Battery Energy Storage Systems: Optimal Sizing and Placement for Distribution System

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***Abstract*—Grid in the current era is witnessing a rapid integration of innovative technologies. Renewable Energy Sources (RES) are being introduced on a large scale along with the implications related to these sources. One of the important aspects of the RES is its intermittency. The introduction of Battery Energy Storage System (BESS) in distribution systems is therefore very essential. BESS is utilized for improving grid parameters and for straightening the load curve. BESS helps reduce the effect of RES intermittency on the grid and improves reliability. Optimal Sizing and Placement (SaP) of BESS can help improve the system's economics and reduce the power losses in the system. In this paper, BESS SaP is optimized for the standard IEEE 33 bus system. Different approaches are used for obtaining the optimized placement and size of BESS. Manta Ray Foraging Optimization (MRFO) method is used to obtain the optimal solution. MATLAB is used for implementing the optimization methods.**

***Index Terms*—Battery Energy Storage System, Distribution System, Power Loss, Manta Ray Foraging Optimization**

I. Introduction

Electricity is a primary need of human society. All activities are dependent on the availability of power. The current grid consists of different types of loads as well as generation sources. RES have penetrated the grid and their contribution to the total generation has been increasing at a fast pace. RES is stochastic in nature and the grid cannot be made dependent on such sources. BESS is therefore one of the important requirements of the grid. It provides flexibility, reliability, and stability to the grid. BESS can also be applied for the provision of power in case of failures. The mitigation of intermittent supply by the RES can also be achieved through BESS [1], [2].

The cost of BESS has been seeing a southward trend. Still, it is not possible and efficient to install BESS on every bus [3]. Optimal SaP of BESS can help the grid realize economic benefits. On the other hand, an oversized BESS will be responsible for increasing the burden on the exchequer [4], [5].

The problem of SaP of BESS is not simple and linear but a complex non-deterministic problem. The variation in obtaining an optimal combination may come from sizing, the number of locations, generation/load of the system, topology, etc [6]. A lot of possibilities exist and the complexity further increases with the increase in the number of buses.

A two-step approach is applied in [6], [7] to find the solution to a SaP problem. The two-step approach in [7] tries to solve the SaP with the objective of reducing losses, improving voltage, and minimizing costs. The same objective is minimized in both steps successively. Genetic algorithm is applied in [7] on an IEEE 13 bus system. In [6], different approaches are applied to solving the SaP problem. It applies Whale Optimization algorithm on a 48-bus system with the objective of reducing losses in the system.

The authors in [8] have included the effect of the duck curve in the SaP problem. Whale optimization algorithm is proposed to solve the problem for a 48-bus system with the objective of reducing the losses. The number of BESS is also considered part of the SaP problem in [9]. The objective of reduction in costs and losses and an improved voltage profile for an Italian distribution network and a modified IEEE 34 bus system is achieved through clustering and sensitivity analysis.

Benders decomposition technique in conjunction with model predictive control is implemented in [10] for solving the SaP problem. The objective of the SaP problem is considered to be the optimal utilization of solar photovoltaic power while minimizing the degradation of the BESS. A CIGRE test grid having 14 nodes is used as a test system. The SaP problem is disintegrated into a master problem and multiple subproblems. In [11], SaP is solved through different optimization techniques like Particle Swarm Optimization (PSO), Differential Evolution (DE), and Reducing Variable Trend Search (RVTS).

SaP has been solved through evolutionary optimization techniques in a number of publications. The evolutionary optimization techniques are robust and easily adapt according to the problem being solved. The SaP problem however has a lot of local optima which makes it very difficult to obtain the optimal results. Manta Ray Foraging Optimization (MRFO) [12] method is applied to present the solution in this paper. Other optimization techniques, like PSO and DE were used to confirm the results.

The main contributions of this research work are:

1) Optimal SaP for BESS is achieved for standard IEEE 33 Bus system
2) Different approaches are employed and compared for BESS placement.
3) The number of buses at which the BESS shall be located are varied and compared.
4) Solar PVs are placed in the distribution system to analyze the effect of BESS placement.

II. Problem Formulation

RES is being integrated and its role in the grid is increasing exponentially. Wind and solar are the main components of RES. Solar produces energy during the day hours when solar irradiation is available. On the other hand, wind turbine produces energy when the wind is available in a proper structure like speed, direction, etc. The grid cannot function in a smooth manner while depending on the RES like solar and wind, due to their intermittency. To counter this demerit, BESS can be introduced in the distribution systems. The BESS shall store excess energy when the RES generates more than the load and will provide energy to the grid when the load exceeds the generation.

