

# Optimal Sizing and Allocation of Energy Storage for Successful Islanding Operations in Smart Grid

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<https://doi.org/10.34118/ajeee.v1i1.4888>

## Abstract

Distributed Generation (DG) has led to the development of Smart Grids (SG) to integrate alternative energy sources and improve the reliability of electricity Distribution Networks (DN), Energy Storage Systems (ESSs) are a promising technology that can increase system stability and reduce environmental impact. This study suggests a cost effective method for designing ESS units to improve distribution system performance, the approach is evaluated on the 33-bus radial DN using MATLAB and the Mountain Gazelle Optimizer (MGO). The main objective is determining the optimal combination of ESS units to manage scenarios while minimising power losses from 203 kw to around 63 kW. This strategy can reduce power losses and enhance the efficiency of DN. The study also provides insights into integrating ESSs into power systems for a more reliable and sustainable energy futurity.

**Keywords:** Distributed Generation (DG), Energy Storage Systems (ESSs), Mountain Gazelle Optimizer (MGO), Distribution Networks (DN), Power System.

## 1. Introduction

Blackouts, produced by equipment failure, severe weather, demand surges, or human error led to substantial disruptions, financial losses, and risk safety, particularly in critical infrastructure such as hospitals and banks. They make it hard to keep power systems stable during disturbances and require a lot of complex analysis because the electrical system doesn't behave linearly after a disturbance. the integration of ESS and effective power system management are proposed solutions to mitigate these issues [1–3]. Load shedding is implemented to prevent grid collapse and overload under high demand but low supply conditions. It entails selectively cutting power to maintain balance and prioritising essential services to minimise impact. Managing load shedding effectively is crucial for the electricity system's security and efficiency, necessitating meticulous planning and the use of advanced technologies. ESSs are recognized for their role in enhancing grid resilience, facilitating the integration of Renewable Energy Sources (RES), and ensuring continuous power in isolated areas, thereby supporting a sustainable energy transition [4]. The risk evaluation of integrated distribution systems that include RES and ESS, necessitate an estimation of the grid's dependability and stability, therefore identifying possible hazards linked to the integration of variable RES and various ESS. The objective is to guarantee an

efficient functioning, reducing the adverse effects of interruptions, and enhancing the ability of the system to recover quickly and smoothly. Implementing efficient risk management strategies in these systems may result in more sustainable and secure energy delivery [5]. However, integrating ESS units into the grid presents significant challenges, due to the high installation costs. Additionally, identifying cost effective locations and sizes complicates the system reliability improvement. Recent research highlights the importance of ESS positioning and sizing for the DN reliability enhancement and the integration of RES. While time series models for predicting RES behaviours and load demand are useful, their dependence on yearly forecasts may not capture variability in environmental conditions. Thus, the development of probabilistic models is recommended for optimising ESS sizing and ensuring power system adequacy more accurately [6–8]. The integration of ESS and Demand Side Management (DSM) strategies significantly enhances the economic operation of RES based DNs by increasing grid performance and optimising the use of energy. Despite their potential, challenges including, high costs and regulatory barriers persist, requiring a specialized analysis of real-world applications, advanced technology and policy developments to harness their benefits entirely [9]. New research illustrates the need to learn more about the reliability of ESS and their functioning with wind energy. It also shows a gap in combining system reliability with cost effectiveness when employing ESS in DNs. A suggested method seeks to improve DN reliability and avoid blackouts by merging reliability assessment and taking into account economical optimisation, prioritising value-oriented ESS investment and reliability objectives. This method involves optimization algorithms that account for economic factors to identify the most cost efficient and reliable ESS investment strategies [10]. The study suggests moving from time-series to probabilistic models for sizing ESS units to improve DN efficiency and reliability without strictly following conventional rules. It highlights the importance of selecting optimal locations for ESS to cut costs and enhance reliability, thus preventing power outages. ESS benefits, including reduced energy consumption, lower costs, and better demand and power quality management, facilitate the integration of RES and contribute to carbon emission reduction. The research advocates for further analysis of ESS's role in optimising demand management and supporting RES integration to strengthen grid reliability and stability. ESS units are crucial for balancing electricity supply and demand, reducing infrastructure needs, storing excess RES, and providing grid services like frequency control and black start

