Optimal Battery Energy Storage System Placement Using Whale Optimization Algorithm

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***Abstract*—This paper proposes a technique to attain the optimal location of battery energy storage system (BESS) where the optimal solution is decided by using whale optimization algorithm (WOA). The objective function is formulated in order to minimize the total system losses in the distribution grid. Two cases are investigated in this paper where the first case focuses on the losses reduction in the conventional power grid while the second case involves a power grid with photovoltaic distributed generation (PVDG). The proposed technique has been applied on a generic distribution network and the results show that WOA can provide the optimal solution for BESS location in the distribution network, thus reducing the total system losses.**

***Index Terms*—Metaheuristic optimization method, optimal BESS placement, whale optimization algorithm**

I. Introduction

In recent years, battery energy storage system (BESS) has emerged as a popular option in the distribution network since BESS provides a number of benefits including time shifting, voltage and grid support, spinning reserve, peak shaving and power factor correction [1], [2]. Meanwhile, for the renewable energy (RE) sources integrated distribution system, BESS enhances the performance for RE generation to become more stable and reliable by providing network support such as smoothing the output from renewable generation, providing ride through capability during loss of generation, and also supplying power during high load demand by storing power when the load demand is low [3]-[5]. Nevertheless, the installation of BESS requires optimal planning since the placement of BESS at each bus in the power system may impose high investment cost to the utilities [6]. In [7], the sensitivity matrix based on bus voltages was computed to obtain the optimal sitting of BESS considering various number of clusters. The results suggested that BESS was constantly being located at critical bus despite the number of cluster. Meanwhile, Benders decomposition method was introduced in [8] and [9] to optimally decide the placement and capacity of BESS in low voltage grid. This method decreased the difficulty of computation process due to the long prediction horizons by modelling the BESS allocation problem into main function and sub-function. A multi-integer linear programming based algorithm with multistage operation was proposed in [10] to attain the optimal sitting and size of BESS which reduced the wind curtailment in a power network with high penetration of wind power. Meanwhile, a mixed-integer non-linear programming method has been proposed by [11] for optimal placement and sizing of BESS where a demand response program was utilized to reduce the system cost more effectively. Apart from the mathematical optimization methods, some work proposed metaheuristic optimization algorithms to obtain solutions for the BESS allocation problem where these algorithms are well-known for the simplicity in implementation, free from complicated computation and capability to escape from local optimal point [12]. Genetic algorithm (GA) is one of the first metaheuristic techniques reported in [13], and [14]. This technique has been employed by [15] for the optimal placement of the BESS in order to reduce the cost that related with the power losses. In [16], GA has been utilized to determine the optimal allocation of ESS to solve the inconsistency of power generation in smart grid, considering the network losses and cost reduction. Besides, particle swarm optimization based weighted minimum module ideal method has been introduced as well in [17] to obtain the optimal size and location of the BESS where the BESS was used to improve the voltage reading and the active power adjustment ability in the active distribution network. Other metaheuristic algorithms such as firefly algorithm and bat algorithm were proposed as well for the optimal allocation of BESS with the purpose of mitigating the voltage deviation and also to reduce the total energy and cost for the grid operation [6], [18], [19].

Nevertheless, these aforementioned metaheuristic algorithms are known with the problems in terms of the ability to converge and to escape from local optimum. Fortunately, whale optimization algorithm (WOA) [12], possesses good exploration and exploitation ability, which are the two crucial features for the population-based metaheuristic optimization algorithm. In this paper

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the WOA is employed to perform the optimization, in the effort to attain the optimal placement of the BESS in the distribution network to minimize total losses.

II. Whale Optimization Algorithm

The WOA was introduced by authors in [12], according to the hunting pattern of humpback whales. It has two main processes, exploration process and exploitation process.

A. Exploitation Model for WOA

The exploitation process is modelled mathematically based-on the bubble-net behavior of the whales. Two components, namely shrinking encircling process and spiral position update are involved in this model.

