Optimal Allocation of Battery Energy Storage Systems in Active Distribution Network

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Abstract. This work presents an approach of finding the optimal location and size of battery energy storage system (BESS) in a distribution network with distributed generation (DG) in order to reduce distribution system losses and control of voltage rise due to DG fluctuation. The optimal site and size of the BESS are obtained by minimising the cost of power losses and battery investment expenditure. IEEE 33-bus standard distribution system is used for simulation and results are evaluated. The optimization problem is solved using Genetic Algorithm (GA). After allocation and scheduling of BESS in the distribution network the daily energy losses are obtained which are found to be low as compared to the case of distribution network without BESS.

Keywords: Battery Energy Storage · Distributed Generation · Distribution Network · Genetic Algorithm

1 Introduction

In this era, renewable based distributed generation sources (DGs), which is clean energy, is being rapidly integrated to power distribution systems to meet growing power requirement. But, renewable DGs because of its dependence on natural resources can only provide fluctuating power which is non dispatchable to the load demand. Moreover, reverse power flow may occur and distribution system operators may go into losses [1]. As a solution to the said problem the energy storage system have come up and facilitated increased integration of renewable DGs. In [2] detailed discussion is done on various ESS technologies, their application and efficiencies. The discussions have shown that BESS have been mostly used in operational projects. However a BESS of improper size may create troubles for commercial operation of ESS in distribution network [3].

An ESS installation with optimization of its location and size can effectively improve distribution system's reliability as well as efficiency [4]. M. Nick et al. have minimised the total investment cost of ESS installation by optimally locating a properly sized ESS and reduced the power system expenditure using second order cone programming (SOCP) [5]. Battery energy storage system (BESS) installation in distribution network can not only increase the power system efficiency but also improve electricity trading flexibility of the power supplier to attain maximised profit [6]. With increasing addition of renewable DGs in distribution network installation of BESS can also support for the increase

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in consumption of electricity [7]. Moreover, optimal control of the power schedule of a BESS together with optimal location and size greatly enhances the efficiency of power system and increase profit of the electricity supplier from the sale of electricity [8].

In this work an approach for daily energy loss minimisation is presented with minimisation of battery investment cost by optimally siting and sizing BESS in distribution network and also facilitating optimal utilization of renewable resources.

2 Modelling of Distribution Network

At present the cost of BESS is high and research is going on to bring down the cost therefore optimization methods need to be applied to facilitate large scale BESS application in distribution system. The siting of BESS to be installed in distribution network is dependent on factors such as bus voltage sensitivity, load characteristic and cost of BESS installation. An optimization problem is designed to determine appropriate bus site and energy capacity of the BESS to be installed so as to minimize the total daily energy loss by maintaining voltage deviation up to certain limit. The proposed method of BESS siting and sizing is designed in order to minimize cost of losses and without violating bus wise voltage requirements.

2.1 Power Flow Equations

Let us consider a radial distribution system which is a one directional network, such as N(V, E), where V is collection of buses and E is the collection of distribution lines. This considered network consists of n buses. A set of the buses V = (1, 2, 3, … n) and overhead lines E = {(i, j)}, where i and j are any two random buses of the network. The numbers of elements in E is given by l. A term $e_k = (i, j) \in E$, $k = 1, 2, \ldots, l$ is taken to represent the overhead line k that connects bus i and bus j. A network topology matrix is defined such that each line of the network is arbitrarily assigned a fixed orientation. For example, $e_k = (i, j)$ is considered as a distribution line that originates at bus i and ends at bus j. The topology matrix is then denoted as $\tilde{E} \in R^{nxl}$ and is defined as follows, $\forall e_k = (i, j) \in E$, $\tilde{E}_{ik} = 1$, $\tilde{E}_{jk} = -1$, and $\tilde{E}_{mk} = 0$, $m = i, j$. In distribution system tree topology is adopted where single path only exists between two nodes. The 'Dist Flow' equation has been adopted in order to model the network load flow as follows–

