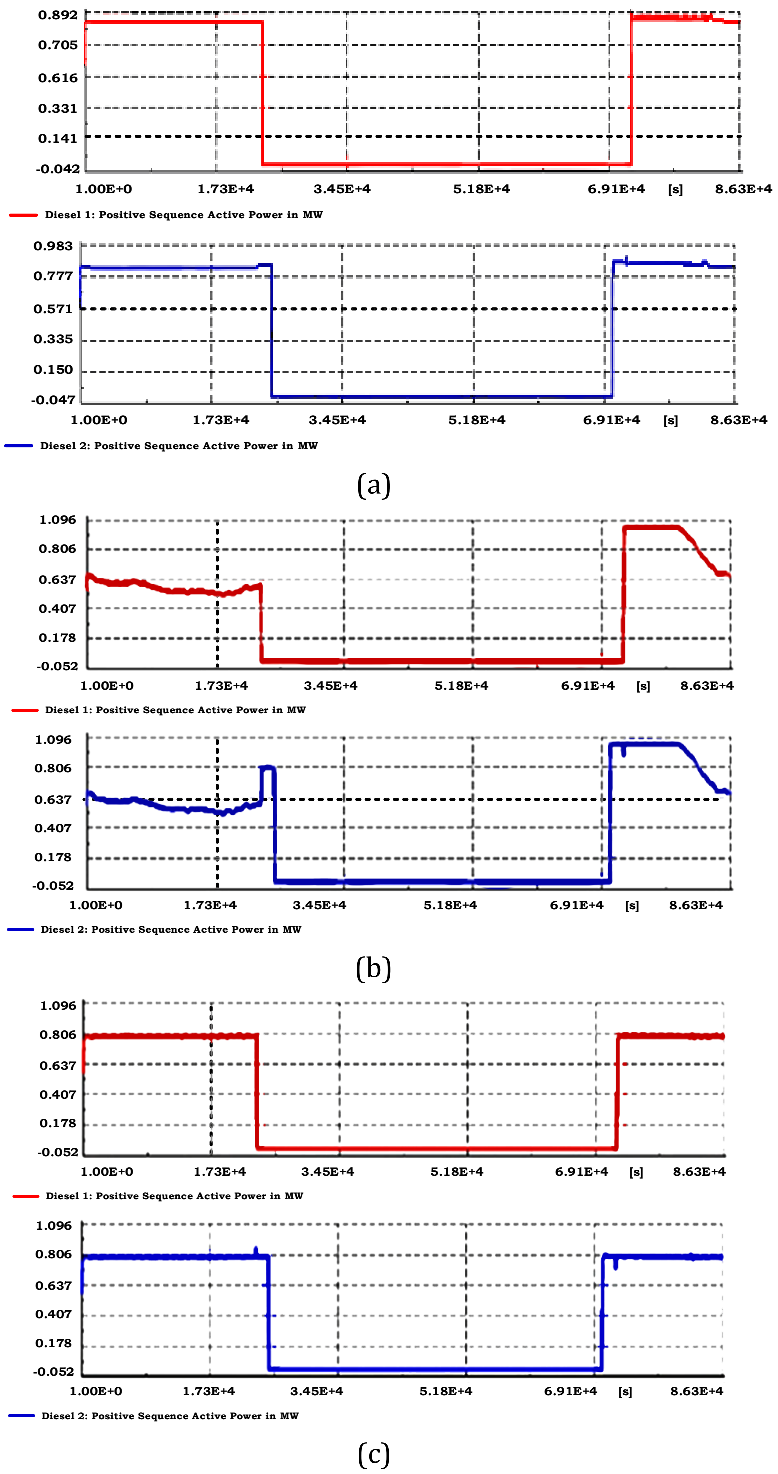