1) Shrinking encircling process

In this process, the whales encircle their prey after they detect the location of the prey. Since the location for optimal solutions in the search space is not identified earlier, the solution attained by the current best candidate will be assumed as the target prey. The updating process of the locations for other searching agents will be carried out accordingly after the best agent is determined. This behavior can be expressed as:

$$\vec{D} = \left| \vec{C} \cdot \vec{X}^*(t) - \vec{X}(t) \right| \quad (1)$$

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A} \cdot \vec{D} \quad (2)$$

where t represents the current iteration, $\vec{X}$ represents the position vector and $\vec{X}^*$ represents the position vector of the current best solution. In the meantime, the coefficient vectors $\vec{A}$ and $\vec{C}$ are formulated as follows:

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a} \quad (3)$$

$$\vec{C} = 2\vec{r} \quad (4)$$

where $\vec{r}$ denotes a random vector between zero and one, while along the iteration, $\vec{a}$ decreases linearly from two to zero.

To model the shrinking encircling process, the variation of $\vec{A}$ is reduced along the iteration process where $\vec{A}$ is decided randomly between [$-a$, a]. The next location of a searching agent after the updating process is somewhere in between of the current agent location and the location of the current best agent for $|\vec{A}|$ smaller or equal to one.

2) Spiral position update

In this process, the spiral position update involves a spiral expression as given by

$$\vec{X}(t+1) = \vec{D}^t e^{bl} \cos(2\pi l) + \vec{X}^*(t) \quad (5)$$

where $\vec{D}^t$ is the distance from the whale to the target at ith iteration with the formula, $\vec{D}^t = |\vec{X}^*(t) - \vec{X}(t)|$, b is a constant which express the logarithmic spiral path, and l is a number created randomly between the interval of -1 and 1.

Equation (5) models the spiral movement of the whales according to the locations of whales and their target.

In this algorithm, it is presumed that equal probability for the whale to apply the shrinking encircling method or the spiral model for the position updating process. The general equation to update the position according to the hunting pattern of the whales during the process of exploitation is given as:

$$\vec{X}(t+1) = \begin{cases} \vec{X}^*(t) - \vec{A} \cdot \vec{D} & \text{if } p < 0.5 \\ \vec{D}^t e^{bl} \cos(2\pi l) + \vec{X}^*(t), & \text{if } p \geq 0.5 \end{cases} \quad (6)$$

B. Exploration Model for WOA

In the exploration process, the whales look for the preys randomly according to each other's position. In this process, the similar method considering the changing of $\vec{A}$ vector is utilized. The searching agents are pushed to move further from a reference whale when the value of $|\vec{A}|$ is randomly assigned to be greater than 1. The locations of the searching agents in this process are updated according to a randomly chosen searching agent. The mathematical formulations that illustrates the global search performed by WOA can be given as:

$$\vec{D} = \left| \vec{C} \cdot \vec{X}_{rand}(t) - \vec{X}(t) \right| \quad (7)$$

$$\vec{X}(t+1) = \vec{X}_{rand}(t) - \vec{A} \cdot \vec{D} \quad (8)$$

where $\vec{X}_{rand}$ represents a random position vector chosen from the current population.

III. Problem Formulation and Implementation of the Optimal Placement Method

In this paper, the BESS are optimally placed in the distribution network so as to minimize the total system losses.

The objective function, ObjFunc as shown below is formulated in order to evaluate the fitness:

$$\text{ObjFunc} = \min\left(\sum_{j=1}^{N_b} \left| I_j \right|^2 R_j \right) \quad (9)$$

where N_b represents the branch numbers in the distribution network, I_j and R_j represent the magnitude and resistance of the current for jth branch.

The optimal location of the BESS can be decided by WOA using the following steps.

i. Generate the initial population, X_i randomly with a given population size, n. Each whale agent carries the information of the potential optimal BESS bus location.

ii. Run the load flow program using Simulink for the chosen power system with PVDG and BESS. The fitness of n individuals are evaluated based on the ObjFunc as given in (9).

iii. Update the position (fitness value) of each whale agent and then update the current best candidate position.