$$P_{ij} + P_j = \sum \mathrm{P_{jk}} + \mathrm{r_{ij}} \frac{\mathrm{P_{ij}^2 + Q_{ij}^2}}{\mathrm{V_i^2}} \tag{1}$$

$$Q_{ij} + Q_j = \sum \mathrm{Q_{jk}} + \mathrm{x_{ij}} \frac{\mathrm{P_{ij}^2 + Q_{ij}^2}}{\mathrm{V_i^2}} \tag{2}$$

$$V_i^2 - V_j^2 = 2\left(r_{ij}P_{ij} + x_{ij}Q_{ij}\right) - 2\left(\mathrm{r_{ij}^2 + x_{ij}^2}\right)\frac{\mathrm{P_{ij}^2 + Q_{ij}^2}}{\mathrm{V_i^2}} \tag{3}$$

where, Nj is the collection of buses k that $(j, k) \in E$. Let us take l_{ij} representing squared magnitude of current from ith to jth bus. This l_{ij} is comparatively lesser than the other variables of the Dist flow model. It may be justified to take this squared magnitude of current from bus i to j as zero. Moreover, an approximation $V_i^2 - V_j^2 = 2(V_i - V_j)$ is taken, as the magnitude of the bus voltages are near to one. Then the approximated model of the dist flow equation becomes linearized as shown below,

$$P_j = \sum \mathrm{P_{jk}} \tag{4}$$

$$Q_j = \sum \mathrm{Q_{jk}} \tag{5}$$

$$V_i - V_j = r_{ij}P_{ij} + x_{ij}Q_{ij}2(\mathrm{c}) \tag{6}$$

The above model is experimentally verified for effectiveness and found error of 0.25% with voltage variation of 5% [10]. Accordingly the above model may be used to study the bus voltage deviation arising because of uncertainties of power injection. Firstly, linearized 'dist flow' equation has been rewritten using network topology matrix and other matrices related to the graph. Vectors $V = [V_i]$, $P = [P_i]$, $Q = \left[Q_i\right]$, $P_{line} = [P_{ij}]$, $Q_{line} = [Q_{ij}]$ are the vectors and $r = diag[r_{ij}]$, $x = diag[x_{ij}]$ are the diagonal matrices which are used below to re-write the dist flow equation.

$$EP_{line} = P \tag{7}$$

$$EQ_{line} = Q \tag{8}$$

$$E^T V + E_1^T V_1 = rP_{line} + xQ_{line} \tag{9}$$

where, $\mathbf{E} \in R^{lxl}$, is a diagonal matrix consisting of the last l rows of $\tilde{\mathrm{E}}$ and $\mathbf{E}1 \in R^{1xn}$ is the first row of $\tilde{\mathrm{E}}$. The voltage at the substation bus i.e. bus 1 is controlled at base value when distribution system is radial in nature. The matrix $\mathbf{E} \in R^{lxl}$ is non-singular [11]. Therefore, the bus voltage deviation caused due to power fluctuation can be formulated as follows.

$$\Delta V = R\Delta P + X\Delta Q \tag{10}$$

where, $\Delta P = [\Delta P_i]$, $\Delta Q = \left[\Delta Q_i\right]$, are the active and reactive power deviations of ith bus, $\Delta V = [\Delta V_i]$ is the voltage deviation of ith bus, and $R = (E^{-1})^T rE^{-1}$, $X = (E^{-1})^T xE^{-1}$.

$$\Delta V_i = R_i\Delta P + X_i\Delta Q = \sum_{j=1}^{n} R_{ij}\Delta P_j + \sum_{j=1}^{n} X_{ij}\Delta Q_j \tag{11}$$

where,

$R_{ii} = \sum Resistances\,from\,substation\,upto\,i'th\,bus$
$R_{ij} = \sum Resistances\,common\,upto\,ij'th\,line$

Similarly, X_{ii} *and* X_{ij} are defined.

