TEPES
TURKISH JOURNAL OF
ELECTRICAL POWER
AND ENERGY SYSTEMS

TEPES Vol 1., Issue. 2, 69-74, 2021 **DOI:** 10.5152/tepes.2021.21002

RESEARCH ARTICLE

The Effects of Mobile Battery Energy Storage Systems on the Distribution Network

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Cite this article as: Karahan O, Özan A, Bağriyanik M. The effects of mobile battery energy storage systems on the distribution network. *Turk J Electr Power Energy Syst.* 1(2), 69-74, 2021.

ABSTRACT

Due to the increased penetration of renewable energy sources in the Electricity Distribution Systems, the idea of connecting a storage system to the distribution systems to provide stable electrical energy is becoming widespread. At this point, Battery Energy Storage Systems (BESS) have emerged as an important option. In this study, Mobile Battery Energy Storage System (MBESS), which have features such as providing island operation of the distribution system, responding to faults in a short time, and can be moved to desired areas and temporarily function as a buffer, have been introduced, and their effect on the distribution system has been investigated. Various scenarios with different battery locations and different short circuit types are produced in the study, using the IEEE 13-bus test system. Simulation studies were carried out on the test system for different scenario types, and the effect of the MBESSs operating mode was examined.

Index Terms—Mobile battery energy storage systems, distribution systems, power loss, short circuit fault, voltage drop.

I. INTRODUCTION

The increasing demand for energy day by day reveals that electricity generation facilities should be diversified. The intermittent energy problem in electricity networks, which arises due to the structure of Renewable Energy Systems (RES), is the subject of many new studies. Short-term and long-term analyses are being carried out for RES, which reveal the problem with energy stability. The areas of application of Battery Energy Storage System (BESS), which have been become widespread recently are increasing, with the solutions they offer [1].

The smart grid concept was developed especially in the early years of the twenty-first century. Although countries differ in their smart grid systems, their goals for the grid are common. In the smart grid model, the RES and battery systems can be integrated into the network, and an island operation feature is provided in the network. Thus, it provides higher reliability. In case of a fault that may occur at any point of the network, the BESSs provide island mode operation, so that the effect of the fault can be reliably and quickly eliminated. It is important to determine the appropriate locations for the BESSs to be used to improve the operating conditions of the electricity distribution network. In addition to the objectives such as ensuring continuity in system operation, reducing losses, and regulating the voltage profile, it is necessary to consider the many limitations such as the limits of current-carrying capacity, voltage limits, etc. There are many studies in the literature to solve these problems and optimize the systems, and to determine the location of BESSs and distributed generation units in the network [2].

Various Energy Management Systems (EMS) have been developed in studies considering the intermittent energy problem caused by RES, while designing distribution systems. The BESSs, which are of two types—fixed and mobile—play an important role at this point, because they have features such as improving the voltage quality in the network, providing reactive power support, reducing demand costs according to the density of the loads, and ensuring power balance. In addition to the fixed BESSs, Mobile Battery Energy Storage System (MBESS) have emerged as an option [3].

The aim of integrating MBESSs into an electricity distribution network is to store excess energy, to contribute to a constant power output, and to provide voltage support with reactive power compensation. To evaluate in terms of cost, the use of MBESSs is beneficial because the energy is provided from the battery when electricity is sold at high prices. In addition, MBESSs can be used for consumers who have a high power demand for a short time [4].

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Received: February 5, 2021
Accepted: May 2, 2021
Published online: August 27, 2021

It is becoming increasingly common for electricity generation units to be located close to loads. The RES, especially, provide a more efficient and reliable network structure. This network structure is called a micro-grid. The network structure, which has the feature of self-isolation in case of errors that may occur on the feeder side, stands out with its lower cost. The presence of intermittent energy in micro grids, high production–consumption imbalance between loads, and the difficulty of controlling this situation increase the use of MBESSs [5].