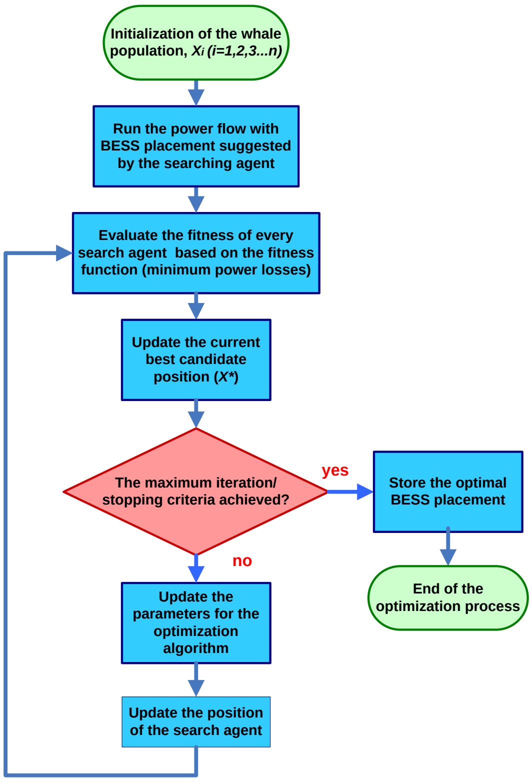

Fig. 1. Flowchart for the proposed optimal BESS placement approach.

iv. Check the stopping criteria where, in this work, it is set as the maximum number of iterations. If the stopping criteria is not achieved yet, update the distance between the whale agent and the target, as well as the coefficient vectors $\vec{A}$ and $\vec{C}$.

v. Repeat step (ii) – (iv) until the maximum number of iterations is achieved.

vi. Store the optimal location for BESS to be placed in the power system for total losses reduction.

The flowchart for the proposed BESS placement method is shown in Fig. 1.

IV. Results and Discussions

The simulation outcomes for obtaining the optimal BESS locations are presented below. The population size and the maximum iteration number for WOA are set to 50 and 20 correspondingly. The optimization processes for each case are repeated for 5 times.

In this work, a generic distribution system model with total load of 3.83 MW as illustrated in Fig. 2 is utilized for the simulation of every scenario. The load and the branch data are shown in Appendix A and Appendix B. Two scenarios are involved in this work where scenario 1 is the optimal BESS placement in the conventional distribution system while in the scenario 2, two PVDG are installed at buses with higher load demand. Each PVDG unit is assumed to have 0.5 MW generation.

A. Otimal Placement of BESS in Conventional Distribution System

Two cases are studied in Scenario 1. For case 1, a single BESS of size 1 MW is to be located optimally in the distribution network. The optimal location for the BESS is found to be placed at bus 19 where the total system losses is 96.02 kW. Comparing with the base case (without BESS and PVDG) which has total losses of 130.84 kW. Hence, a total reduction of 34.82 kW has been achieved with the optimal placement of only one BESS in the distribution network.

Meanwhile, for case 2, two BESS rated at 0.5 MW each are to be placed optimally in the system. The BESS are suggested to be located at bus 20 and bus 24 where there is further losses reduction to 73.57 kW compared to case 1. The optimal placement results for Scenario 1 are shown in Table I. It can be seen that the optimal locations suggested are the buses with heavy load or the buses which are linked with few heavy-loaded buses. The optimal placement of BESS reduces the system losses by providing the local power supply to the neighboring buses.