2.2 Voltage Deviation Risk

BESS may be used for compensation of short term voltage deviation of critical buses. To determine such critical buses voltage deviation risk for each bus should be considered for optimal allocation of BESS. Such voltage deviation is due to uncertainties of injected power of buses and demand of buses. Here only injection deviations of active power are considered for determination of voltage deviation risk in order to maintain simplicity. The voltage deviation risk is formulated using two components. One is the voltage violation allowable limit of a particular bus and the other is the voltage deviation index (I_i). Taking the active power injection disturbances equal to unity for all non substation buses, the voltage deviation index (I_i) of i'th bus becomes $I_i = \sum_{j=1}^{n} R_{ij}$. The voltage deviation caused by short term power uncertainty is characterized by the above formula, therefore, it may be approximate vector to define voltage deviation. Voltage deviation magnitude of different buses may be different. Such allowable limits denoted by (ΔV_{ai}) should be considered in evaluation of voltage deviation risk. The voltage deviation risk S_i can be formulated as follows,

$$S_i = \frac{\Delta V_{ai}}{I_i} \tag{12}$$

From the above description it is established that the bus voltage deviation risk may be obtained using $\mathrm{S_i}$. The target buses of BESS are the ones which have low values of $\mathrm{S_i}$.

2.3 BESS Modelling

The simulation of BESS is done by taking the charging/discharging rates at equal intervals of a day. BESS is modeled as energy available at different time intervals of a day. Here the interval is taken as one hour, i.e. 24 nos. intervals.

$$C_{iT} = \begin{matrix} E_B(1) \\ E_B(2) \\ \vdots \\ E_B(24) \end{matrix} \tag{13}$$

Battery discharging power can be written as,

$$P_B(t) = \frac{\Delta E_B}{\Delta t} \eta_d \tag{14}$$

where, $\Delta E_B = E_B(t) - E_B(t-1)$
$\eta_d = Battery\, discharging\, efficiency$

Now, sets of data for different seasons have been obtained. The optimization process which is shown in following section will be run for different seasonal data separately. Battery size will be determined from the $\mathrm{E_B^{max}}$ and $\mathrm{E_B^{min}}$ of each seasonal data.

$$Battery\, size = \frac{E_B^{max} - E_B^{min}}{DoD} \tag{15}$$

where, DoD = 80%, is the depth of discharge of the BESS. One operation cycle of a battery is indicated by each round of charging and discharging with full capacity discharging. Here, for calculation of battery cycle the charging/discharging energy magnitude of each interval have been added and average taken by dividing with 2. Thus the battery daily cycle in found as follows,

$$\text{Battery Daily cycle} = \frac{1}{2}\frac{\sum_{t=1}^{T}|E_B(t) - E_B(t-1)|}{DoD \times Battery\,size} \tag{16}$$

Now, a cost function ($C_{Battery}$) that considers BESS investment and operational expenditures in the form of daily cost is given as follows [9],

$$C_{Battery} = \frac{Battery\,Daily\,Cycle}{Cyclelife} \cdot \text{BUC} \cdot \text{Battery size} \tag{17}$$

where, cyclelife is the total charge/discharge cycles, for Li-ion battery cyclelife = 3221 is nominal.

BUC = \$132/kWh, is the battery unit cost.

$$\begin{aligned} \therefore C_{Battery} &= \frac{1}{2}.\frac{\sum_{t=1}^{T}|E_B(t) - E_B(t-1)|}{DoD \times Cyclelife}.BUC \\ &= \frac{1}{2}.\frac{\sum_{t=1}^{T}|P_B(t)|}{DoD \times Cyclelife \times \eta_d}.BUC \end{aligned} \tag{18}$$

3 Problem Formulation

The objective is to determine the optimal bus location and required capacities of the BESS to be installed for energy cost saving by reducing losses while simultaneously maintaining the voltage deviation of buses of the distribution system within limits. For a given number of BESS, an iterative process based on voltage sensitivity analysis totally dependent on the topology of the network may be used in order to select the most useful siting location. The formulation of BESS capacity optimization is done by taking one bus at a time and optimizing the operation schedule using genetic algorithm.

