Optimal Sizing and Siting of BESS in Distribution Networks

K. Pranavi, P. Linga Reddy, S V N L Lalitha

Abstract**:** ***The penetration of renewable energy sources (RES) in the power system is increasing in the recent years. Integrating the energy storage systems (ESS) into the network can increase the reliability of the system and facilitate the penetration of renewable RES. Among different kinds of ESS, battery energy storage systems (BESS) are compact and faster. Optimal sizing and location of the BESS in network which is essential to decrease the overall cost of the system is done with Genetic Algorithm (GA). To account the stochastic nature of RES, a probabilistic approach is adopted and the optimal operation of BESS is determined using Forest Optimization Algorithm (FOA).***

Index Terms**:** ***Battery energy storage systems (BESS), Forest Optimization Algorithm (FOA), Genetic Algorithm (GA), renewable energy sources (RES).***

NOMENCLATURE

Sets and Indices

B	Set of buses for installation of BESS
ch	Script indicating charging
dis	Script indicating discharging
d	Index representing interruption
hr	Index representing hour
i, j	Network bus indices
k	Index for reinforcement
l	Index representing load state
$\mathcal{L}$	Set of load states
min	Script indicating minimum values
max	Script indicating maximum values
off-peak	Script indicating off-peak demand
peak	Script indicating peak demand
s	Index representing combined load-DG states
S	Set of combined load-DG states
y_k	Year index when reinforcement k is necessary
yr	Year index
CE_{loss}	Energy losses' cost

Variables

C_R	NPV of the DS replacement cost
E_{DS}^{rated}	Rated capacity of the DS
E_{DS}	Energy stored by the DS
NPV_{AR}	NPV of arbitrage benefit
NPV_{ECOST}	NPV of interruption cost
NPV_{LO}	NPV of losses costs
NPV_{UP}	NPV of system upgrade costs
P_{DS}	DS output power
P_{loss}	Power losses in the network
P_{DS}^{rated}	DS rated charging/discharging power
r	Replacement period of the DS
R_{kS}	Reinforcement costs
x_i	Integer decision variable to control the power rating of the DS placed at bus i
y_i	Integer decision variable to control the energy rating of the DS placed at bus i

Parameters

c	Price of the electricity
C_P	Capital cost of DS with respect to power
C_E	Capital cost of DS with respect to energy
C_M	Operation and maintenance cost of DS
F	Inflation rate
FR	Future value of replacement cost
IR	Interest value
IR'	Effective interest rate
M	Total number of required upgrades
N	Number of buses in the network
N_{yr}	Number of years in the planning period
PVF	Present value function
T_d	Duration of interruption in hours

I. INTRODUCTION

Gradual depletion of fossil fuels and environmental pollution are few of the problems faced by the conventional power system. These problems can be overcome by generating power locally using non-conventional/renewable energy sources (RES) like natural gas, wind energy, solar energy.

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This type of power generation is termed as distributed generation (DG). Stochastic nature of wind and solar energies cause fluctuations in the output power. Energy storage systems (ESS) can balance the energy mismatch in the network. BESS can store surplus power and dispatch the stored energy when necessary. BESS can provide power to loads in an island formed by contingency thereby increasing the reliability of the system and preventing loss of load [1].

Optimal allocation of VRESS (Vanadium Redox Energy Storage System) considering extreme usage of wind and solar energy, total costs is done in [2] using dynamic programming. Dynamic programming consumes more memory and long running time. Better utilization of ESS & mitigating operational risk with battery operation strategy and minimization of cost of ESS, power losses, energy purchasing cost is done in [3] using Fuzzy Particle Swarm Optimization. PSO's performance is dependent on the parameters like inertia weight and learning factors. In FPSO, fuzzy control method is used to vary the control parameters. In [4] optimal sizing of ESS in micro grid established on cost benefit analysis for grid connected and standalone modes is done using MILP (Mixed Linear Integer Problem). MILP cannot be implemented for nonlinear problems.