capabilities. Optimising the size and allocation of ESS for islanding operations in SG is essential for enhancing grid resilience and flexibility. This involves assessing critical load requirements, analysing grid topology, and conducting power flow studies to determine strategic ESS siting. The sizing of ESS is based on peak demand and load profiles, with considerations for integration with RES to ensure a continuous power supply during grid disconnections. The choice of storage technology considers factors like energy density and cost effectiveness. Economic feasibility is evaluated through cost benefit analysis, factoring in potential revenues from grid services like demand response. Regulatory compliance is also crucial. Advanced simulations using optimisation algorithms refine ESS sizing and location, ensuring optimal operational outcomes. A phased deployment and pilot testing are recommended to validate ESS performance in real world scenarios, ensuring the SG maintains stability and service quality during islanding events [11–13]. This study adds to the body of research on SG resilience by looking into how to use ESS size and placement best to improve islanding operations. This area has not been fully covered in previous studies. Prior studies, such as those by [14], primarily target optimisation for cost and efficiency within grid connected microgrids using methodologies like PSO. In contrast, this study employs a sophisticated approach by integrating sequential and concurrent optimisation techniques to address the dual challenge of maintaining grid stability and ensuring energy availability during autonomous operations. This research is significant because it focuses on ESS's strategic location and sizing to support the grid's operation during emergency islanding scenarios. This is critical as the increasing penetration of intermittent RES heightens the risk of grid instability during isolation from the leading power system. The literature extensively discusses the impacts of RES integration on grid dynamics but often overlooks specific optimisation strategies for islanding operations [15]. By concentrating on these strategic aspects, this study fills a notable gap in SG research and contributes valuable insights into optimising grid resilience against disruptions caused by unplanned separations. Therefore, this research advances theoretical frameworks and provides practical guidance for enhancing the robustness and sustainability of power systems, positioning it as an essential reference for future advancements in SG technology. The main contributions of this article are:

- The optimal sizes and locations for ESS will be determined using the MGO algorithm to ensure the power system's efficiency and reduce power losses.
- Enhance grid stability and support local energy needs.
- Improves islanding operations where grid sections operate independently, ensuring power quality and availability.
- Enhances the robustness and dependability of the grid, allowing it to endure and bounce back from disturbances.

The organization of this article is as outlined below: Section II addresses the formulation of the problem, while Section III discusses the objective function and the constraints. Section IV presents the methods used in more detail. Section V is dedicated to presenting the load modelling. Section VI

focuses on the economic analysis related to the sizing and location of the ESS. Section VII presents the results derived from the simulations. The document concludes with Section VIII, which summarizes the findings of the study.

## 2. Problem Description

Figure1. illustrates a simplified distribution network design incorporating DG systems, ESS, and loads. Adding DG systems, like RES, to DNs has changed the one-way flow of power to a two-way flow [16]. This makes things more technical and cost-effective, but it also creates problems because DG outputs are not always stable, which throws off the balance between power demand and supply. ESS is acknowledged as an effective solution for mitigating these challenges by allowing for the storage and supply of power as necessary, thereby optimising power flow and minimizing energy losses within DNs. The research highlights that while the deployment. The study employs the MGO technique to find the of DG systems and ESS at demand centres has already improved energy efficiency by reducing current flow and losses, further optimisation in the placement and sizing of ESS could lead to even greater reductions in power losses [16]. Optimal location and sizing of ESS units within DNs, aiming to enhance overall network efficiency and reliability.

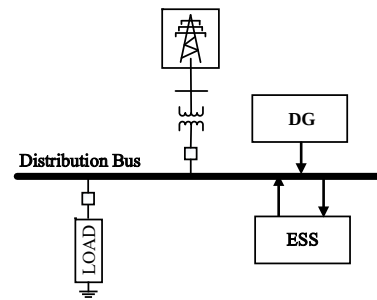


Figure 1: A typical DN configuration comprising DG and ESS

### 2.1. Objective Functions

The total power losses in distribution systems are considerably high, primarily due to their radial structure. Thus, there is a crucial need to minimize these active power losses ( $P_{loss}$ ) [17]. The calculation of distribution system losses, concerning the total power loss  $P_{loss}$ , is determined through the application of the branch current loss formula, represented as:

$$P_{loss} = \sum_{i=1}^{Nbr} R_i |I_i|^2 \quad (1)$$

where  $i$  is the branch number,  $Nbr$  is the total number of branches,  $|I_i|$  is the absolute value of the current flowing through branch  $i$ , and  $R_i$  is the branch resistance.