3.1 BESS Siting

In the current section attempt has been made to find out favorable location for placement of BESS of a given number in the distribution network which is radial in nature. The voltage deviation risk of each bus will be determined and there by the most risky bus for voltage deviation will be found out to deploy BESS. In this work the buses which are risky in respect of voltage sensitivity are only considered for installation of BESS to maintain simplicity. After selection of a risky bus using voltage deviation risk BESS has been installed in that bus. Then the voltage deviation risk of other buses are updated so that the effect of BESS installation at the selected bus is counted while selecting other buses in the subsequent iterations. As BESS is used at different buses for compensation of power injection uncertainty, the deviation index (I_i) is updated iteratively. In each iteration, higher the value I_i the higher will be the voltage deviation risk of bus i. Then, if k'th bus is selected for locating BESS then update $I_i = \sum_{j=1}^{n} R_{ij} - R_{ik}$. Then again the bus with higher value of I_i will be the potential BESS installation bus. As different buses may have different allowable limits of voltage deviation, therefore, bus selection is done using Eq. (12). Accordingly, the optimal BESS location can be obtained one by one iteratively.

3.2 BESS Sizing

For the optimization of capacity of BESS the power loss of network has been taken as the component of objective function after taking care of the other distribution network constraints. In this work a component of objective function is to minimize cost of power loss (CLoss). The BESS sizing algorithm flowchart is shown Fig. 2.

$$
\begin{aligned}
C_{Loss} &= \sum_{t=1}^{T} \sum_{l=1}^{n-1} \frac{V_{ij}^2}{R_{ij}} \cdot \Delta t \cdot r_{Loss}(t) \\
C_{Loss} &= \sum_{t=1}^{T} \sum_{l=1}^{n-1} \frac{\left(V_i \angle \delta_i - V_j \angle \delta_j\right)^2}{R_{ij}} \cdot \Delta t \cdot r_{Loss}(t) \\
&= \sum_{t=1}^{T} \sum_{l=1}^{n-1} \left| V_i^2 + V_j^2 - 2 V_i V_j \cos\left(\delta_i - \delta_j\right) \right| g_{ij} r_{Loss}
\end{aligned} \tag{19}
$$

where, $r_{Loss}(t) = \mathit{Cost\ of\ losses}$ at time t.

3.3 Objective Function

The primary component of objective cost function in this work is to minimize distribution system daily energy loss cost (CLoss). However, BESS investment and operating costs also needs to be included in the cost function to optimize benefit tradeoffs. Hence, a cost component which expresses daily cost of BESS investment and maintenance expenditures (Cbattery) as found in the earlier section is included in the objective function:

$$
\begin{aligned}
f_{loss}\left(P_B^k(t)\right) &= \lambda C_{Loss} + (1-\lambda) C_{Battery} \\
&= \boldsymbol{\lambda} \sum_{t=1}^{24} \sum_{l=1}^{n-1} \left| V_i^2 + V_j^2 - 2 V_i V_j \cos\left(\delta_i - \delta_j\right) \right| g_{ij} r_{Loss}(t) \\
&\quad + (1-\boldsymbol{\lambda}) \frac{1}{2} \cdot \frac{\sum_{t=1}^{24} \left| P_B^k(t) \right|}{DOD \times Cyclelife \times \eta_d} \cdot BUC
\end{aligned} \tag{20}
$$

where, λ, V_i, V_j, g_{ij}, $P_B^k(t)$ are, a constant between zero and one, sending bus voltage, receiving bus voltage, conductance of ij-th line and battery injected power at bus k at time interval t respectively. After each iteration the bus voltages are updated with BESS at kth bus at t-th interval as shown below,

$$
V_{i(new)}(t) = V_i(t) + R_{iK} P_B^K(t) \tag{21}
$$

3.4 Constraints

3.4.1 Voltage Constraint

The allowable limit of bus voltage for each and every bus should not exceed specified lower and upper limit for the period of consideration. Deviation is allowed up to 5% of the reference voltage.

$$V_{lower} \leq V_{i(new)} \leq V_{upper} \forall \quad i = 1, 2, \ldots .24 \tag{22}$$

where, V_{lower} and V_{upper} are the bus voltage lower and upper limits at i'th bus, respectively.