Optimal ESS allocation (size, location, number) is determined ensuring minimum cost, reducing losses, maintaining voltage profile in [5] using genetic algorithm (GA). In [6] optimal combination of DSs to be placed, the loads which should be shed at the time of contingencies for improving system reliability is determined using GA. Authors in [7] and [8] have implemented sizing of ESS for standalone micro-grids. In [9] an algorithm for allocation of ESS in distribution networks to defer system upgrades is presented. The authors in [10] presented a methodology for optimal sizing of ESS in micro-grids using matrix real coded genetic algorithm.

Several optimization techniques have been considered to solve the optimal sizing of ESS problem. GA has showed its supremacy in terms of accuracy and speed [11]. Probabilistic approach is adopted to account for intermittent behaviour of the system components. In this paper, the methodology is based on GA [11] and forest optimization algorithm (FOA) [12]. The main objective is to optimize the distributed storage (DS) units' allocation considering the installation, operation and maintenance costs. The optimal operation of DS units is determined at every load state using FOA. Probabilistic load and DG models, electricity prices and cost parameters of BESS are the inputs to the methodology. The outputs are optimal sizing, siting of DS units and the optimal BESS operation at each load state.

The rest of the paper is divided into four sections. The problem description is in section Ⅱ. Section Ⅲ describes the methodology and mathematical formulation. Section Ⅳ includes sample case study. The results are shown in section Ⅴ and conclusions are in section Ⅵ.

II. PROBLEM DESCRIPTION

The main objective is to find the optimal size of the BESS and its placement in the distribution network with DG considering the capital, maintenance and replacement costs of battery, costs of losses in the network, network upgradation cost and the arbitrage benefit. The inputs provided are probabilistic load, probabilistic DG models, the cost parameters of the battery, prices of the electricity during peak and off-peak hours. The outputs obtained are the power ratings of BESS and the bus number where the BESS has to be placed.

III. METHODOLOGY FOR THE SOLUTION OF THE PROBLEM

The main objective function is minimized using GA. Each chromosome denotes the size of the DS unit to be placed in the distribution network. For each population of GA, four steps are performed to estimate fitness function as shown in Fig.1 [11]. The methodology is adopted for a planning period to evaluate net present values (NPV) of system costs and profits. In the first step load modelling is done. The second step is to conduct power flow analysis at each state to obtain the system upgrades and the losses. In the third step N-1 contingency analysis is carried out so as to obtain the power to be supplied by the DS to meet the demand required for all possible islands formed. In the next step annual arbitrage benefit and interruption cost (ECOST) are determined.

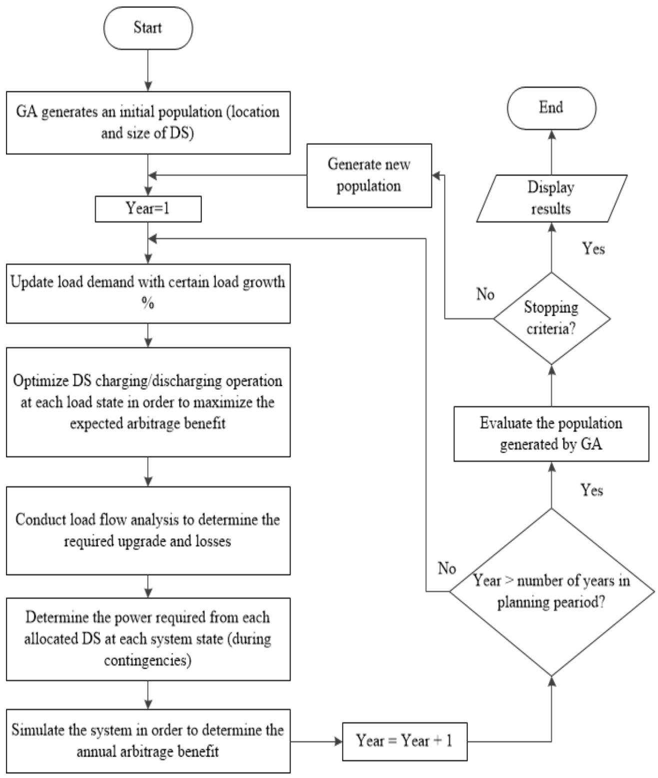

Fig. 1. Flowchart of the methodology [11]

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a. Load Modelling

The load demand is expected to follow the hourly load shape of the IEEE-reliability test system (RTS) [13]. The load data is divided into ten states as shown in TABLE I [14], where each state represent the magnitude of the load and its associated probability.