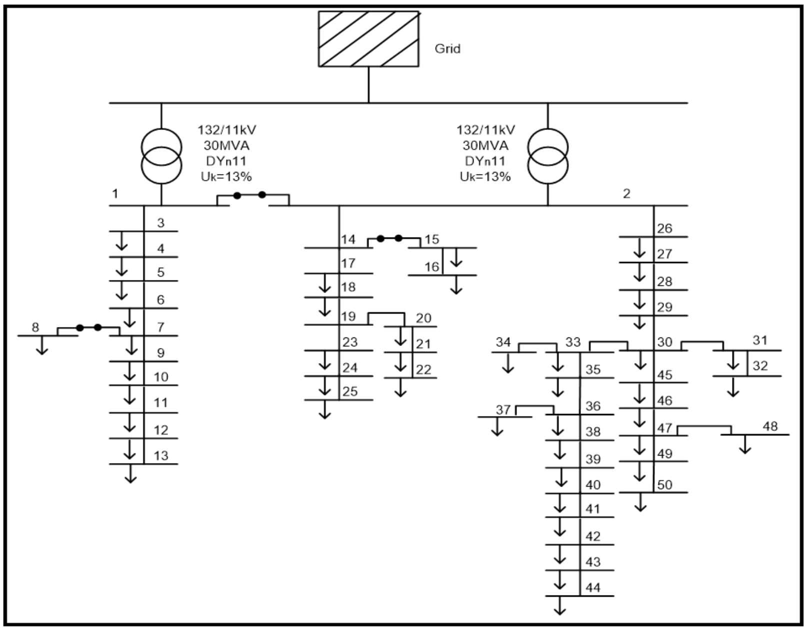

Fig. 2. Single line diagram for a generic distribution system model.

TABLE I: PERFORMANCE OF WOA IN OBTAINING OPTIMAL BESS PLACEMENT FOR SCENARIO 1

Case	Amount of BESS	BESS size (MW)	Optimal BESS Location (Bus)	Power losses (kW)
	0	N/A	N/A	130.84
Case 1	1	1	19	96.02
Case 2	2	0.5 (2 units)	20, 24	73.57

TABLE II: BESS PLACEMENT RESULT FOR SCENARIO 2

Case	Amount of BESS	BESS size (MW)	Optimal BESS location (Bus)	Power losses (kW)
	0	N/A	N/A	119.50
Case 1	1	1	24	64.05
Case 2	2	0.5 (2 units)	14, 24	51.84

Meanwhile, for case 2, two BESS rated at 0.5 MW each are to be placed optimally in the system. The BESS are suggested to be located at bus 20 and bus 24 where there is further losses reduction to 73.57 kW compared to case 1. The optimal placement results for Scenario 1 are shown in Table I. It can be seen that the optimal locations suggested are the buses with heavy load or the buses which are linked with few heavy-loaded buses. The optimal placement of BESS reduces the system losses by providing the local power supply to the neighboring buses.

B. Optimal Placement of BESS in PVDG Integrated Distribution System

For Scenario 2, two PVDG each with generation of 0.5 MW are connected at bus 18 and bus 30. A total system losses reduction of 11.34 kW compared to the base case has been achieved after the integration of PVDG into the distribution network. Similarly, two case studies as performed in Scenario 1. From case 1, which is to find the optimal location of single BESS in the PVDG integrated distribution system, it is observed that the BESS is placed at bus 24 instead of bus 19 as suggested in Scenario 1 (case 1). This is due to the placement of PVDG at bus 18 which is close to the bus 19. The local load at bus 19 in this scenario is then supplied by PVDG generation. Thus, the BESS is proposed to be located at bus 24 which is near to the end of the feeder, with high load demand as well. The total system losses in this case is reduced to 64.05 kW, which is a further reduction of 31.97 kW compared to the case 1 of Scenario 1.

On the other hand, it can be observed from case 2, the BESS are located optimally at bus 14 and bus 24 with power losses of 51.84 kW, which is 21.73 kW less than the one in Scenario 1 (case 2). It can be deduced from the results that the BESS are usually placed at heavy loaded feeder in order to reduce the supply from the grid which then reduce the power losses along the distribution lines. The results for Scenario 2 are presented in Table II.

