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Optimal location and sizing of battery energy storage system using grasshopper optimization algorithm

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ABSTRACT

An energy storage system called a battery energy storage system (BESS) collects energy from various sources, builds up that energy, and then stores it in rechargeable batteries for future use. The battery's electrochemical energy can be discharged and supplied to buildings such as residences, electric cars, and commercial and industrial buildings. The advantages of utilizing BESSs, such as minimizing energy loss, improving voltage profile, peak shaving, and increasing power quality, may be reduced if incorrect decisions about the appropriate position and capacity for BESSs are chosen. Furthermore, the optimal position and size for BESSs are critical since deploying a BESS at every bus, particularly in an extensive network, is not a cost-effective option, and installing oversized BESSs would result in higher investment expenses. Hence, this study suggests a proficient method for identifying the most suitable position and the sizes of BESS to save costs. The grasshopper optimization algorithm (GOA) and evolutionary programming (EP) were employed to address the optimization challenge on the IEEE 69-bus distribution test system. The goal of the optimization is to minimize the overall cost. The findings indicate that the GOA has strong resilience and possesses a superior capacity for optimizing cost reduction in comparison to EP.

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1. INTRODUCTION

The adoption of renewable energy sources (RESs) has experienced significant acceleration in recent decades as a means to mitigate environmental deterioration and meet the challenges posed by climate change. The absence of carbon dioxide or other greenhouse gas (GHG) emissions from RESs such as photovoltaic, wind, and hydroelectric power plants contributes to the mitigation of global warming. Consequently, scholars initiated investigations into battery types that are both non-polluting and environmentally advantageous [1], [2]. One effective approach to promote the production of power using cost-effective and environmentally friendly energy is to integrate RESs with distribution generation (DG). Since they are a more reliable, cleaner source of energy for power production, RESs have largely replaced fossil fuels. This renewable energy can be erected flexibly and at a scale, and the energy collected may be stored for use later. BESS has recently gained popularity due to its rapid reaction time, practical controllability, and geographic independence. These qualities allow BESS to meet the system's requirements, such as overcoming overvoltage, reducing system cost, decreasing power loss, alleviating reverse power flow, and achieving peak shaving [3]-[5]. Although there are many benefits of BESS, they can also affect the electricity supply because of their intermittent nature and reliance on the weather [6], [7]. This may result in adverse consequences for the distribution system, specifically concerning power system performance and power quality concerns.

As a rapidly developing country, Malaysia shows a trend of increasing demand for energy resources. This has encouraged the government to strengthen the security of energy supply, increase efficiency, improve the quality of utility services, and deal with issues related to the environment, social and governance. There have been many conversations regarding climate change, sustainable energy, and energy efficiency during the past few decades. As a result, we have seen a significant increase in the production and usage of renewable energy worldwide, and Malaysia is no exception [8]. The Malaysia Renewable Energy Roadmap (MyRER) has revised the target for renewable energy generation in the national electricity supply to 31% in 2025 and 40% in 2035. This is expected to reduce the dependency on coal, increase the flexibility of the grid, increase solar capacity generation, and mainstream energy efficiency practices. Malaysia's plans include the implementation of battery energy storage systems (BESS) starting in 2030, aiming to harness the immense potential of solar energy. These BESS units will have a combined capacity of 500 MW. This will help to reduce the margin of energy storage and further reduce GHG emissions. Malaysia has updated its RE target, which aims for a 45% reduction in carbon emission intensity from the power sector in 2030 and an additional 60% reduction in 2035, relative to 2005 levels. Malaysia's targets are aligned with its Nationally Determined Contributions (NDCs) under the Paris Climate Agreement. Malaysia also agrees with the objective of attaining net-zero carbon emissions by 2050 [9]. Since BESS installation in distribution systems is gaining popularity, renewable energy power plants can have BESS installed so that the plant is operational during high demand [10].