In the literature, methods have been proposed to enhance overall network performance by using BESSs, and the optimal placement, sizing, and operation of the storage units have been studied [6]. The effects of mobile battery systems in battery Electric Vehicles (EV) and plug-in hybrid EVs on the grid were examined in Wong [1]. Optimization has been achieved to solve problems, for instance, by reducing both the power loss and the voltage drop that will occur on the system when the battery system is recharged [1]. In the studies on MBESSs, various optimization methods have been used to obtain optimum results. The Monte Carlo simulation method was used in Abdeltawab and Mohamed [2] during the integration of MBESSs into the network. In Samara [3], using the particle swarm optimization method, the cost analysis of MBESSs on a 41-bus system was performed. Considering the voltage drop and power loss constraints, a system that can work in harmony with the RES has been designed, thanks to the proposed EMS [3]. In Barra [4], an MBESSs with a capacity of 480 kWh and an initial state of charge of 35% was used. Serving 19 customers, the MBESS made an optimum profit of $327/day using the day-ahead forecasting method. In addition to the power loss and voltage drop, which should be considered during the integration of MBESSs into distribution systems, the optimum location, size, and time are important [7]. In Sarıkurt and Balıkçı [8], it was seen that 4% profit was obtained by integrating the MBESSs into the system at the optimum time. It is stated that the algorithm used in this study can be used in large-scale systems.

In Abdeltawab and Mohamed [2], the use of MBESSs is included when the faulty part of the network is isolated from the system and the energy demand is met by distributed generation units. The study focused on reliability analysis. In reliability analysis, the startup time after a fault and the capacity of the storage system are important parameters. It is also assumed that the distribution system is radial, that all switches are reliable, and that two faults do not occur at the same time. Moreover, when the MBESS reaches the fault location, the state of charge is accepted as 50% [2].

The MBESS is connected to different nodes in a simple distribution system in [5]. The effects of MBESSs on the system in case of three-phase fault currents was simulated with the PSCAD/EMTDC program. Considering the test system with four buses, the effects of MBESSs on the system against short circuit faults that may occur in every bus were examined in terms of overcurrent protection [5].

In this study, the MBESSs have been integrated into the 13-bus test system so that analysis can be performed in a larger scale test system. MBESSs were connected to different suitable buses for determining the optimum location. Since power losses and voltage profiles are the most important parameters when designing EMS, the results of these two parameters obtained in case studies were evaluated in the study. In addition, by applying short circuits to different nodes, the behavior of the MBESSs in the system at the time of short circuit was monitored. Most studies in the literature focused on the effect of MBESSs on the energy management system, aiming to optimize the operational cost. In this study, the effect at the time of short circuit has been examined with dynamic analysis.

Main Points

- The integration of Mobile Battery Energy Storage System (MBESS) into distribution systems has many advantages. However, parameters such as power loss, voltage drop and short circuit must be carefully examined during the integration of MBESSs.
- Optimum MBESSs positioning is very important, especially in short-circuit analysis. It is seen that the short-circuit current changes depending on the location of the MBESSs.
- Since short circuits in electrical distribution systems are instantaneous events, the effects of MBESSs on the current short circuit can be seen more clearly with transient analysis.
- Since loads in a distribution system can vary over time, time series analysis must be made.

II. MBESS

In recent years, MBESSs are considered instead of fixed BESSs due to their mobility and easy access to the point of need. The biggest problems seen in BESSs are the high cost and low lifespan. Since small BESSs placed on different load busbars lead to costly undesirable quantities, it may be more advantageous to use a single, large BESSs instead of being placed in pieces. A large BESSs, where determination of the most suitable connection point is much more important, cannot support some parts of the system, especially when the topology of the system is restructured. At this point, MBESSs, which can be transported to the desired area, are more useful than the fixed BESSs [3]. The MBESSs have many benefits, from the manufacturer to the consumer.

A. Benefits for Utility

- High power quality is provided due to the low voltage loss.
- Less power loss and thus high efficiency is achieved.
- When there is high demand, the need for grid power is reduced.
- Optimal usage of grid power is ensured.

B. Benefits for Consumers

- The high cost caused by the load imbalance is reduced.
- In case of faults, reliability is provided with fast intervention.
- The network can be operated in island operating mode.

C. Benefits for Society

- They provide ease of access to remote areas within the distribution network.
- Business efficiency can be increased by reducing interruptions due to faults.

