Optimal placement and sizing of BESS in RES combined IEEE network

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***Abstract*— This study presents an approach for the optimal allocation and sizing of a Battery Energy Storage System (BESS) to mitigate power losses and voltage deviation indices in the Renewable Energy Source (RES) incorporated distribution system. The optimal positioning and capacity determination of BESS within RES-connected test systems are derived using a metaheuristic optimization algorithm. Utilizing the ETAP simulation platform, a comprehensive investigation is performed to estimate the impact of BESS deployment. The ETAP software facilitates detailed modeling and simulation of BESS integration by incorporating critical parameters such as RES generation variability, load fluctuations, and network constraints. The projected optimization approach is implemented on the IEEE-33 and IEEE-34 bus test systems, demonstrating a substantial drop in voltage deviations and power losses following the amalgamation of RES and BESS units. The findings provide significant insights for power system operators, aiding in the strategic locating of BESS to enhance system efficiency, stability, and reliability**

Keywords- Renewable Energy Sources (RES), Battery Energy Storage System (BESS), Distribution Systems.

1. INTRODUCTION

In the contemporary power landscape, maintaining system stability and reliability amidst rising electricity demand presents significant challenges, as noted in the study by Butt, O. M. 2021, Recent advancement in smart grid technology [1]. To address these concerns, the power grid is undergoing a major transformation, shifting towards a more decentralized structure. A key aspect of this transition is the integration of renewable Distributed Generation (DG) units directly at distribution load buses, which has emerged as a prevalent trend in modern energy systems. These DG units are small-scale power generation facilities strategically located near end-users and are collectively referred to as Renewable Energy Sources (RES) [2][3]. Unlike conventional centralized power generation methods, the Distribution Network (DN) is evolving towards a more distributed and decentralized model, ensuring greater flexibility and efficiency in energy delivery [4].

This research focuses on methodologies and technologies that optimize the seamless integration of RES into distribution networks. It underscores the significance of decentralized power systems in enhancing reliability, sustainability, and overall grid performance [5]. However, a major challenge in integrating RES is the inherent variability in power generation. These variations can compromise grid stability, introduce reliability concerns, and result in energy supply shortfalls [6].

To address these challenges, various approaches have been adopted for efficient energy management in modern smart grids. Among these solutions, Battery Energy Storage System (BESS) stands out due to its superior adaptability and controllability [7]. BESS exhibits rapid and stable response characteristics, along with environmental benefits and geographical independence, making it a preferred choice over alternative energy storage solutions.

With the growing emphasis on green energy solutions, BESS are expected to play an increasingly pivotal role in balancing electricity supply and demand. By integrating BESS with RES, including wind and solar generators (DG), a wide range of functions across different sectors can be realized. The integration of BESS with RES, specifically distributed generators like wind and solar, provides a versatile set of relevance across various sectors. These applications include energy storage, effective load management to meet fluctuating power demands, enhanced grid stability, and peak load shaving, all of which contribute to improved effectiveness and reliability of the power grid [8].

The primary intentions of this research are outlined as follows:

a. Optimal Allocation of BESS in IEEE 33 and IEEE 34 Bus Test Systems
b. Minimization of Power Losses in IEEE 33 and IEEE 34 Bus Test Systems
c. Voltage Profile Enhancement under Different Operating Conditions
d. Comprehensive Analysis of BESS Integration Using ETAP Simulation

For these objectives structure of the Paper, sequence is: Section 1 familiarizes the paper. Section 2 defines the detailed analysis of BESS. Section 3 describes the previously reported research work.

1.1. Battery Energy Storage Systems (BESS)

A **BESS** is an energy storage solution that utilizes batteries to store and distribute electrical energy efficiently. Its primary function is to capture energy from various sources, store it in rechargeable batteries, and release it when needed. The key apparatuses of a BESS include the following parts [9].

Electrochemical Battery Technologies:

Grid-connected electrochemical storage systems are evaluated based on key parameters such as energy density, efficiency, lifespan, and cost, as analyzed and discussed in the literature [9]. The electrochemical characteristics of lithium-ion batteries are defined by their chemical structure, which consists of a lithium metal oxide as the cathode and graphite as the anode. This expertise is known for its high efficiency.