Optimal location, sizing, operation, and power quality are vital aspects in harnessing the full potential of BESS within distribution systems. As the demand for electricity continues to grow and renewable energy integration becomes increasingly prevalent, strategic deployment and efficient utilization of BESS play a pivotal role in enhancing grid performance, cost-effectiveness, and power reliability [11]. Depending on the benefits desired, determining the best BESS locations within a distribution network may involve one or more optimization problems. In the previous work, it has been demonstrated that BESSs have the ability to reduce power quality issues and maintain balanced networks. However, the most crucial objective is to maximize the benefits of using BESSs for improving power quality through the best placement of BESSs in a distribution network [12]. The application of artificial intelligence has undergone a revolutionary transformation in the power system domain in recent years, redefining the way in which electricity is generated, transmitted, distributed, and consumed. Due to their ease of use, ability to escape from local optimal points, and lack of need for gradient calculations, metaheuristic methods for optimization have gained popularity in engineering applications, such as BESS allocation in electrical networks, including BESS allocation in the power system network. There are several techniques that have been used to determine the optimal sizing of BESS such as particle swarm optimization (PSO) [13], Cuckoo search algorithm [14], and whale optimization algorithm [15].

The natural swarming behavior of grasshoppers has inspired the development of a new swarm intelligence technique called the grasshopper optimization algorithm (GOA). The method was created by Saremi *et al*. [16]. The algorithm's mathematical model is documented in publications [17]-[18]. The literature has utilized it to tackle many optimization problems such as flexible AC transmission systems (FACTS) controller design [19], generation scheduling [20], optimal network reconfiguration [21], economic dispatch [22], and more. The literature has elucidated the advantages of GOA, which was derived from the feeding and swarming behavior exhibited by grasshoppers in their natural habitat. Due to the ability of GOA to solve many optimization problems, this paper presents GOA to determine the optimal location and capacity of BESS in a distribution network. The performance of GOA is compared to the performance of the evolutionary programming (EP) technique in terms of its fitness value and convergence curve. The efficacy of the suggested technique was evaluated using the IEEE 69 bus distribution system.

2. RESEARCH METHOD

2.1. Battery energy storage system

Electrochemical BESS uses a reversible chemical reaction to store and release electrical energy. Batteries, an inverter, protection devices, a transformer, and a system controller are the core components of BESS and work together to coordinate the functioning of all system components [23]. BESS has recently gained popularity due to its rapid reaction time, practical controllability, and geographic independence. These qualities allow BESS to meet the system's requirements, such as overcoming overvoltage, reducing system cost, decreasing power loss, alleviating reverse power flow, and achieving peak shaving [24]. A BESS can store energy from renewable sources, such as solar and wind, for later use. This allows for the release of stored energy during periods of high demand, helping to balance the grid and reduce reliance on fossil fuels. By connecting to the grid during periods of low demand for charging or utilizing additional energy from the batteries during peak load demand. The goal of this paper is to determine the location and size of BESS in the best possible position while minimizing total cost expenses (C_{system}) and power loss (P_{loss}) associated with the distribution system using GOA and a stochastic optimization approach called EP. These population-based optimization methods may locate global solutions to a variety of difficult combinatorial power system issues [25]. The objective function to be minimized is system cost, (C_{system}), which is calculated as the product of the power loss (P_{loss}) and lost cost rate (r_{loss}) as shown in (1). The magnitude of the voltage must be restricted within a certain range, as shown in (2) [23].

$$C_{system} = P_{Loss} \cdot r_{Loss} \tag{1}$$

$$V_{min} < |V_i^t| < V_{max} \tag{2}$$

The voltage magnitude of bus i at time t must be within the range. Furthermore, it is necessary to restrict the power and energy of the BESS to ensure that they remain within safe thresholds during both the charging and discharging processes [19]. In addition, it is necessary to restrict the power and energy of BESS within the specified battery security thresholds throughout both the charging and discharging processes. This is referred to as the battery constraints, and it is expressed in (3) and (4) [23].