3.4.2 Battery Constraint

The battery output power and output energy should be limited within upper and lower bounds so that the BESS does not operate beyond boundary limits.

$$\mathrm{E}_{\text{B-min}} \leq E_B^K(\mathrm{t}) \leq \mathrm{E}_{\text{B-max}} \tag{23}$$

$$\mathrm{P}_{\text{B-min}} \leq P_B^K(\mathrm{t}) \leq \mathrm{P}_{\text{B-max}} \tag{24}$$

where, $\mathrm{P}_{\text{B-min}}$, $\mathrm{P}_{\text{B-max}}$ are the minimum and maximum values of powers of BESS, respectively at time t. $\mathrm{E}_{\text{B-min}}$, $\mathrm{E}_{\text{B-max}}$ are the minimum and maximum values of energy capacities of BESS, respectively.

4 Methodology

4.1 Genetic Algorithm

Genetic algorithm is an evolutionary optimization method inspired from Charles Darwin's evolution theory. Firstly, the initial population is randomly generated and converted to binary string. The string size is the multiplication of decision variables and the bit number assigned to each decision variable. Each population is represented by a binary string which is transformed into decimal numbers. Following that the primary steps of the algorithm are performed which are parent selection from the population having the optimum objective value, then crossover is operated between the selected parent strings according to the cross over probability. Finally, mutation is done in the children strings as per the mutation probability. Then the children binary strings are converted into decimal numbers and objective functions are evaluated. Then the best fitness value is found. This is repeated until maximum iterations are reached.

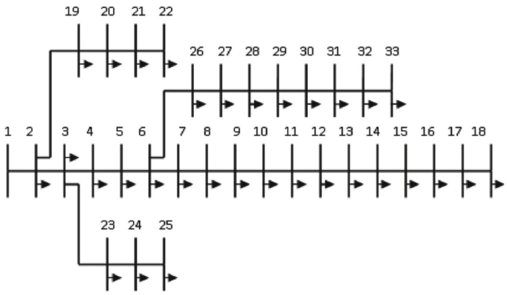

Fig. 1. IEEE 33 bus system

4.2 Test System

The standard distribution network of 33-bus feeder of IEEE which is shown in Fig. 1 is considered to figure out the optimal location and capacity of the BESS. Bus wise load profile is taken such as it is equal to IEEE 33-bus standard peak load during peak time of day, however, during other times of day the load of a bus is the fraction of its standard peak demand. Also PV generation is taken at bus no. 7 of 100 kWp and at bus no. 18 of 125 kWp.

5 Simulation Results

The algorithm is run to get the favourable locations of BESS installation depending explicitly on network data. In the beginning the number of BESS is considered as per operator's convenience and corresponding locations are obtained iteratively using Eq. (12) which is primarily based on voltage sensitivity. Then the sizing algorithm is run and optimal 24-h schedules of BESS active powers at each location bus are found. The energy capacity i.e. size of the BESS at that bus is obtained from Eq. (15). Similarly sizes of BESS at other buses are obtained. Figure 3 depicts the reduction in losses after incorporation of BESS at the location set bus. Table 2 illustrates the operation schedules of different time intervals of a day for the BESS installed at different location buses as obtained from the location determining algorithm.

The positive values of the operation schedules denotes charging power where as the negative values are to specify discharging of BESS. Maximum among the 24-h schedules of a BESS may be taken as the required power rating of that BESS and the required energy rating i.e. the size of the BESS for each bus of location set are obtained as below.

Table 1. Summary of Results

Objective fun	Location bus	V_{max} (pu)	V_{min} (pu)	Energy Loss/day (min) (kWh)	Battery Size (kWh)
f_{loss}	18	1.02	0.94	1328.7	199.30
f_{loss}	17	1.00	0.94	1337.0	224.10
f_{loss}	16	1.01	0.95	1322.1	210.44