In the research work presented in this paper, the BESS is placed optimally in the distribution system, which is represented by the standard IEEE 33 bus system. The system considered is a radial distribution system. Different approaches are applied to obtain the optimal solution to the SaP problem. The objective of the SaP problem is minimizing losses in the system and is represented through Eq 1.

$$OF = min \sum_{t=1}^{N_t} |I_t|^2 R_t \tag{1}$$

where N_t is the total number of transmission lines

I_t is the current in line 't'

R_t is the resistance of line 't'

Subject to Eq 2 and Eq 3:

$$V_{min} \leq V_b \leq V_{max} \tag{2}$$

$$P_{BESS_{min}} \leq P_{BESS_i} \leq P_{BESS_{max}} \tag{3}$$

The constraints signify the limits of bus voltages and power being considered from the BESS.

The line and bus details of the 33 bus system as presented in Table I and II, respectively.

The SaP is solved through different approaches as presented in Fig 1.

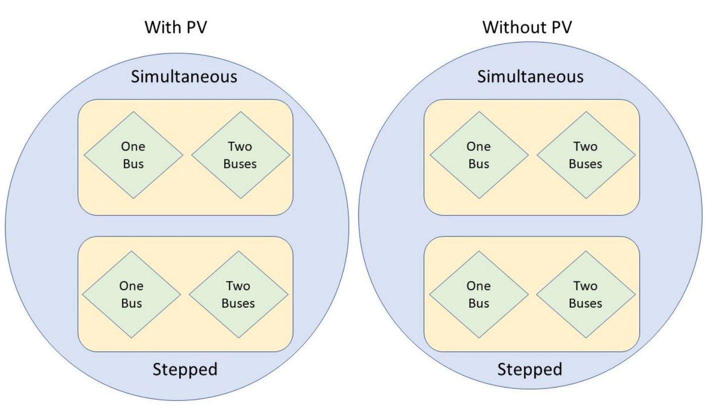

Fig. 1. Different Approaches

In the research presented in this paper, the different scenarios are considered. The classification of these scenarios are: with and without PV being present in the distribution system, simultaneous and stepped optimization and BESS at a single bus or two buses. Under the first classification, the SaP problem is optimized while considering the presence or absence of PV systems. On the other hand, the scenarios are also classified as simultaneous and stepped. In simultaneous approach, the size and placement of BESS are optimized simultaneously whereas in a stepped optimization process, the location of the BESS is first obtained after which the sizing of the BESS is optimized for respective locations. Lastly, the SaP problem is optimized, when the BESS is placed at a single

TABLE I
LINE DATA

Sr. No	From Bus	To Bus	R	X
1	1	2	0.0922	0.0470
2	2	3	0.4930	0.2511
3	3	4	0.3660	0.1864
4	4	5	0.3811	0.1941
4	5	6	0.8190	0.7070
6	6	7	0.1872	0.6188
7	7	8	0.7114	0.2351
8	8	9	1.0300	0.7400
9	9	10	1.0440	0.7400
10	10	11	0.1966	0.0650
11	11	12	0.3744	0.1238
12	12	13	1.4680	1.1550
13	13	14	0.5416	0.7129
14	14	15	0.5910	0.5260
15	15	16	0.7463	0.5450
16	16	17	1.2890	1.7210
17	17	18	0.7320	0.5740
18	2	19	0.1640	0.1565
19	19	20	1.5042	1.3554
20	20	21	0.4095	0.4784
21	21	22	0.7089	0.9373
22	3	23	0.4512	0.3083
23	23	24	0.8980	0.7091
24	24	25	0.8960	0.7011
25	6	26	0.2030	0.1034
26	26	27	0.2842	0.1447
27	27	28	1.0590	0.9337
28	28	29	0.8042	0.7006
29	29	30	0.5075	0.2585
30	30	31	0.9744	0.9630
31	31	32	0.3105	0.3619
32	32	33	0.3410	0.5302

TABLE II
BUS DATA

Bus No	P	Q	Bus No	P	Q
1	0	0	18	90	40
2	100	60	19	90	40
3	90	40	20	90	40
4	120	80	21	90	40
5	60	30	22	90	40
6	60	20	23	90	50
7	200	100	24	420	200
8	200	100	25	420	200
9	60	20	26	60	25
10	60	20	27	60	25
11	45	30	28	60	20
12	60	35	29	120	70
13	60	35	30	200	600
14	120	80	31	150	70
15	60	10	32	210	100
16	60	20	33	60	40
17	60	20			

bus in the distribution system and at two buses in the system. Thus the SaP is optimized for a total of 8 scenarios as can be observed from Fig 1.