TABLE I
PROBABILISTIC LOAD MODEL [11]

Load state	Load magnitude	Probability
1	0.351	0.033
2	0.406	0.0473
3	0.451	0.0912
4	0.51	0.163
5	0.585	0.163
6	0.65	0.1654
7	0.713	0.1654
8	0.774	0.1057
9	0.853	0.056
10	1	0.01

b. DG Modelling

Intermittent DGs are modelled using probability distribution functions (PDFs). The probability density functions can be acquired from the available data of the DGs. Rayleigh PDF is supposed to be suitable for modelling wind speeds. The continuous PDFs are divided into a number of states with their associated probabilities, thereby obtaining probabilistic model for the DG. The number of states should be chosen in such a way that the easiness and accuracy of the analysis are not compromised. High number of sates improves accuracy but the complexity increases but less number of states has the contrary consequence.

c. Optimize the charging/discharging operation of DS units

In this stage the optimal charging/discharging power at each load state is obtained. Depending upon the magnitude of load at each state, the states are classified either as charging state or discharging state. The first four states are considered as off-peak states and they form candidate states for charging, the remaining six states are regarded as candidate states for discharging. This sub problem is solved using FOA whose flowchart is shown in Fig. 2 [12]. The objective function is to maximize the arbitrage benefit (1).

$$\sum_{l\in\mathcal{L}_{dis}} \rho_l \times P^{dis}_{DS_l} \times c_{peak} - \sum_{l\in\mathcal{L}_{ch}} \rho_l \times P^{ch}_{DS_l} \times c_{off-peak} \qquad (1)$$

From (1), it can be understood that the objective function depends on the prices of electricity and the load state probabilities. The objective function in (1) is to be maximized subjected to the constraints mentioned below. The first constraint shows that the energy stored in a particular duration should be equal to the energy that is discharged in the same duration. The amount of energy that is stored during a day is bounded by the ESS energy size, shown by (3). The third constraint implies that the power to be discharged at the highest peak load state (i.e., state 10) should be equal to the DS power size.

Subjected to the constraints:

$$\sum_{l\in\mathcal{L}_{dis}} \rho_l \times P^{dis}_{DS_l} = \sum_{l\in\mathcal{L}_{ch}} \rho_l \times P^{ch}_{DS_l} \times \eta \qquad (2)$$

$$\sum_{l\in\mathcal{L}_{ch}} 24 \times \rho_l \times P^{ch}_{DS_l} \times \eta \le E^{rated}_{DS} \qquad (3)$$

$$P^{dis}_{DS_{10}} = P^{rated}_{DS} \qquad (4)$$

$$0 \le P^{dis}_{DS_l},\ P^{ch}_{DS_l} \le P^{rated}_{DS} \quad \forall l \qquad (5)$$

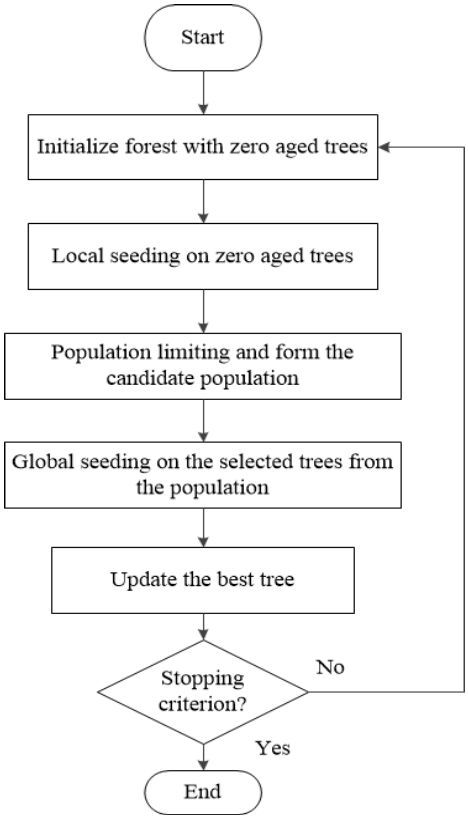

Fig. 2. Flowchart for forest optimization algorithm[12]