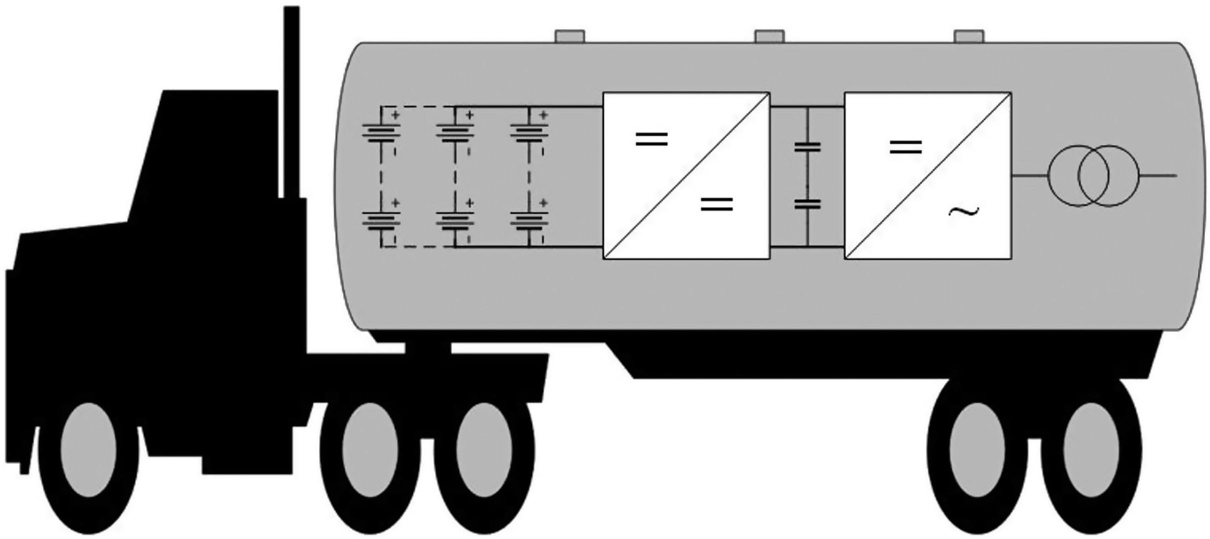

Fig. 1. Representative MBESS.

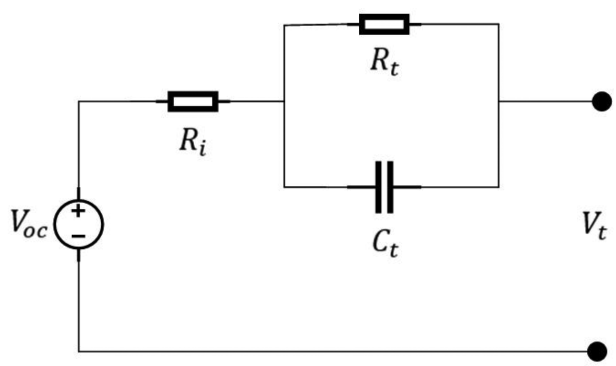

Fig. 2. Battery equivalent circuit model.

- Private individuals/companies enable the development of the free market structure with the operation of MBESSs.
- EVs are encouraged. Thus, a conscious society is formed in order to provide clean energy [8].

The MBESSs consist of two parts, the carrier vehicles and the storage systems, and are connected with the network by first using a DC/DC/AC bidirectional converter. In addition, there is a DC/DC converter, which is a current-controlled Buck–Boost converter, and a control device in the EMS that regulates the power of the battery in charge/discharge situations [3]. The MBESSs, whose general structure is described, can be seen in Fig. 1.

A simple equivalent circuit model of the battery is given in Fig. 2. The model, consisting of internal resistance and a resistor–capacitor block between open circuit voltage and terminal voltage, is used as the general battery model [9].

The idea of Vehicle for Grid (VfG) is becoming widespread. Compared to EVs and the Energy Storage System (ESS), the VfG increases network reliability, is more environment friendly, and provides economic gain to the distribution and production system. Structures with two operating systems, the Vehicle to Grid (V2G) and the Grid to Vehicle (G2V), are separated from the ESSs. The ability to operate in the optimum location and at the optimum time will increase the use of VfGs instead of EVs with external chargers. In an electricity network, the VfGs are MBESSs that provide economic gain in terms of generation and distribution units. They differ from fixed BESSs thanks to their mobile feature. This mobility provides advantages such as load shifting in the network, fast response in case of fault, and island operation [10].