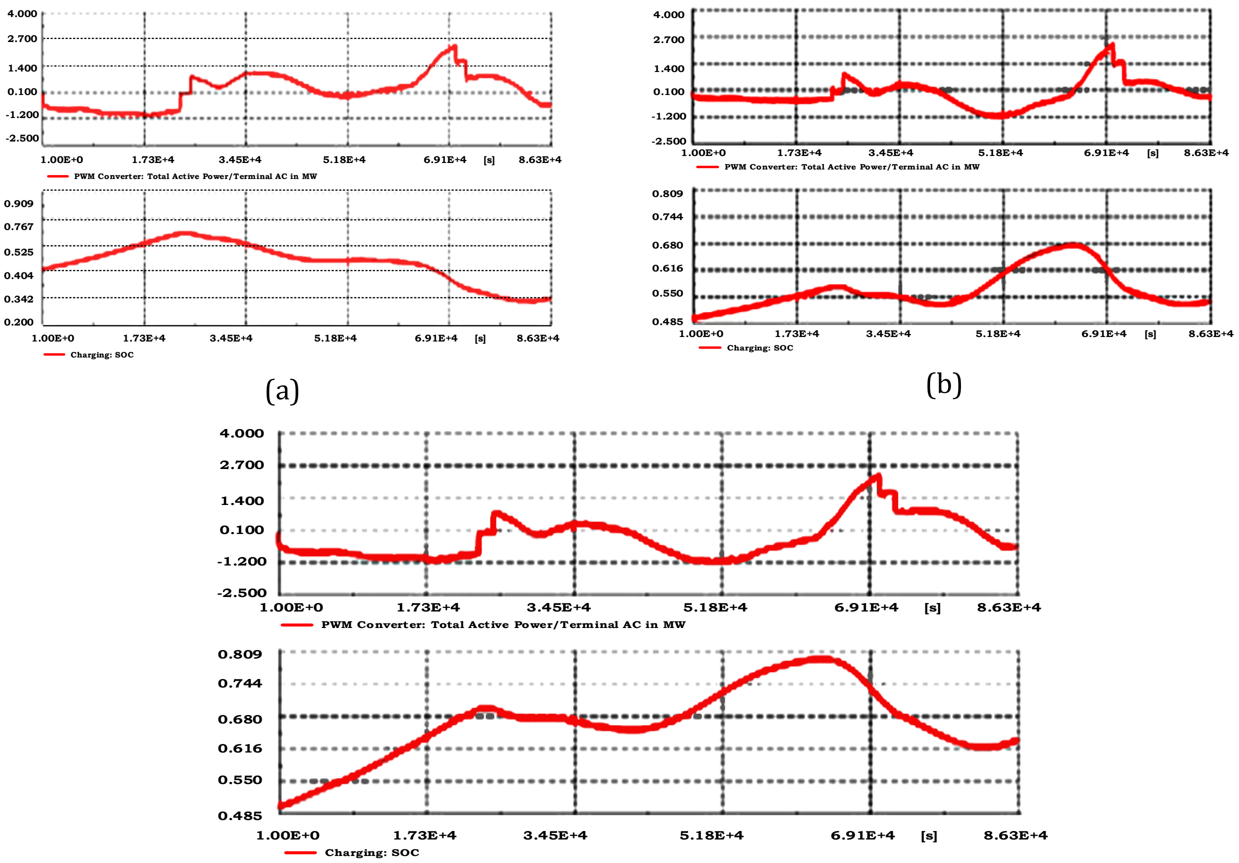