$$P_{B\,min} < P_B^t < P_{B\,max} \tag{3}$$

$$E_{B\,min} < E_B^t < E_{B\,max} \tag{4}$$

2.2. Development of grasshopper optimization algorithm for optimal location and sizing of battery energy storage system

This paper aims to optimize the location and sizing of a BESS using the innovative GOA. The process involves gathering data on the distribution network, load profiles, and potential locations for BESS installation. The GOA will then be employed to iteratively explore different combinations of BESS sizes and locations, considering factors like load demand, grid constraints, and cost-benefit analysis. Through this iterative optimization process, the algorithm will identify the optimal location and size of the BESS that maximizes grid stability, minimizes power quality issues, and enhances the integration of RESs, culminating in a cost-effective and efficient BESS deployment plan for the distribution network. The flowchart for GOA implementation for determining the optimal placement and sizing is presented in Figure 1. GOA starts by setting all parameters initially as specified in Table 1. A random initial population of Grasshoppers is then generated; in this instance, the size and location of BESS are set to 0.008 and 0.352 kWh, respectively. The system's load flow is then run for the objective function in order to generate the fitness function. The fitness considered is the cost expenses, C_{system}. Grasshoppers iteratively change their positions during the optimization process based on their fitness or objective value and the positions of other individuals in the population. The grasshoppers collectively converge to 1×10^{-7} towards an optimal or nearly optimal solution, in this case, power loss and system cost, through these interactions and adjustments. The grasshopper's ideal position will be displayed.

2.3. Development of evolutionary programming for optimal location and sizing of battery energy storage system

A similar analysis has been conducted using the EP technique. EP offers an alternative approach to artificial intelligence that aims to achieve intelligent behavior by simulating evolution. This method is a stochastic optimization technique and leverages the principles of natural evolution to generate optimal solutions for a given problem. One of the key considerations in EP is to strike a balance between exploration and exploitation, ensuring that premature convergence is avoided. This feature has been a significant topic of attention in the research of EP since it allows the algorithm to efficiently investigate the range of possible solutions while making use of promising areas to achieve the best possible outcomes. By adopting this approach, EP enhances its ability to find robust and efficient solutions to complex problems.

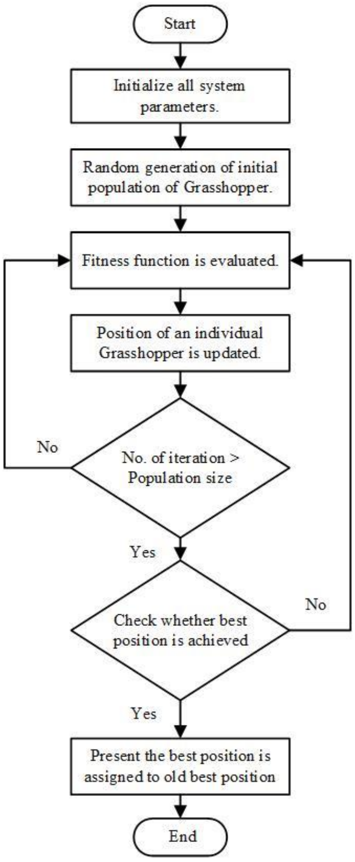


Figure 1. Flowchart of GOA for optimal BESS planning

Table 1. The utilized parameters for the simulation

Parameters	Values
Search agents	50
Maximum iterations	200
Voltage limits	$0.90 \leq V_j \leq 1.05$ p.u
BESS sizing limits	0.008 kWh$\leq P_{BESS} \leq$0.352 kWh
Charging and discharging power rate	0.001 kW$\leq P_{charge}/P_{discharge} \leq$0.044 kW

3. RESULTS AND DISCUSSION

The IEEE 69-bus system, which has 68 lines and 69 buses with a total load of 2694.6 kVar and 3801.5 kW, was subjected to the proposed GOA. The parameters used in the analysis are listed in Table 1. The suggested approach was tested out several times to ensure it was optimal, and the best outcome was chosen as the best course of action. Using numerical results and convergence traits, the GOA was also contrasted with EP. Table 2 presents the results of the load flow before installation of BESS.