d. Estimate the losses' costs

The combined load-DG model is obtained by convolution of load probabilistic model and probabilistic DG model, supposing that the models are independent as in [15] and [14]. Hence, the number of states is same as the product of the number of states of each individual model. Load flow analysis is done to evaluate the costs of system upgrade and the losses in the network. System upgrade includes the lines' reinforcement and reinforcement of the substation so that the growth in the load is accounted.

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For radial distribution networks, upgrades are determined at the circumstance of extreme power flow in the lines. The method for determining system upgrade and losses costs is elucidated below:

1- Update load demand by a certain load growth percentage in each year.

2- Solve the power flows (6) to (9), and determine the necessary upgrades for all the equipment and the total power losses *(Ploss)* in the network.

$$P_{G_{i,s,yr}} - P_{D_{i,s,yr}} - P_{DS_s}^{ch} = \sum_{j=1}^{N} V_{i,s,yr} \times V_{j,s,yr} \times Y_{ij} \times \cos(\theta_{ij} + \delta_{j,s,yr} - \delta_{i,s,yr}) \quad \forall i, s \in S_{ch,yr} \tag{6}$$

$$P_{G_{i,s,yr}} - P_{D_{i,s,yr}} + P_{DS_s}^{dis} = \sum_{j=1}^{N} V_{i,s,yr} \times V_{j,s,yr} \times Y_{ij} \times \cos(\theta_{ij} + \delta_{j,s,yr} - \delta_{i,s,yr}) \quad \forall i, s \in S_{dis,yr} \tag{7}$$

$$Q_{G_{i,s,yr}} - Q_{D_{i,s,yr}} = -\sum_{j=1}^{N} V_{i,s,yr} \times V_{j,s,yr} \times Y_{ij} \times \sin(\theta_{ij} + \delta_{j,s,yr} - \delta_{i,s,yr}) \quad \forall i, s, yr \tag{8}$$

$$V_{min} \le V_{i,s,yr} \le V_{max} \quad \forall i, s, yr \tag{9}$$

3-Determine the expected energy losses' costs using (10) in each year

$$CE_{loss_{yr}} = 8760 \times \left\{ \sum_{s \in S_{dis}} \rho_s \times P_{loss_s} \times c_{peak} + \sum_{s \in S_{ch}} \rho_s \times P_{loss_s} \times c_{off-peak} \right\} \tag{10}$$

4-Finally, evaluate the NPV of upgrades and losses costs as shown in (11) and (12), respectively

$$NPV_{UP} = \sum_{k=1}^{M} \frac{R_k}{(1+IR')^{y_k}} \tag{11}$$

$$NPV_{LO} = \sum_{yr=1}^{N_{yr}} \frac{CE_{loss_{yr}}}{(1+IR')^{yr}} \tag{12}$$

E. Evaluate the Power Required From the DS Units under Contingencies

N-1 contingency analysis is implemented considering the failure of each line in the network. Failure of the line causes island formation. If either DGs or DS units are present in the island then the load in the island formed can be met by them. The contingency analysis is to solve the power flow equations in all the formed islands to know the power necessary from each DS unit for all the system states. The contingency analysis is described in [6].