### 2.2. Problem Constraints

To address the problem of ESS siting in the distribution system, it is crucial to consider two fundamental constraints, which are as follows:

### 2.2.1 Equality constraints

The power flow in the distribution system needs to be balanced, meaning that the power supplied from the substation, and the power generated from DG and ESS units must satisfy the load demand and power losses requirements, as specified in [18]

$$P_s + \sum_{i=1}^{N_{ESS}} P_G(i) + \sum_{i=1}^{N_{ESS}} P_{ESS}(i) = P_D + P_{loss} \quad (2)$$

$$Q_s + \sum_{i=1}^{N_{DG}} Q_G(i) = Q_D + Q_{loss} \quad (3)$$

In the aforementioned equation,  $P_s$  and  $Q_s$  represent the active and reactive powers drawn from the substation, while  $P_G$ ,  $Q_G$ , and  $P_{ESS}$  denote the incoming active and reactive powers generated by the installed DG and ESS units, respectively. Similarly,  $P_D$ ,  $Q_D$ ,  $P_{loss}$ , and  $Q_{loss}$  refer to the active and reactive load demands and power losses, respectively.

### 2.2.2 Inequality constraints

**Voltage Limits:** The voltage magnitude at each bus in the power system must remain within the allowable limits, which can be expressed as [19, 20]

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad (4)$$

**Branch Current Limits:** As stated in [20], the branch current must not exceed its maximum allowable limit:

$$I_{i,j} \leq I_{i,j}^{\max} \quad (5)$$

**ESS Power Limits:** The active power output range of ESS units is expressed as [21, 22]

$$P_{ESS}^{\min} \leq P_{ESS} \leq P_{ESS}^{\max} \quad (6)$$

**ESS Size Constraints:** The ESS sizing constraints are further given by

$$S_{ESS_i} = x_i \times \text{certain discrete size}, \quad \forall i \in CB \quad (7)$$

$$S_{ESS_i} \leq S_{ESS}^{\max}, \quad \forall i \in CB \quad (8)$$

$$E_{ESS_i} = y_i \times \text{certain discrete size}, \quad \forall i \in CB \quad (9)$$

$$E_{ESS_i} \leq E_{ESS}^{\max}, \quad \forall i \in CB \quad (10)$$

where  $S_{ESS}$  and  $E_{ESS}$  denote the ESS power and energy capacities, respectively. The variables  $x_i$  and  $y_i$  are integer decision variables controlling the ESS size installed at bus  $i$ . Moreover,  $CB$  represents the set of candidate buses for ESS installation.

## 3. Optimization Method

The MGO is a metaheuristic optimisation technique for solving complex problems in domains like engineering, finance, and machine learning that draws inspiration from the adaptive behaviours of mountain gazelles. By mimicking gazelles' strategies for avoiding predators and searching for food the MGO employs a search strategy that effectively avoids local optima and seeks global solutions. It stands out for its ability to deliver promising results across various problem types, including constrained, unconstrained and multi objective scenarios by adjusting parameters like population size and iteration frequency to navigate toward optimal solutions efficiently [23].

### 3.1. Mathematical Model

MGO algorithm considers mountain gazelles' bachelor male herds, maternity herds, solitary territorial males, and food-searching movement patterns.

The MGO optimisation technique may optimise many applications by replicating these tendencies. An overview of the optimisation method utilising the agents in the MGO is shown in Figure 2. In addition, Figure 3 illustrates the flowchart of the MGO algorithm [23].