The optimization for all the scenarios is performed through MRFO which is implemented using MATLAB software.

III. Manta Ray Foraging Optimization

The Manta Ray Foraging Optimization method is derived from the foraging behavior of Manta Rays [12]. The foraging behavior is classified and mathematically modeled through three processes, i.e., chain, cyclone, and somersault foraging.

In the first foraging pattern, the manta ray moves towards positions with a higher concentration of planktons. The best solution till the current iteration can be used for this movement. However, the manta ray does not move individually toward the higher concentration position. Instead, they form a head-to-tail chain. Thus a manta ray is guided towards the best position through the manta ray ahead of it.

The cyclone foraging behavior indicates plankton recognition in deep waters. The manta rays shall form a long chain and move spirally. Thus in this part of foraging, not only does a manta ray follow the manta ray ahead of it but it also moves spirally towards the food. Exploitation is achieved through this part of the foraging. For some manta rays, random positions are generated and this helps in the exploration of the search space as well.

In the last part of the foraging, the food is viewed as a pivot around which each individual manta will somersault. Thus the name of somersault is given to it. The food around which the manta rays will somersault is the best position found so far. This is quite similar to convergence in other optimization techniques.

The equations used for realizing MRFO are explicitly presented in [12] and are thus not repeated here for simplicity.

IV. Results and Discussion

SaP problem is implemented on IEEE 33 bus system in this paper. The SaP problem is complex, and different approaches are explored, with each approach being presented as a scenario. Different scenarios considered while solving SaP are presented in Table III.

TABLE III
Different Scenarios

Sr. No	PV / Without PV	Simultaneous / Stepped	One / Two Bus
1	Without PV	Simultaneous	One
2	Without PV	Stepped	One
3	Without PV	Simultaneous	Two
4	Without PV	Stepped	Two
5	PV	Simultaneous	One
6	PV	Stepped	One
7	PV	Simultaneous	Two
8	PV	Stepped	Two

The maximum capacity of the BESS that can be placed is considered to be 60% of the total load. In case the BESS is being placed at two buses, their sum should not be greater than 60% of the total load in the distribution system. The solar PV generation being introduced is placed on buses 24 and 25 with a capacity of 500kW each.

The results presented in this paper are obtained by executing MRFO method for each scenario for 40 number of executions.

After obtaining the results, it was observed that in the scenarios involving BESS placement at a single bus, the results were similar for both the simultaneous and stepped approaches.

For scenarios 1 and 2, MRFO was able to obtain a near constant result of 141.5045kW loss when the BESS is placed at bus 7 with a capacity of 2250KW. A similar result is obtained for scenarios 5 and 6, with a loss of 123.9754kW for placing BESS with a capacity of 2250kW at bus 7.

In scenario 3, the minimum loss of 110.6098kW is obtained by placing the BESS at bus 30 and 13 with a capacity of 1214.8kW and 856.78kW, respectively. The total BESS capacity is 2071.58kW.

In case of scenario 4, a constant output objective of 151.6819kW is obtained. In all the executions, it is found that bus 30 should have BESS of capacity 1632.06kW. However, for the second bus, there are multiple variations and sizes. The minimum BESS capacity obtained is of 92.0172kW which is required to be placed on bus 14.

For the output of scenario 7, a constant loss of 91.352kW can be observed with the BESS being placed at buses 30 and 14. The BESS capacity at these buses is 1127.9kW and 768.42kW, respectively.

Lastly, in scenario 8, a loss of 127.2237kW is achieved. The BESS is placed on bus 30 and has a capacity of 1503.33kW. The second bus is not similar for all executions. The minimum BESS installation is obtained at bus 1 with a capacity of 38.8263kW.

A summary of these observations is presented in Tables IV and V.

TABLE IV
Single Bus Scenarios

Scenario No	Bus No	Capacity (kW)	Loss (kW)
1	7	2250	141.5045
2	7	2250	141.5045
5	7	2250	123.9754
6	7	2250	123.9754

TABLE V
Two Bus Scenarios

Scenario No	Bus Nos	Capacities (kW)	Loss (kW)
3	30 & 13	1214.8 & 856.78 (2071.58)	110.6098
4	30 & 14	1632.06 & 92.02 (1724.08)	151.6819
7	30 & 14	1127.9 & 768.42 (1896.32)	91.352
8	30 & 1	1503.33 & 38.83 (1542.16)	127.2237

Table IV contains the results of all the single bus scenarios. From the table, it can be observed that similar results are obtained for stepped and simultaneous approaches. The BESS installations in these scenarios are equal to the maximum allowable limits. Also, the losses taking place in the system are similar. In the table, the first two scenarios do not have

PV installations in the system, whereas the PV installations are considered in the remaining two scenarios.