1.1.1. Power Electronics DC-AC Converter:

Battery energy storage systems interface with the AC distribution grid through power electronics converters [10]. While the Power Conditioning System (PCS) currently accounts for a smaller fraction of the total system cost, the ongoing reduction in battery cell prices is likely to make the PCS a more significant cost component. As a result, it becomes crucial to develop highly efficient and reliable power electronic converters to reduce the overall ownership costs.

1.1.2. Battery Management System (BMS):

The BMS is a crucial component of any lithium-ion Energy Storage System, tasked with performing several critical safety functions. In contrast to the Energy Management System [12], the BMS does not oversee energy distribution across the system. Its main role is to protect the battery from damage by ensuring that each cell operates within safe limits for State of Charge (SOC), voltage, current, and temperature under various operating conditions.

1.1.3. Energy Management System (EMS):

The EMS is accountable for coordinating the dispatch operations of the Energy Storage System (ESS). It directly communicates with the PCS and BMS to efficiently manage on-site components, often using external data inputs for optimization [13]. The EMS determines the optimal timing and method for dispatching stored energy, primarily based on financial strategies such as demand-charge supervision, time-of-use negotiation, and solar self-consumption.

1.1.4. Safety Systems:

A BESS incorporates several safety features based on its operating and eco-friendly conditions. These include fire suppression systems, smoke detectors, and heating, ventilation, and air conditioning systems. To ensure safe and reliable operation, a dedicated control and monitoring system is employed to mitigate risks and prevent incidents such as fires or other hazardous events.

1.2. System Performance Calculation

The functioning of the system can be scrutinized only after installment of BESS. After the BESS is set up in the system, the voltage deviation and power losses are detected.

1.2.1. Voltage Deviation Index (VDI):

To estimate %VDI, Equations (1) and (2) are utilized.

$$\%VDI_i = max_i^T\left(\frac{|v_{ref} - v_{bi}|}{v_{ref}}\right)100 \qquad (1)$$

Equation 1:

- Purpose: Calculates the voltage deviation percentage at the *ith* bus.
- v_{ref}: Reference voltage (typically 1 p.u. or nominal voltage).
- v_{bi}: Actual voltage at bus *i*.
- max_i^T: Maximum deviation over time or operation duration *T*.
- Interpretation: Measures how far the bus voltage deviates from the reference, in percentage.

$$\%VDI = \sum_{i=1}^{N} \%VDI_i \qquad (2)$$

Equation 2:

- Purpose: Provides the total system-wide VDI
- N: Total number of buses in the system.
- Interpretation: Aggregates all individual bus voltage deviations to assess overall system voltage profile.

1.2.2. Power Loss:

Equation 3: Active Power Loss:

- Represents: Real energy loss (in kW) due to resistance in distribution lines.
- Depends on: Current squared and line resistance.

$$P_L = \sum_{s=1}^{M} P_L^1 \qquad (3)$$

Here, P_L represents Active Power Loss.

Equation 4: Reactive Power Loss:

- Represents: Energy loss (in kVAR) due to reactance in distribution lines.
- Also depends on: Current squared and line reactance.

$$Q_L = \sum_{s=1}^{M} Q_L^1 \qquad (4)$$

Here, Q_L represents Active Power Loss.

Equation 5: Apparent Power Loss:

- Represents: Total power loss (in kVA), combining both active and reactive losses.
- Formula: Calculated using the Pythagorean theorem.

$$s_L = \sum_{s=1}^{M} s_L^1 \qquad (5)$$

Here, s_L represents Active Power Loss.

S defines the total branch count, and M represents the number of branches. Equations (3), (4), and (5) are computed and compared with without BESS in the distribution systems.

2. LITERATURE SURVEY

Several researchers have explored strategies to minimize transmission losses and improve voltage profiles in renewable energy-integrated distribution systems. Studies by Barla et al., Mohan Chaitanya et al., and Dipu Sarkar et al. [7] optimized the placement and sizing of BESS in wind and solar integrated IEEE 33-bus networks. Meanwhile, Yuvaraj T. et al. [13] utilized a cuckoo search optimization algorithm to allocate Distributed Generators (DG) and Distribution Static Compensator (DSTATCOM) units in a radial IEEE 34-bus system. The line impedance and load profiles used were based on data from Chis M. et al., M. A. Salama et al., and Shesha Jayaram et al. [14], who addressed capacitor placement using heuristic methods.