F. Evaluate the Annual Arbitrage Benefit and Interruption Cost

The annual arbitrage benefit (13) and interruption costs (14) are estimated using MCS. The process for executing MCS is described in [11]

$$\frac{1}{N_y} \sum_{hr=1}^{8760*N_y} \{-c_{off-peak} \times \max(0, E_{DS_{hr+1}} - E_{DS_{hr}})/\eta + c_{peak} \times max(0, E_{DS_{hr}} - E_{DS_{hr+1}})\} \tag{13}$$

$$ECOST = \frac{1}{N_y} \sum_{i=1}^{N} \sum_{\forall d} \sum_{hr=1}^{T_d} CDFN(f_d) \times P_{SH_{i,hr}} \times P_{D_{i,hr}} \tag{14}$$

Determine the net present value of the arbitrage benefit and interruption cost with interest rate (IR), inflation rate (F), and planning period as in (15) and (16) respectively [6] .

$$NPV_{AR} = \sum_{yr=1}^{N_{yr}} \frac{Arbitrage\ benefit_{yr}}{(1+IR')^{yr}} \tag{15}$$

$$NPV_{ECOST} = \sum_{yr=1}^{N_{yr}} \frac{ECOST_{yr}}{(1+IR')^{yr}} \tag{16}$$

$$IR' = \frac{IR - F}{1 + F} \tag{17}$$

G. Evaluate the Objective Function

The main objective (fitness) function as shown in (18) minimizes the system costs and maximizes the arbitrage benefit.

$$\sum_{i=1}^{N} \{(C_P + C_M \times PVF) \times P_{DS_i}^{rated} + (C_E + C_R) \times E_{DS_i}^{rated}\} + NPV_{UP} + NPV_{LO} + NPV_{ECOST} - NPV_{AR} \tag{18}$$

The batteries have to be replaced at least once in the planning period (5 years). Hence CR is calculated as in (19) [16].

$$C_R = FR \times [(1+IR')^{-r} + (1+IR')^{-2r} + \cdots] \tag{19}$$

Subject to:

$$P_{DS_i}^{rated} = x_i \times \text{discrete step} \quad \forall i \in B \tag{20}$$

$$E_{DS_i}^{rated} = y_i \times \text{discrete step} \quad \forall i \in B \tag{21}$$

$$P_{DS_i}^{rated} \le P_{DS}^{max} \quad \forall i \in B \tag{22}$$

$$E_{DS_i}^{rated} \le E_{DS}^{max} \quad \forall i \in B \tag{23}$$

$$x_i \text{ and } y_i = 0 \quad \forall i \notin B \tag{24}$$

The first and second constraints imply that the discrete power and energy ratings of the BESS in terms of the integer decision variables. (22) and (23) confine the power and energy sizes of the BESS to the maximum available sizes. The decision variables of BESS placement are restricted to the set B as in (24).

IV. CASE STUDY

IEEE 33-bus distribution network, as presented in Fig. 3, is considered in the case study. All the data including the bus data and the line data is taken from [17]. The peak demand of the system during the base year is 3715 kW which is assumed to grow every year with an annual rate of 5 %. The planning period is considered as 5 years. The interest rate and the inflation rate are assumed to be 5% and 1% respectively. The electricity prices during peak (₹1890) and off-peak (₹1260) hours are taken from the prices given by the IESO.

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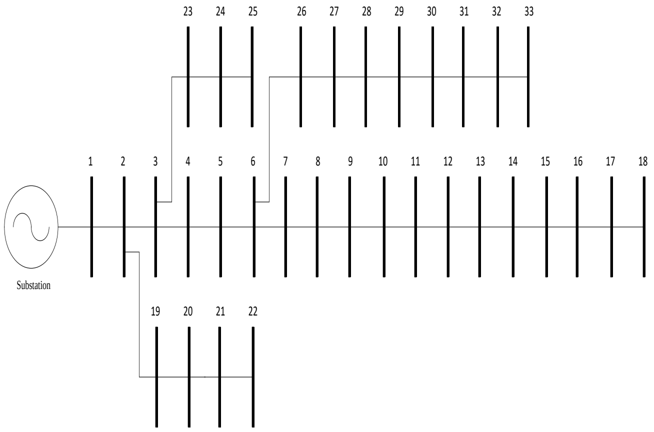

Fig. 3. System under study [11]

The DG considered is an intermittent DG based on wind and is assumed connected at bus 18 as the voltage at that bus is minimum. The costs for DS installation are categorized into: the capital power cost, the capital energy cost of storage capacity, the capital replacement cost, and the operation and maintenance (O&M) cost shown in TABLE II. Lead-acid battery (LA), has been selected as ESS. Depending on the availability of the land, the candidate buses for DS placement have to be incorporated in the set B: (16, 17, 21, 22, 25, 32).