In Table V, the scenarios considered have two buses on which the BESS is proposed to be installed. It can be observed that when the SaP problem is solved simultaneously in scenarios 3 & 7, more BESS capacity is utilized, and the losses are also less as compared to corresponding stepped approaches implemented in scenarios 4 & 8. However, none of the methods have utilized the maximum BESS capacity. The buses on which the BESS should be installed are also not similar when simultaneous and stepped approaches are adopted.

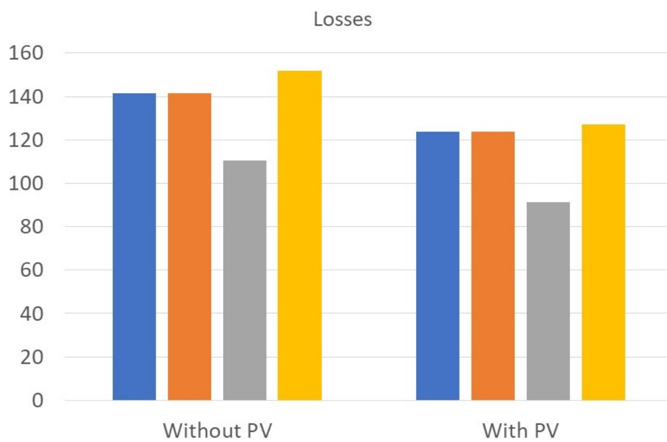

Fig. 2. Loss Variations for with / without PV Installation

In Fig 2, the losses are compared based on the inclusion of PV in the system. The graph shows system losses for scenarios 1-4 in the first group and scenarios 5-8 in the second group. It can be observed that when PV is not included in the system, the losses remain constant for single-bus BESS installations. However, for two-bus BESS installations in scenario 3, the losses fall remarkably by 21.83% for the simultaneous approach. In this scenario, the cumulative BESS capacity installed on two buses is lesser than on single-bus approaches. On the other hand, in the two-bus stepped approach even though the installation capacity for BESS reduces further, the losses increase by 7.2% as compared to single-bus scenarios.

In the case of inclusion of PV in the system, a 26.31% reduction in losses is observed between single bus scenarios (5 & 6) and two bus, simultaneous approach, i.e., scenario 7. An increase in losses is observed in this case as well for the stepped approach in scenario 8. The losses increase by 2.62% in a stepped two-bus approach as compared to single-bus scenarios.

As a last part of observations, Fig 3 gives the change in losses for corresponding scenarios with and without PV. It can be seen that for single bus scenarios, the loss in the system reduces by 12.38%, in stepped and simultaneous approaches. In the two-bus simultaneous approach, the loss reduction is 17.41%, whereas, for the stepped approach, the loss reduction is 16.12%.

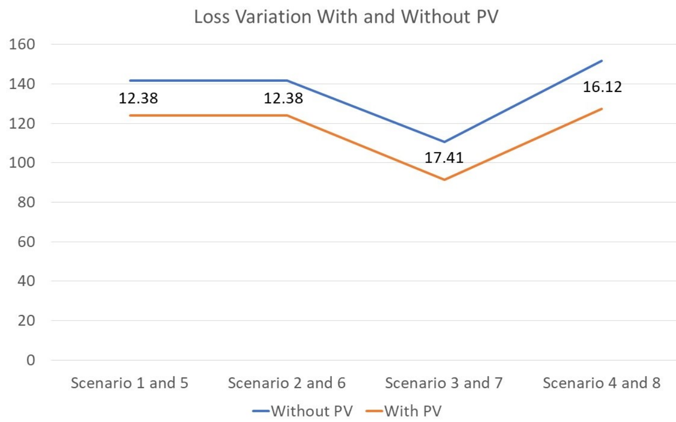

Fig. 3. Loss Variation With and Without PV

V. Conclusion

The SaP problem is a complex problem. The output of this problem can directly affect the economics of the distribution system. The basic objective of a SaP problem is the reduction in losses. The secondary objective can be a reduction in BESS installation cost through optimized sizing. It was found through simulation that a simultaneous optimization of location, as well as sizing, gives far better results as compared to any other approach. The losses are reduced as well as the sizing of the BESS is also optimized.

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