The MBESSs, which are used to provide an island operation feature, can feed the isolated region in case of any fault in the network. The MBESSs act as a temporary buffer until distributed generation units provide energy support again. Some parameters of MBESSs are taken into consideration in long-term dynamic investigations. These are given in Equations 1, 2, and 3 [11]:

$$t_{up\_MBESS} = k_{traff} \frac{D}{S_{MBESS}} + t_{install} \tag{1}$$

where t_{up_MBESS} represents the startup time of MBESSs after fault (*h*), k_{traff} represents traffic condition factor, *D* represents distance between starting location and fault location (*km*), S_{MBESS} represents movement speed (*km/h*) and $t_{install}$ represents installation time (*h*):

$$\Delta E(t) = \int_{t}^{t+\Delta t} \left[P^{Dis\backslash Chr}(t) - \eta_c \left| P^{Dis\backslash Chr}(t) \right| \right] dt \tag{2}$$

where *E* represents the energy stored in the battery (*MWh*), $P^{Dis\backslash Chr}$ represents the charge\discharge power of the battery (*MW*), η_c represents the charge losses (*%*), and Δt represents the time interval (*hs*):

$$SoC(t) = \frac{E(t)}{E_r} \tag{3}$$

where $SoC(t)$ represents the charge level of the battery at time *t* (*%*), *E(t)* represents the energy stored by MBESSs at time *t* (*MWh*), and E_r represents the storage capacity of the MBESSs (*MWh*) [11].

III. EFFECTS OF MBESS ON THE DISTRIBUTION NETWORK

The MBESSs have many effects on distribution systems. Some of the most important effects are on total power loss, voltage drop, and short circuit currents. Reducing the total power loss is one of the most important goals in distribution systems. The power loss in the system can be calculated as in Equation 4:

$$P = \sum_{j=1}^{n} R_j \times I_j^2 \tag{4}$$

where *P* represents the total active power loss on the distribution lines, (*kW*), R_j represents the resistance of the *j*th line (*Ω*), and I_j represents the current of the *j*th line (*A*).

When examining energy distribution systems, another important parameter is the voltage drop. While providing electrical energy to the loads in the network, the voltage values at the nodes must comply with the limits. According to the standards, the voltage range should be between 0.95 and 1.05 pu [12]:

$$\Delta V_{ij} = V_j - V_i \tag{5}$$

where ΔV_{ij} represents the voltage drop on the line between buses *i* and *j* (*V*), V_j represents voltage of the *j*th node (*V*), and V_i represents voltage of the *i*th node (*V*).

The integration of distributed generation units in energy distribution systems can affect the magnitude and direction of the fault current during short circuit. In the literature, although there are studies on balanced fault currents, there are also studies dealing with the effect of unbalanced fault currents. The MBESSs, whose locations can be changed, also have an effect on short circuit currents [13].

IV. CASE STUDY

In the study, the IEEE 13-bus test system was used. The system includes a single feeder, a regulator, two step-down transformers, and nine loads. There are 115, 4.16, and 0.48 kV voltage values in the test system. In addition, a 500 kW MBESS was used in the study [14]. The OpenDSS program was used in the simulation studies. The test system that exists in the software's library is shown in Fig. 3.

Analyses in OpenDSS program were carried out in dynamic mode. Various scenarios have been produced in order to observe the effect of MBESSs on the distribution system. First of all, the battery is examined in scenarios where there is no short circuit fault. Then, the total power loss and maximum voltage drops in the system are determined for the cases in which there is no battery and the battery operates in discharge mode, and at various locations. In addition, by applying two different short circuit types to different locations, the fault current values for different battery locations are determined.

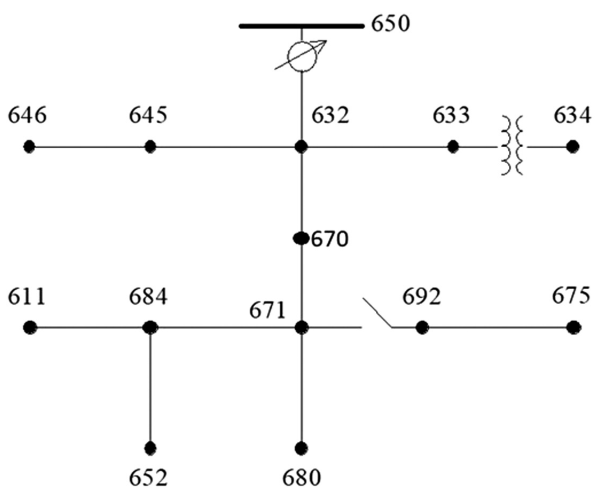

Fig. 3. IEEE 13-bus test system.