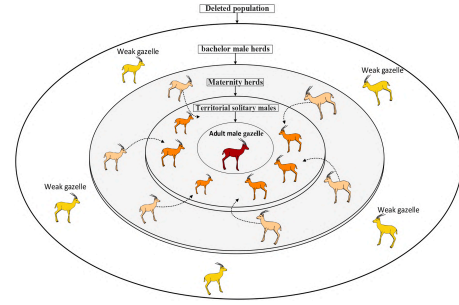


Figure 2: MGO optimization procedure

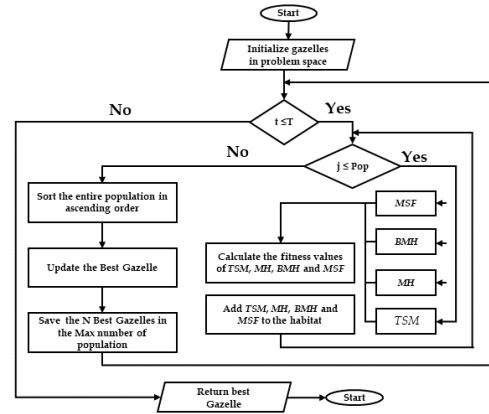


Figure 3: Flowchart of MGO

## 4. Load Modelling

The security and dependability of RES have been improved by suggesting ESS. Figure 4 displays the typical configuration of the DG and ESS integrated into the grid, with different loads types. The majority of studies found in the literature have centred around the power flow problem, utilising constant load models or constant active and reactive powers. Nonetheless, the actual load characteristics depict the dependence of load power on the bus voltage [24].

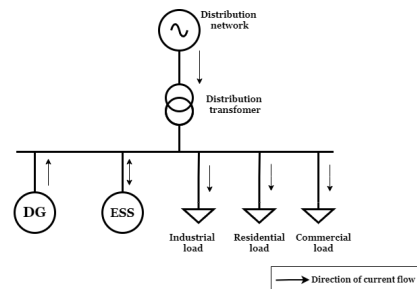


Figure 4: Standard DN configuration with DG, ESS, and loads.

Typically, the DN's load can be categorised into industrial, residential, and commercial. This research tackles a real world problem by constructing voltage dependent models for industrial, residential, and commercial loads. The mathematical expression for the formulation of voltage dependent load models is presented as follows

$$P_i = P_0 V_i^\alpha \quad (11)$$

$$Q_i = Q_0 V_i^\beta \quad (12)$$

In the voltage-dependent load formulation,  $P_i$  and  $Q_i$  denote the active and reactive powers, respectively, while  $P_0$  and  $Q_0$  represent their corresponding values at nominal voltage. The voltage magnitude is denoted by  $V_i$ , whereas  $\alpha$  and  $\beta$  are the active and reactive power exponents, respectively. Table 1 presents the values of  $\alpha$  and  $\beta$  used in this study for different load types, obtained from [19, 25].

Table 1: Load types and exponent values

| Load Type   | $\alpha$ | $\beta$ |
|-------------|----------|---------|
| Constant    | 0        | 0       |
| Residential | 0.92     | 4.04    |
| Commercial  | 1.51     | 3.40    |
| Industrial  | 0.18     | 6.00    |

## 5. Study the economical part of size and location of an ESS

**Economic Feasibility of ESS:** The economic feasibility of ESS is determined by analyzing its size and placement for grid-scale, residential, and commercial applications. This process involves load profile analysis, storage capacity evaluation, optimal site selection, and a comprehensive cost-benefit assessment. Financial indicators such as net present value and sensitivity analysis are employed to identify the most economically viable ESS size and location under different operational and economic assumptions [26, 27].

$$COF = \frac{AC + OMC + ARC}{AED} \quad (13)$$

$$AED = P \times n \times H \times D \quad (14)$$

The cost of ESS technology depends on the initial investment cost and operational lifetime, including the cost per kWh of storage systems and auxiliary subsystems, maintenance expenses, and charging energy costs. Unlike many other technologies, the ESS cost strongly depends on the required energy capacity and can be evaluated annually using Equation (14) [28].

where  $COF$  is the cost of energy,  $AED$  is the annual energy discharged,  $AC$  is the annual capital cost,  $OMC$  is the annual operation and maintenance cost, and  $ARC$  is the annual replacement cost. Moreover,  $P$  denotes the rated power capacity of the storage system,  $n$  is the number of charge/discharge cycles per day,  $H$  is the duration of each discharge cycle, and  $D$  represents the annual operating days of the storage system.

## 6. Simulation Results

The proposed load model is the IEEE 33 bus test system. The system consists of 33 buses and 32 nodes. The single line diagram is presented in Figure 5. The base voltage and base power apparent are 12.66 kV and 100 MVA respectively [29].