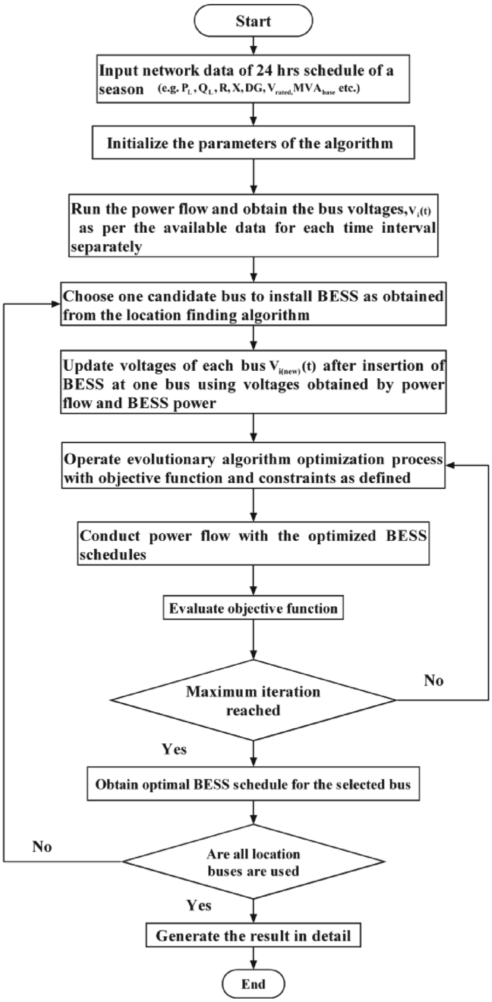

Fig. 2. Proposed optimization Flowchart

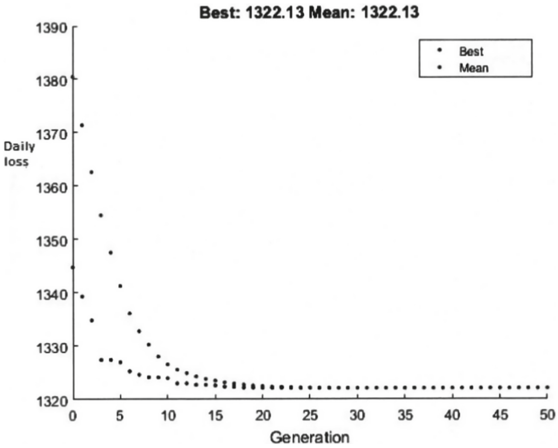

Fig. 3. Convergence of Daily Loss function

Table 2. BESS Operation Schedules

Time Interval	Operation Schedules in kW		
	Bus 18	Bus 17	Bus 16
1	99.56	50.08	0.14
2	98.16	49.9	40.26
3	−197.62	50	39.66
4	99.08	49.42	39.58
5	98.26	−65.12	39.44
6	−98.26	−59.02	40
7	−97.08	−74.9	−66.34
8	65.38	50.2	−66.7
9	65.16	49.2	−62.52
10	64.8	49.62	199.54
11	−197.1	29.38	−199.44
12	99.44	−41	77.2
13	99.56	−92.02	33.92
14	−196.98	65.52	40.28
15	197.04	−65.9	39.88
16	−69.1	−25.3	15.68
17	−99.08	18.48	−65.5
18	58.14	185.92	−46.44

(*continued*)

Table 2. (*continued*)

Time Interval	Operation Schedules in kW		
	Bus 18	Bus 17	Bus 16
19	−35.68	−65.38	−59.76
20	49.76	−63.54	99.6
21	−53.58	−80.26	6.6
22	−22.9	141.66	−93.92
23	98.9	−75.82	−39
24	−53.92	−79.06	114.92

6 Conclusion

After Installation of BESS at the targeted locations which is based on network characteristics, voltage sensitivity etc. and with proper size determination of the BESS using the formulated Optimization problem and solution by Genetic algorithm, a reduction of overall energy loss per day from 1404.10 kWh (without BESS) to around 1322.13 kWh (with BESS) has been observed, i.e. reduction of energy losses up to around 5.84% can be obtained with installation of BESS as shown in Table 1 along with controlled voltage at the buses. Further study of optimal BESS siting and sizing schemes may be done with different weight factors (λ) and it may be shown that weight factor can be adjusted as per operational preferences.

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