Table 2. Initial load flow results

Vmin (p.u)	Power loss (MW)
0.9093	0.225

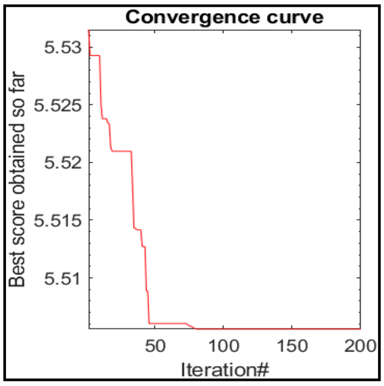
3.1. Results of single battery energy storage system installation

In this paper, two different scenarios are considered, the first is with single BESS, the second case with installation of five BESS are comparatively examined to maximize the performance of BESS and the impact of BESS installation on the power system. By contrasting two optimization techniques, EP and GOA, one may determine the goal function of this system based on the simulated simulation. Finding the ideal placement and BESS size in an IEEE 69-bus distribution system with the lowest system cost and power loss is the aim function of this. The effectiveness of BESS installation in each system was examined in terms of system cost. Both algorithms have a maximum population size and iteration count of 50 and 200, respectively. The results of the analysis are presented in Table 3. The results presented show that GOA recommended installing the BESS at bus 65, with a size of 0.0374 kWh. This installation resulted in a reduction in power loss to 0.2200 MW, a decrease of 2.22%. The integration of the BESS also led to a system cost reduction of 2.20%.

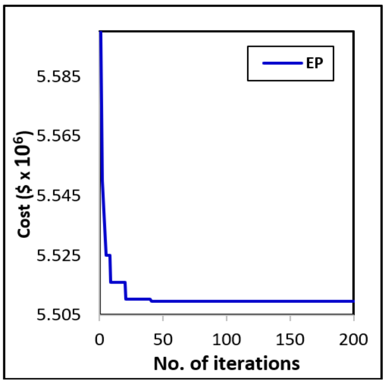
Table 3. Result of single BESS installation

Technique	Location	Size (kWh)	Vmin (p.u)	Ploss (MW)	Cost ($\$x10^6$)
GOA	65	0.0374	0.9093	0.2200	5.5056
EP	64	0.0387	0.9101	0.2204	5.5096

To evaluate the performance of the optimization techniques further, the convergence graphs for each approach are contrasted. Figure 2 shows the convergence graphs for both algorithms using GOA (Figure 2(a)) and EP (Figure 2(b)). As can be observed, every algorithm found the best solution for every situation. At the 43rd iteration, EP converged to a workable solution, followed by GOA at the 75th iteration. Nevertheless, GOA's final finding was the best.



(a)



(b)

Figure 2. Convergence curve for single BESS using (a) GOA and (b) EP

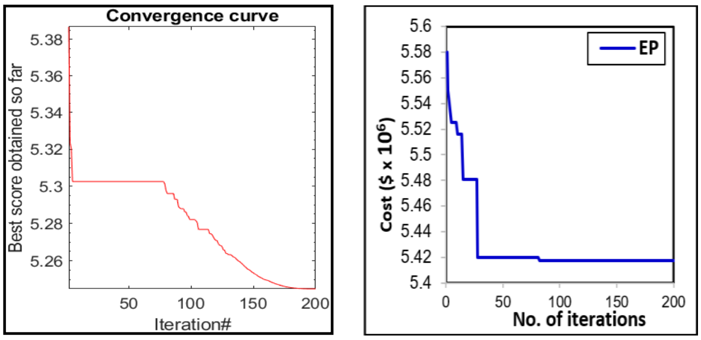
3.2. Results of multiple battery energy storage system installation