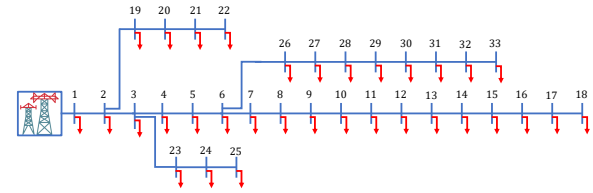


Figure 5: 33-Bus test distribution system

### 6.1. Case Study

The study looks at a radial DN with 33 buses and DG units connected to buses 18 and 33, as shown in Fig.7 [30]. The study looks at a radial DN with 33 buses and DG units connected to buses 18 and 33, as shown in Figure 6 [30]. Specifically, a gas turbine is connected to bus 18, and a wind turbine is connected to bus 33. The voltage profiles, both in scenarios with and without the integration of these DG units, are displayed in Figure 7.

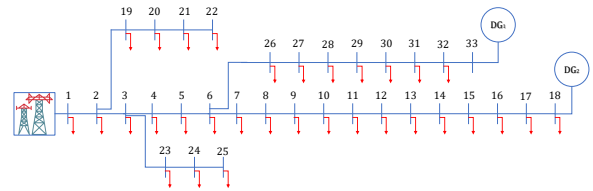


Figure 6: 33-Bus test distribution system with two DG

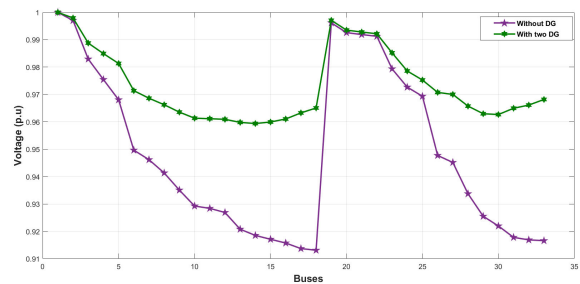


Figure 7: Voltage profile without and with DG

### 6.1.1 Result and discussion

This section applies the technique MGO to a standard 33 bus system. Multiple ESS units' optimal capacity and sitting are determined to minimise the total power loss as a single objective optimisation problem. Our analysis zeroes in on a 33 bus distribution system comprising 33 buses and 32 branches with a total load capacity of 3715 kW and 2300 kVar. Given these specifications, the expansion of ESS units is strategically limited to three to avoid diminishing returns in power loss reduction. The MGO algorithm and two DGs were used to figure out where and how big to put ESS units in Table 2 when the load conditions change. Table 3 shows that the MGO algorithm reduces power losses in the best ESS configurations. The calculations for this were done in MATLAB. This underscores the critical role of strategic ESS deployment in enhancing network efficiency and the robust potential of MGO for network optimisation.

Table 2: Optimal ESS location and size of the different load level with 2 DG

| Case  | Overloading | 2 DG (18,33) |          |
|-------|-------------|--------------|----------|
|       |             | Size (kW)    | Location |
| 1-ESS | 1           | 1200         | 24       |
|       | 1.25        | 1700         | 7        |
|       | 1.5         | 2500         | 6        |
| 2-ESS | 1           | 600          | 8        |
|       |             | 1000         | 24       |
|       | 1.25        | 2000         | 3        |
|       |             | 900          | 8        |
|       |             | 1600         | 24       |
|       |             | 1500         | 8        |
| 3-ESS | 1           | 500          | 7        |
|       |             | 300          | 9        |
|       |             | 1000         | 24       |
|       | 1.25        | 1000         | 6        |
|       |             | 500          | 10       |
|       |             | 1200         | 24       |
|       |             | 600          | 11       |
|       | 1.5         | 1500         | 6        |
|       |             | 1200         | 25       |