Korra B. et al. [15] anticipated a novel metaheuristic algorithm for optimal DG siting and sizing. A comprehensive review covering optimization techniques, constraints, and emerging issues was presented by Hannan M. A. et al. [16], while RicValencia et al. [17] detailed strategies for selecting and operating both RES and BESS. Research by Pompern Natsawat et al. and Boonluk Panyawoot et al. [18][19] focused specifically on BESS deployment in RES integrated distribution networks.

The application of BESS sizing has been categorized into microgrids, distributed and hybrid RES, and unconventional energy plants [20]. Yang Yuqing et al. [21] provided an in-depth analysis of BESS integration in PV systems for minimizing energy losses. Das Choton K. et al. [22] focused on BESS sizing for renewable systems. A holistic review of optimal sizing in hybrid PV-wind systems was offered by A.S. Al Busaidi et al., H.A. Kazem et al., A.H. Al-Badi et al., and M. Farooq Khan et al. [23].

Kumar et al. [24] emphasized the versatile support services BESS can provide, including acting as backup power. Studies by Ralon Pablo et al. [25] examined various BESS technologies, including lead-acid, UltraBattery, and NaS. Figgener Jan et al. [26] highlighted the widespread adoption of Li-ion batteries, particularly in Germany. According to Tsiropoulos Ioannis et al., Dalius Tarvydas, and Natalia Lebedeva et al. [27], falling Li-ion costs are driven by electric vehicle market growth. Kempener Ruud and Eric Borden [28] project continued cost reductions due to maturing technologies, although Olatomiwa et al. [29] noted that economic challenges still limit large-scale BESS adoption.

Issues such as suboptimal dispatch strategies can cause operational inefficiencies and accelerated degradation, as discussed by Jinqiang et al. [30]. Research in [31] investigated optimal BESS sizing and placement to mitigate congestion in Northern Ireland's distribution systems. A revenue-maximizing approach for peak shaving and frequency control was proposed in [32]. Study [33] introduced a method for maximizing profit while maintaining voltage support through optimally located multiple BESS in radial networks.

A multiscale framework for BESS planning and operation was presented in [34]. PV-dense networks were studied in [35], evaluating how BESS sizing impacts performance and investor returns. Studies [36], [37] discussed the financial benefits of increasing BESS capacity for unified market participation in Ireland. However, [38] found that market-only participation may not ensure a return on investment.

3. METHODOLOGY ADOPTED

This research focuses on the IEEE 33 and IEEE 34 systems to evaluate transmission loss minimization and voltage profile enhancement through the optimal placement and sizing of BESS in wind and solar RES integrated networks.

3.1 System Description

- The IEEE 33-bus system entails 33 buses and 32 distribution lines, operating at a voltage level of 12.66 kV.
- The IEEE 34-bus system entails 34 buses and 33 distribution lines, operating at a voltage level of 11 kV.

3.2 Placement of Wind Turbine Generators (WTG)

To introduce renewable energy integration into the system, WTG are strategically placed at specific buses based on previous research findings [7]. Table 1 below summarizes the placement of WTGs in the IEEE 33-bus system:

Table 1: RES location

Name of RES	**WTG**
Quantity	2
Bus Location	18 and 24
Measurements	1 MW each

The selection of these locations ensures maximum power generation efficiency while maintaining grid $s_L$stability.

3.3 Placement of BESS

The study explores various scenarios of BESS placement to assess their impact on reducing distribution losses and controlling voltage fluctuations in the system. Different locations were chosen, which provided the best results in both the IEEE 33 and IEEE 34 test systems, as outlined in Table 2 below:

Table 2: Locations of BESS

Scenario	**IEEE 33 Bus System**	**IEEE 34 Bus System**
Location of BESS	Bus No. 6, 7, and 26	Bus No. 4 and 8

4. JUSTIFICATION OF RESULTS AND DISCUSSIONS

To inspect the efficacy of the projected methodology, two scenarios with separate case studies have been conducted. This part describes the results of optimally placing the BESS in two different distribution systems, namely the IEEE-33 and IEEE-34 test systems. ETAP software simulation is carried out and the output results are shown in the following tables, which are depicted in the graphs shown below. There are a total of 2 cases. 4 cases in each scenario are examined:

i. Case 1(a) and 2(a): Allocation of a WTG at bus no. 18 and 24
ii. Case 1(b) and 2(b): Allocation of a WTG at bus no. 18 and 24 with the integration of BESS

4.1 Allocation of a wind turbine generator (WTG) in IEEE 33 Bus Distribution System

The optimal allotment for BESS connected in the IEEE 33 system is primarily attained in the backing of two conditions, i.e., drop in power loss and decrease in voltage deviation. Two different cases are considered for a fair comparison of the proposed methodology. Table 3 indicates the losses achieved and %VDI values of the IEEE 33 system. It was detected that the value of power loss was higher i.e. 0.203 MW and 0.136 Mvar, before installation of the RES and BESS in the base case.