Two techniques, the GOA and EP, were used to identify the ideal location and size for a BESS in an IEEE 69-bus distribution system. Without the BESS, the initial network architecture had a minimum voltage of 0.9093 p.u. and a power loss of 0.225 MW. The GOA and EP algorithms were employed to determine the best position and size for the BESS. Table 4 summarizes the outcomes of five BESS installations utilizing GOA and EP, including the best placement, dimensions, power loss, voltage profile, and cost. GOA determined the best sites at buses 65, 22, 64, 63, and 25. The cost obtained is significantly lower than the cost acquired using the EP approach. The cost calculated with GOA is $\$5.2967\times10^6$, while the cost calculated with EP is $\$5.4175\times10^6$.

Table 4. Result of multiple (five) BESS installation

Technique	Location	Size (kWh)	Vmin (p.u)	Ploss (MW)	Cost ($\$x10^6$)
GOA	65, 22, 64, 63, 25	0.0302, 0.0390, 0.0440, 0.0300, 0.0361	0.9093	0.2100	5.2967
EP	63, 18, 60, 33, 35	0.0268, 0.0362, 0.0335, 0.0209, 0.0419	0.9104	0.2167	5.4175

Figure 3 showcases the convergence curve of the GOA (Figure 3(a)) and EP (Figure 3(b)) algorithm for the installation of five BESS. It can be observed that the algorithm converged at the 175th iteration, and its performance was deemed superior to that of EP. Overall, using GOA to determine the best location and size for a single BESS produced promising results in terms of lowering power loss, improving system cost, and accelerating convergence, making it the better option than using EP.



(a) (b)

Figure 3. Convergence curve for multiple BESS using (a) GOA and (b) EP

4. CONCLUSION

This paper introduces a method for determining the optimal placement and dimensions of BESS in distribution networks. The evaluation of the approach to the IEEE 69-bus system involved the utilization of two algorithms, namely EP and GOA. The outcomes demonstrate that BESS installation can significantly lower system costs and power losses. GOA was determined to be the best algorithm for this task because it was able to locate the ideal solution with the least amount of system cost and power consumption. Both EP and GOA were successful in stopping the reverse power flow that happens during periods of high load demand. According to the GOA simulation results, a single BESS and five BESSs reduced power loss by 2.22 and 6.67%, respectively. Additionally, the system cost was decreased by 5.68% for 5 BESSs and by 1.96% for a single BESS. In EP, power loss and system costs were reduced by 2.044 and 1.89% for a single BESS and by 3.69 and 3.53% for five BESSs, respectively. In upcoming work, this method can be used to identify the optimal location and size of BESS installations in actual distribution networks with high DG penetration, such as photovoltaic systems. In this paper, a technique for the location and sizing of BESS within distribution networks is presented. Two algorithms, EP and GOA, were used to evaluate the method on the IEEE 69-bus system. The outcomes demonstrate that BESS installation can significantly lower system costs and power losses. GOA was determined to be the best algorithm for this task because it was able to locate the ideal solution with the least amount of system cost and power consumption. Both EP and GOA were successful in stopping the reverse power flow that happens during periods of high load demand. According to the GOA simulation results, a single BESS and five BESSs reduced power loss by 2.22 and 6.67%, respectively. Additionally, the system cost was decreased by 5.68% for 5 BESSs and by 1.96% for a single BESS. In EP, power loss and system costs were reduced by 2.044 and 1.89% for a single BESS and by 3.69 and 3.53% for five BESSs, respectively. In upcoming work, this method can be used to identify the optimal location and size of BESS installations in actual distribution networks with high DG penetration, such as photovoltaic systems. This could boost the efficiency of distribution networks with high DG penetration and increase the use of BESS in Malaysia to support the expansion of renewable energy production.

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