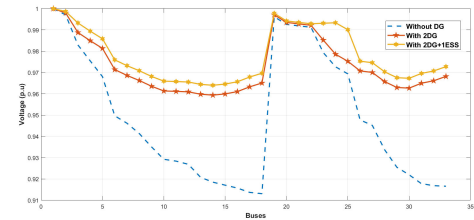
Table 3: Power losses of optimal ESS location and size with 2 DG

| Case       | DGs And Overloading | Size (kW,kVAr)        | Bus Location | Power losses (kW) | Losses reduction % |
|------------|---------------------|-----------------------|--------------|-------------------|--------------------|
| Without DG |                     | -                     | -            | 202.78            | -                  |
| With 2-DG  | DG1                 | PDG 1 =500            | 18           | 92.31             | 54.48%             |
|            | DG2                 | PDG2= 900<br>QDG2 100 | 33           |                   |                    |
| 1-ESS      | 1                   | 1200                  | 24           | 73.29             | 64.09%             |
| 2-ESS      | 1                   | 600                   | 8            | 63.63             | 68.82%             |
|            |                     | 1000                  | 24           |                   |                    |
| 3-ESS      | 1                   | 500                   | 7            | 62.56             | 69.35%             |
|            |                     | 300                   | 9            |                   |                    |
|            |                     | 1000                  | 24           |                   |                    |
|            |                     |                       |              |                   |                    |

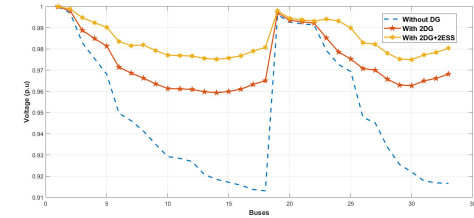
Table 4: Total  $P_{loss}$  of the 33-bus system for the four load types before and after the integration of DGs and ESS

| Cases           | Scenario | Bus | Size (kW/kVAr) | Const. | Res.  | Comm. | Ind.  |
|-----------------|----------|-----|----------------|--------|-------|-------|-------|
| Without DG      | Base     | -   | -              | 203    | 160.4 | 155.6 | 162.5 |
| With DG         | DG1      | 18  | 500            | 92.3   | 65.3  | 66.2  | 60.9  |
|                 | DG2      | 33  | 900 / 100      |        |       |       |       |
| With DG (18,33) | 1-ESS    | 6   | 1200           | 73.3   | 48.3  | 50.1  | 42.8  |
|                 | 2-ESS-A  | 8   | 600            | 64     | 41.5  | 44.6  | 34.3  |
|                 | 2-ESS-B  | 24  | 1000           |        |       |       |       |
|                 | 3-ESS-A  | 7   | 500            |        |       |       |       |
|                 | 3-ESS-B  | 9   | 300            | 62.5   | 41    | 45    | 33.6  |
|                 | 3-ESS-C  | 24  | 1000           |        |       |       |       |

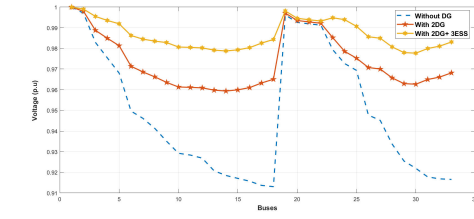
Figure 8 illustrates the voltage profiles before and after the deployment of two DGs and highlight the optimal placement for one to three ESS units. Figure 10 reveals that the strategic addition of ESS units can significantly mitigate active power losses across different power system configurations. Notably, within the IEEE 33 bus framework, installing a 1200 kW ESS at bus 24 dramatically reduces active power losses from 203 kW to 73.29 kW, translating to a 64.09% decrease. Similarly, positioning ESS units with capacities of 600 kW and 1000 kW at buses 8 and 24, respectively, further reduces losses to 63.63 kW, or a 68.82% decrease. Integrating a third ESS unit amplifies this effect, cutting losses by 69.35% and highlighting the incremental efficiency gains achievable through additional ESS installations. Figure 9 corroborates these findings



(a) 1-ESS



(b) 2-ESS



(c) 3-ESS

Figure 8: Voltage profile without and with DG and ESS

by illustrating a notable reduction in total active power losses post-ESS integration. This also enhances voltage stability within the 33-bus radial distribution system by maintaining voltages within the desired thresholds. The 33 bus system has four different types of loads, and Table 4 shows how the active power losses are spread out.