The graph representing the total power loss for the scenarios of the basic case, where there is no battery, and the location of the battery to the three-phase buses, is shown in Fig. 4. Batteries are located at three-phase nodes in the distribution system. When Fig. 4 is examined, the power loss in the system in the basic substation without battery is noted as 110.5 kW. As the location of the battery moves away from the feeder, the total power loss in the system decreases. When the battery is located on the bus number 675, which is the node farthest from the feeder, the total power loss in the system is calculated to be at least (85 kW).

The graph of the maximum voltage drops obtained for different scenarios is given in Fig. 5. When Fig. 5 is examined, the maximum voltage drop in the base case without a battery is measured as 2.503%. The battery is operated in the discharge mode, like a generation unit. As the battery system is positioned far from the feeder, the voltage drop decreases, depending on the loads. Accordingly, the least voltage drop is seen whevn the battery is positioned at the farthest point from the feeder, as expected. While the least voltage drop is seen in bus 675, and its value is 1.809%.

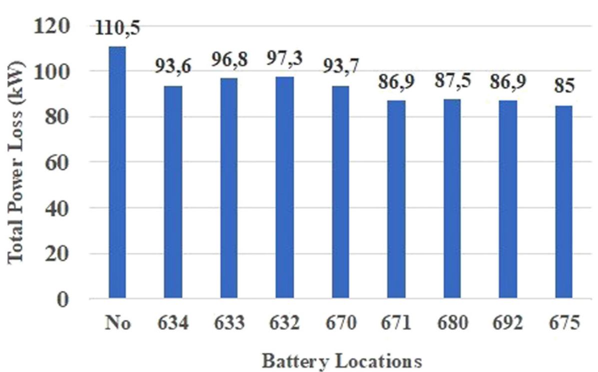

Fig. 4. Total power losses according to battery locations.

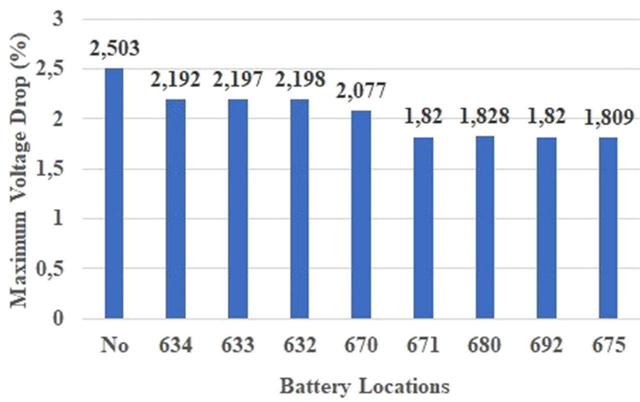

Fig. 5. Maximum voltage drops according to battery locations.

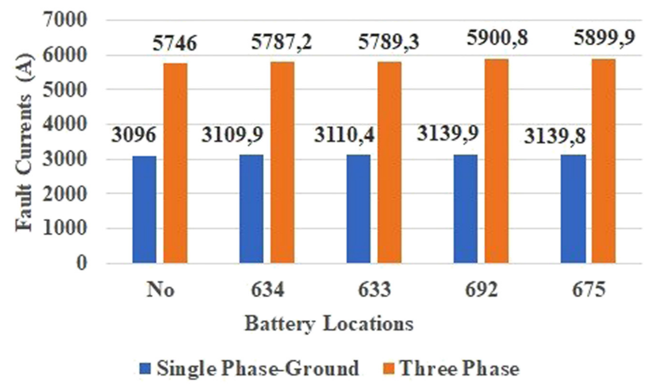

Fig. 7. In case of short circuit faults at 671, fault currents according to battery locations.

The effect of the change of the battery location on the fault currents are observed when different short circuit faults are applied. For the case where the short circuit fault is in bus 632, the single phase-ground and three-phase fault current values in scenarios with no battery and different battery locations are shown in Fig. 6. As can be seen clearly in Fig. 6, the three-phase short circuit fault current is higher than the single phase-ground short circuit fault current. Positioning the battery close to the fault location slightly increases the fault current.

For the case where the short circuit fault is in bus 671, the single phase-ground and the three-phase fault current values in scenarios with no battery and different battery locations are shown in Fig. 7.