TABLE II
COSTS OF BESS TECHNOLOGY

	LA
Rated output power (kW)	2500
Round-trip efficiency (%)	75
Capital and maintenance costs	
Capital power cost (₹/kW)	12250
Capital energy cost (₹/kWh)	21350
Capital replacement cost (₹/kWh)	21350
Annual O& cost (₹/kW)	1050
Number of charge/discharge cycles	3200

V. RESULTS

The results from the adopted methodology for a planning period of 5 years using LA battery are shown in TABLE IV. The capital costs, maintenance costs, replacement costs and the size of battery in kW are shown. The optimal charging/discharging operation done by FOA is shown in TABLE V. The voltage profile of 33 bus distribution network with and without ESS are shown if Fig. 4 and Fig. 5 respectively. The optimal charging and discharging schedule for different batteries using linear programming [11]and FOA are shown in TABLE VI and TABLE VII respectively. The arbitrage benefit obtained using FOA is more than the arbitrage benefit obtained using Linear Programming (LP).

TABLE IV
BESS COSTS AND RATINGS

Scenario		LA
NPV of DS costs	Capital costs (₹)	6,720,000
	Maintenance costs (₹)	935,900
	Replacement costs (₹)	1,747,200
	Total (₹)	9,403,100
Installed DS units (kW)	Bus 16	0
	Bus 17	100
	Bus 21	100
	Bus 22	0
	Bus 25	0
	Bus 32	0

TABLE V
Optimal DS Charging/Discharging Schedule

Load state no.	DS status	LA
1	Charging	5.4
2	Charging	36.7
3	Charging	65.0
4	Charging	90.4
5	Discharging	8.1
6	Discharging	49.8
7	Discharging	99.5
8	Discharging	21.0
9	Discharging	39.5
10	Discharging	100

TABLE VI
Optimal DS Charging/Discharging Schedule using LP

Load State	DS status	LA	Na/S	VR
1	Charging	595.6862	28.3916	27.6863
2	Charging	599.2812	17.1571	13.5272
3	Charging	598.0047	40.1606	48.0789
4	Charging	597.9155	0.0010	0.0865
5	Discharging	213.7863	1.8992	1.0932
6	Discharging	212.1146	1.8774	1.0749
7	Discharging	212.1146	1.8774	1.0749
8	Discharging	225.3859	8.2245	10.2174
9	Discharging	270.7510	24.4057	27.7308
10	Discharging	600.00	100.00	100.00
Arbitrage benefit (₹)		31,498	1058	370

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TABLE VII
Optimal DS Charging/Discharging Schedule using FOA

Load State	DS status	LA	Na/S	VR
1	Charging	525.00	33.00	62.00
2	Charging	478.00	9.10	23.60
3	Charging	434.70	52.70	57.00
4	Charging	423.20	65.80	62.80
5	Discharging	49.80	25.10	0.00
6	Discharging	119.10	85.70	36.50
7	Discharging	223.60	0.20	30.00
8	Discharging	511.60	63.00	0.20
9	Discharging	284.60	15.20	84.90
10	Discharging	600.00	100.00	100.00
Arbitrage benefit (₹)		78,593	29,186	8272

VI. CONCLUSIONS

In this work, the optimal size and placement of ESS considering NPV of BESS capital costs, maintenance costs, replacement costs and arbitrage benefits is determined using Genetic Algorithm. The methodology is adopted for a planning period of five years with an increment of load every year by 5%. The optimal charging/discharging operation of the DS during all the load states is done by using FOA. Integration of ESS in distribution network increases the system reliability, defers upgrades and also reduces the losses in the network. This work can be extended with different combinations of DGs and different DS technologies.

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