V. CONCLUSION

In this study, the optimal location of BESS in the distribution system with and without the integration of PVDG have been decided using WOA. The goal of this study is to minimize the total system losses in the distribution system. Two scenarios have been studied where the first and second scenarios involved conventional distribution grid and the grid with PVDG integrated, respectively. Besides, the effect of different number of BESS in power losses reduction is also studied. It is found that the placement of BESS at the optimal locations effectively reduces the system losses where the BESS are typically placed at the buses with heavy loads. It is also revealed that for the same total installed BESS capacity, the distributed placement of two BESS in the system has better performance than single placement of BESS in reducing total system losses.

APPENDIX A LOAD DATA FOR GENERIC DISTRIBUTION SYSTEM

Bus Number	PL(kW)	QL (kVAr)	Bus Number	PL(kW)	QL (kVAr)
1	–	–	26	364.79	182.39
2	–	–	27	35.13	17.56
3	22.4	12.8	28	31.2	19.5
4	18.9	10.5	29	35.13	17.56
5	30.5	21.2	30	35.13	17.56
6	30.87	15.4	31	36.9	12.9
7	313.55	–375.40	32	29.8	14.3
8	154.48	15.21	33	31.1	14.9
9	30.87	15.4	34	22.1	10.1
10	25.7	14.3	35	35.1	18.0
11	19.8	12.17	36	35.13	17.56
12	25.4	14.3	37	35.13	17.56
13	38.2	14.1	38	44.2	20.8
14	–	–	39	21.6	13.7
15	789.12	394.56	40	30.4	18.2
16	13.35	6.67	41	35.13	17.56
17	192.45	96.23	42	29.5	18.1
18	192.45	96.23	43	33.2	12.8
19	–	–	44	30.2	17.5
20	120.28	60.15	45	35.13	17.56
21	135.28	70.15	46	38.2	18.6
22	85.28	54.9	47	35.13	17.56
23	144.34	72.17	48	31.4	19.6
24	144.34	72.17	49	35.13	17.56
25	144.34	72.17	50	31.2	15.4

APPENDIX B BRANCH DATA FOR GENERIC DISTRIBUTION SYSTEM

Sending end bus	Receiving end bus	R (Ω)	X (Ω)	Sending end bus	Receiving end bus	R (Ω)	X (Ω)
1	3	0.5313	0.3267	27	28	0.2532	0.1236
3	4	1.127	0.693	28	29	0.422	0.206
4	5	0.9338	0.5742	29	30	0.844	0.412
5	6	0.4267	0.2624	30	31	0.1477	0.0721
6	7	0.4154	0.2554	31	32	0.3798	0.1854
7	9	0.4347	0.2673	30	33	1.6669	0.8137
9	10	0.8211	0.5049	33	34	0.5275	0.2575
10	11	0.1449	0.0891	33	35	0.9073	0.4429
11	12	0.161	0.099	35	36	0.5908	0.2884
12	13	0.7406	0.4554	36	37	0.211	0.103
2	14	1.0363	1.143	36	38	0.211	0.103
15	16	0.053	0.0212	38	39	0.422	0.206
14	17	0.5275	0.2575	39	40	0.211	0.103
17	18	0.1055	0.0515	40	41	0.633	0.309
18	19	0.2321	0.1133	41	42	0.325	0.108
19	20	0.3798	0.1854	42	43	0.975	0.324
20	21	0.1899	0.0927	43	44	0.3575	0.1188
21	22	0.211	0.103	30	45	0.211	0.103
19	23	0.211	0.103	45	46	0.7596	0.3708
23	24	0.4853	0.2369	46	47	0.5697	0.2781
24	25	0.211	0.103	47	48	0.6541	0.3193
2	26	0.422	0.206	47	49	0.633	0.309
26	27	0.211	0.103	49	50	0.4431	0.2163

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

L. A. Wong conducted the research, analyzed the data and wrote the draft paper. V. K. Ramachandaramurthy planned the research outline, followed the research process, joined the paper writing process and proofread the final draft; all authors had approved the final version.

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