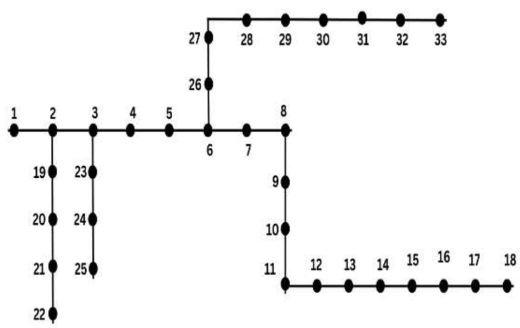

Figure 1: IEEE-33 Bus system single line diagram

4.1.1 Optimal allocation of BESS for the reduction in power loss

Power loss minimization in distribution systems can help to improve reliability and decrease economic loss. To achieve this wind turbine generators and BESS are optimally placed on different buses.

In Case 1(a), the WTG of 1 MW are placed on buses no. 18 and 24 in the IEEE 33 system. Table 3 depicts the outputs acquired in this case. This results in minimized losses of 0.124 MW and 0.09 Mvar.

In Case 1(b), after the installment of BESS at bus no. 6, 7, and 26 in the same case, the losses are further reduced to 0.082 MW and 0.065 Mvar. Comparison of Power Losses in Case 1(a) and Case 1(b) are shown in Figure 2.

Table 3: Analyses of Results of Case 1(a) and Case 1(b)

Parameters	Base case	WTG at bus 18 and 24	
		WTG	WTG with BESS
Losses (MW)	0.203	0.124	0.082
Losses (Mvar)	0.136	0.09	0.065
Min. Voltage (V)	91.309	93.557	95.378
%VDI	5.156	2.690	0.968

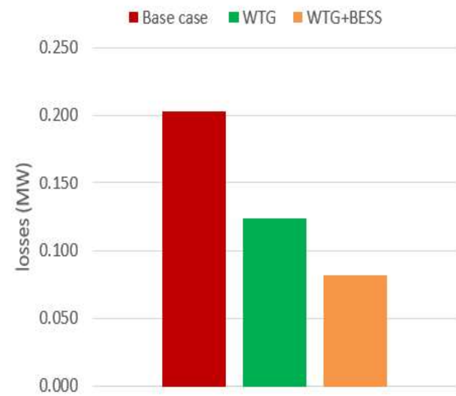

Figure 2: Case 1(a) and Case 1(b): Comparison of Power Losses

4.1.2 Optimal allocation of BESS for the reduction in voltage deviation

The VDI is the variance between the predictable and actual voltage levels in a power distribution system.

In Case 1(a), the 1 MW wind turbine generators (WTG) are placed on buses no. 18 and 24 in the IEEE 33 system. Conferring to the outputs shown in Table 3, the value of %VDI decreased from 5.156 to 2.690. The minimum voltage is achieved at 93.557MW, which was 91.309MW before the placement of the WTG

In Case 1(b), after the installation of BESS at bus no. 6, 7, and 26 in the same case, the value of %VDI in this case further decreased to 0.968. The minimum voltage after the BESS installation is achieved at 95.378MW.

Voltage Profile of Case 1(a) and Case 1(b) are represented in Figure 3. Here vertical line represents the minimum voltage (V)

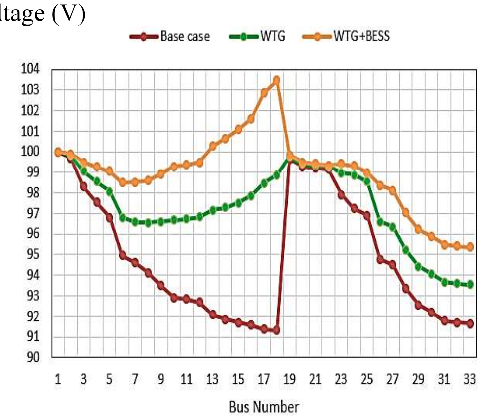

Figure 3: Case 1(a) and Case 1(b): Voltage Profile

4.2 Allocation of a wind turbine generator (WTG) in IEEE 34 Bus Distribution System

The optimal allotment for BESS installed in the IEEE 34 system is primarily attained in the backing of two cases considered for a fair comparison of the proposed methodology. Table 4 specifies the losses achieved and %VDI values of the IEEE 34 system in three different cases. It was observed that the value of power loss was higher, i.e., 0.222 MW and 0.065 Mvar, before the installation of the RES and BESS in the base case.