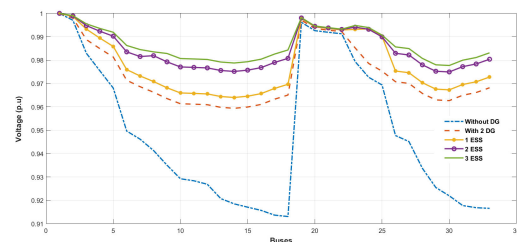
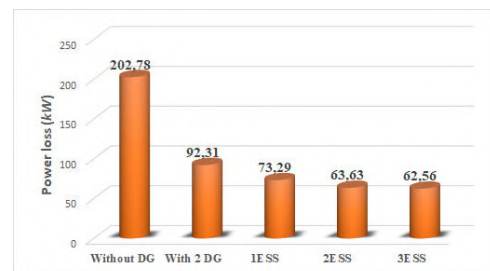


Figure 9: Voltage profile without and with DG and ESS in the different cases

Figure 10: Total  $P_{loss}$  before and after integration of ESS with and without DG in systems 33

## 6.2. Comparison cost of ESS

Our study detailed economic parameters (5% interest, 1% inflation) and categorised ESS costs into initial, capacity investment, and yearly operational and maintenance expenses. We evaluated Lead-Acid (LA), Compressed Air, Sodium-Sulfur (CAS), Vanadium Redox (VR) and Na/S batteries for their power and discharge suitability, offered in 100 kVA/kWh increments. Projected 30-year capital and maintenance costs for these technologies are listed in [6].

Table 5: Optimal ESS Allocation And the total annual cost (million \$)

|                                | ESS | bus | LA         | CAS        | Na/S       | VR         |
|--------------------------------|-----|-----|------------|------------|------------|------------|
| Optimal ESS size (kVA, kWh)    | 1   | 6   | 1200, 1200 | 1200, 1200 | 1200, 1200 | 1200, 1200 |
|                                |     | 8   | 1600, 1600 | 1600, 1600 | 1600, 1600 | 1600, 1600 |
|                                | 2   | 24  | 1800, 1800 | 1800, 1800 | 1800, 1800 | 1800, 1800 |
|                                |     | 9   | 1800, 1800 | 1800, 1800 | 1800, 1800 | 1800, 1800 |
|                                | 3   | 24  | 0.05       | 0.12       | 0.13       | 0.075      |
|                                |     | 8   | 0.068      | 0.16       | 0.17       | 0.1        |
| Total annual cost (million \$) | 1   | 6   | 0.077      | 0.18       | 0.191      | 0.113      |
|                                |     | 8   |            |            |            |            |
|                                | 2   | 24  |            |            |            |            |
|                                |     | 9   |            |            |            |            |
|                                | 3   | 24  |            |            |            |            |
|                                |     | 8   |            |            |            |            |

### 6.2.1 Discussion

Table 5 presents an exhaustive summary of the yearly accumulated expenses for the four evaluated battery technologies. An in-depth examination of the patterns depicted in Figure 11 reveals a conspicuous trend, highlighting Lead-Acid (LA) batteries are the most economically beneficial choice within the range of technologies examined. This data establishes their cost-efficiency and underscores their position in sustainable energy alternatives.

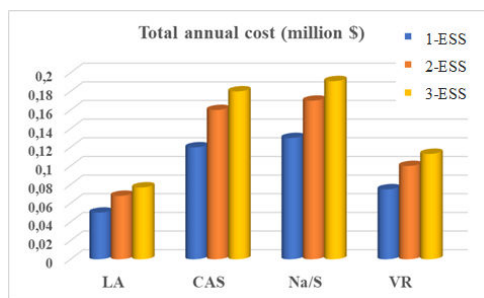


Figure 11: Total annual costs for the different storage technologies

## 7. Conclusion

The main goal of this research was to determine the necessary number of ESS installations required to improve the dependability of the distribution system in a cost-efficient way. To achieve this objective, we used a two-step approach to strategically position ESS units inside the power distribution network, focusing on enhancing system dependability and ensuring uninterrupted customer service. We used a probabilistic approach to deal with system uncertainties, taking into account the features of all its parts, like loads and existing DGs, in order to get a good idea of how much power the ESS units

could produce. The empirical aspect of this study included analysing four different storage techniques, compared to a baseline scenario without ESS units, to assess their efficacy in enhancing system reliability and efficiency.

## Conflict of Interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Funding

"This research received no external funding."

Authors are encouraged to provide information regarding the availability of the data used in this study. Data may be publicly available, included within the article, or provided upon reasonable request.

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