Figure 8. (a) Output power of diesel generators of strategy 1.
(b) Output power of diesel generators of strategy 2.
(c) Output power of diesel generators of strategy 3.

4.2. BESS output power

This paper aims to survey batteries' performance on spinning reserves to control frequency and increase network reliability; three important points should be investigated. The first one is the fluctuations of charge (power consumption from the network) and

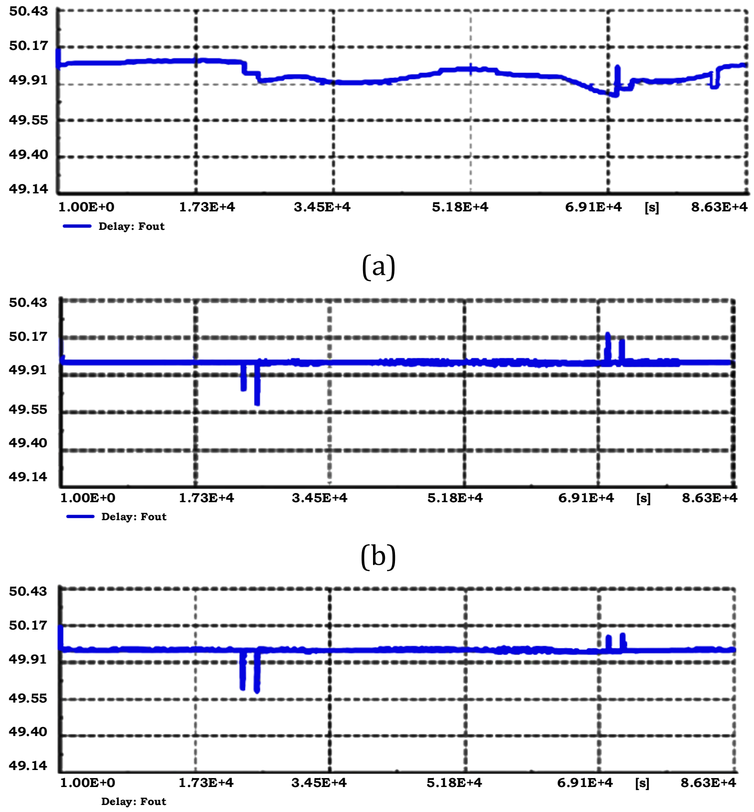


(a) (b)

(c)

Figure 9. (a) BESS output power of strategy 1.
(b) BESS output power of strategy 2. (c) BESS output power of strategy 3.

discharge (power injection to the battery). The second one is the changes in battery state of charge (SOC), which affect battery lifetime. The third one is the reaction of the BESS control system and the secondary control) to the entry and outage events of diesel generators, load, and PV. Figure 9 indicates the fluctuating output power of BESS. These fluctuations are more evident when PV generates power during the daytime. Figure 9(a) shows constant value output for diesel, which has no role in frequency correction but the BESS control system responds quickly to these fluctuations. In Figure 9(b), after applying secondary control on diesel generators and BESS, it Causes changes in BESS production and consumption. It is quite clear that power generation and consumption are lower compared to strategy three. The charge rate of strategy three is higher than others because the output of PV and diesel generators is more than the amount of load consumption which indicates there is excess power in the network and it is better to utilize this excess power in spinning reserve. Strategy 3 minimizes fluctuations in battery charge and discharge. Comparing three strategies to describe BESS's response in network events indicates that the third strategy operates better than others. Moreover, battery SOC changes are in a respectable performance range in all three strategies [30].



(a)

(b)

(c)

Figure 10. Frequency during a day
(a) Strategy 1. (b) Strategy 2. (c) Strategy 3.

4.3. Frequency analyzing

Frequency deviation analysis for three strategies is surveyed in this section. Figure 10 describes the frequency fluctuation of the network in 24 hours. As can be seen, when secondary control is not utilized in Figure 10(a), the frequency response after the mentioned events is not reasonable because of its fluctuations, but it is satisfactory for the third strategy as shown in Figure 10(c). The result of the second strategy is also acceptable, but the output of diesel generators changes, and as mentioned before this approach is not economical.

5. Conclusions

In this paper, secondary control is introduced for controlling frequency deviation and rapid control of the SR in an islanded microgrid. The secondary control operates in such a way that the diesel generator and BESS have participated in secondary control. Three strategies in the presence of diesel generators, PV, and BESS have been investigated and the best one has been introduced.

As a result, the outcomes of the proposed method are as follows:

- Using BESS as a SR contributes to:
    - preventing the use of diesel generators (as spinning reserves), thus reducing the variable cost of the system (including fuel and repair/maintenance) and air pollution (greenhouse gases).

  - saving surplus energy of PV.
  - increasing the response time of the system and thus stability.
- Power fluctuation is compensated based on the primary and secondary control of BESS; therefore, the output power of diesel generators becomes more constant and closer to the nominal value.

Frequency deviation becomes lower when the primary and secondary control is performed by the BESS.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the authors.

Credit Authorship Contribution Statement

Saeed Jamshidi: Conceptualization, Formal analysis, Methodology, Roles/Writing - original draft. **Hossein Bagheri**: Data curation, Funding acquisition, Methodology, Software. **Saeed Hasanvand**: Conceptualization, Methodology, Supervision, Roles/Writing - original draft. **Mohammad Esmaeil Hassanzadeh:** Conceptualization, Methodology, Software, Supervision, Roles/Writing - original draft. **Arash Rohani:** Formal analysis, Resources, Roles/Writing - original draft

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