Adding the battery to the system increases the fault current in two different short circuit types. As can be seen in the graph in Fig. 7, the three-phase short circuit fault current is 5746 A in the base case without the battery, and it is calculated as 5787.2 when the battery is connected to bus 634.

In the analysis made with dynamic mode in OpenDSS, the fault current graph in the scenario where the short circuit fault is at 671 and the battery is at 633 is shown in Fig. 8. While a short circuit fault occurs in the system in 0.5 seconds, the protection element separates the faulty part from the system with a delay of 0.1 seconds. After the faulty part is separated from the feeder network, the effect of the fault current of the battery is seen. In Fig. 8, black represents phase current 1 (I_1), red represents phase current 2 (I_2), and blue represents phase current 3 (I_3).

In the scenario without connecting any battery units, when a short circuit fault occurs in bus 671, the fault current is calculated as 5746 A at most. During the scenario, represented by the graph in Fig. 8, the fault current reaches a maximum of 5789 A. This result shows that the battery has an additional effect of 43 A on the system.

V. CONCLUSION

Most studies in the literature focused on the effect of MBESSs on the energy management system with an aim to optimize the operational cost. In this study, the distribution system with MBESSs has been examined to find the impact of faults on the distribution system. The

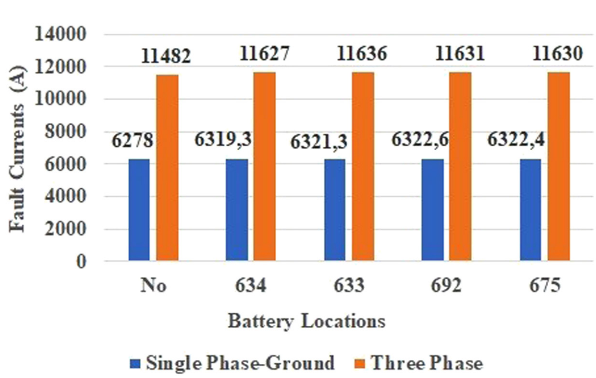

Fig. 6. In case of short circuit faults at 632, fault currents according to battery locations.

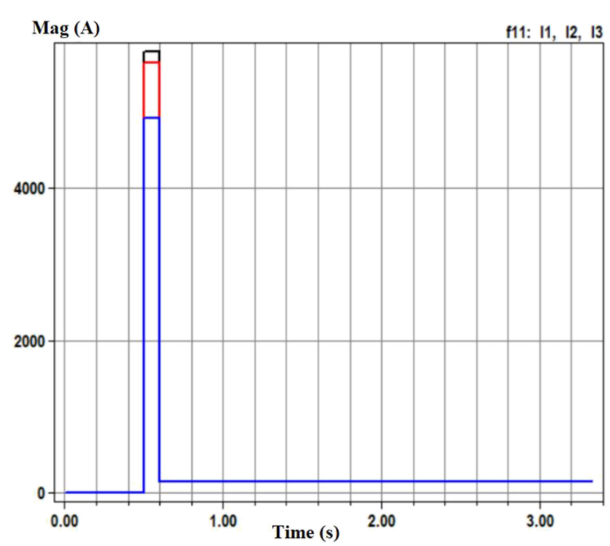

Fig. 8. In case of a short circuit fault at bus 671 and battery at bus 633, the graph of fault current.

integration of MBESSs into electrical distribution systems and their effect on parameters such as power loss, voltage drop, and short circuit current in the distribution system were obtained for different scenarios, tested on the IEEE 13-bus test system.

According to the simulation results obtained using OpenDSS program, the effects of MBESSs on distribution systems in different battery locations are interpreted as follows;

- When the scenarios are analyzed, a maximum decrease of power loss (23.07%) was observed compared to the base case.
- All bus voltages remained within the limits for considered scenarios.
- It has been observed that the location of the battery has little effect on the short circuit current. It is concluded that optimum battery placement is important at this point.

It will be useful to perform a time series analysis to deal with the effects in more detail and to study transient analysis to see the effect of MBESSs on the system in case of abnormal conditions, such as faults and overloads.

Peer-review: Externally peer-reviewed.

Conflict of Interest: The authors have no conflicts of interest to declare.

Financial Disclosure: The authors declared that this study has received no financial support.

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