Table 4: Analyses of Results of Case 2(a) and Case 2(b)

Parameters	Base case	WTG at bus 18 and 24	
		WTG	WTG with BESS
Losses (MW)	0.222	0.183	0.165
Losses (Mvar)	0.065	0.053	0.047
Min. Voltage (MW)	94.166	96.714	97.102
%VDI	3.426	2.289	1.957

4.2.1 Optimal allocation of BESS for the reduction in power loss

In *Case 2(a)*, the wind turbine generators (WTG) of 1 MW are placed on buses no. 18 and 24 in the IEEE 34 system. Table 4 depicts the outputs acquired in this case. This results in minimized losses of 0.183 MW and 0.053 Mvar. In *Case 2(b)*, after the installation of BESS at bus no. 4 and 8 in the same case, the losses are further dropped to 0.165 MW and 0.047 Mvar.

These results justify that the power loss minimization in distribution systems can help to improve reliability and decrease economic loss by installing wind turbine generators and BESS on different buses.

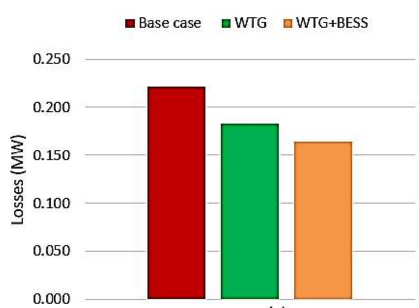

Figure 4: Case 2(a) and Case 2(b): Comparison of Power Losses

4.2.2 Optimal allocation of BESS for the reduction in voltage deviation

In *Case 2(a)*, the 1 MW WTG are placed on buses no. 18 and 24 in the IEEE 34 system. According to the outputs shown in Table 4, the value of %VDI also decreased from 3.426 to 2.289. The minimum voltage is achieved at 96.714MW, which was 94.166MW before the placement of the WTG.

In *Case 2(b)*, after the installation of BESS at bus no. 4 and 8 in the same case, the value of %VDI in this case further decreased to 1.957. The minimum voltage after the BESS installation is achieved at 97.102MW. Representations of Voltage Profile of Case (2a) and case 2(b) are shown in Figure 5.

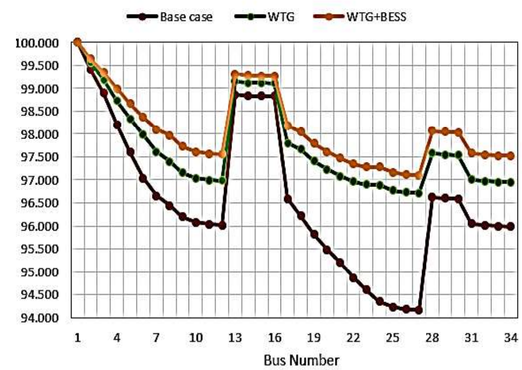

Figure 5: Voltage Profile of Case 2(a) case 2(b)

5. CONCLUSION

This study systematically investigates the optimal placement and sizing of BESS in distribution systems integrated with RES. The primary objectives are to decrease total power losses and improve voltage stability by minimizing the VDI. The effectiveness of the proposed approach is quantitatively demonstrated through mathematical formulations that assess system performance under various BESS configurations.

To validate the methodology, simulations were conducted on the IEEE 33-bus and IEEE 34-bus systems. These simulations were carried out using ETAP software, which enabled detailed and accurate modeling of the power system, including BESS and RES integration. The results clearly demonstrate that the proposed strategy significantly improves system performance by reducing both real power losses and voltage deviations across the network. The findings align with earlier studies but provide enhanced precision due to improved methodology. While prior studies reported limited improvement, this approach achieves significantly better outcomes.

The findings provide valuable insights for power system operators and planners, highlighting the potential of BESS as a critical asset for enhancing grid reliability, operational efficiency, and the amalgamation of renewable energy. This methodology serves as a practical framework for future implementations in real-world power distribution networks.

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