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# Optimal BESS Allocation and Market Equilibrium for Improving Distribution System Reliability

**S. Bhargava Reddy*, J. Sreenivasulu** and P. Srinivasa Varma*****

***Abstract:*** The increase in deployment of distribution generation, especially renewable- based due to feed-in-tariff led the concept of smart grids in distribution system. Integration of large scale Distributed Energy Sources is essential to achieve high system reliability and efficiency of smart grids. Energy storage in distribution system helps to connect large scale of renewable sources and meets customer needs by decreasing the total customer interruptions. In this paper, the price of battery storage is optimized based on willingness to pay by customers' to avoid interruptions. In literature Genetic algorithm is used for optimization. But, in this paper, Particle Swarm Optimization algorithm is proposed to arbitrate the storage system and further the impact of energy storage size on market margin pricing is also investigated.

***Keywords:*** Distributed energy sources, storage system, particle swarm optimization, market pricing.

## NOMENCLATURE

BESS – Battery Energy Storage System

CDF – Customer Damage Function

CIC – Customer Interruption Cost

DES – Distributed Energy Sources

PSO – Particle Swarm Optimization

RES – Renewable Energy Sources

RDS – Radial Distribution System

EENS – Expected Energy not Supplied

## 1. INTRODUCTION

In the past Power System networks are centralized, which narrows the Power System operators to provide quality of power and also per unit cost is high. Keeping in mind, Power Systems are evolving from centralization to decentralized power system structures which introduce new trends in power generation where customers can directly involve in market pricing. Decentralized Power System allows us to connect small scale generation units like RES directly in to the distribution systems. The RES in distribution networks brought revolution in smart grid concepts. The powers from RES are stochastic and it is difficult to connect directly to load points. With the introduction of storage systems like storage batteries, increases the power handling capacity by RES. This BESS improves the efficiency and reliability of Power Systems by delivering power during network contingencies.

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Classical power structures suggest unidirectional glide of energy from generating stations to distribution structures through transmission and sub-transmission networks. This scheme has been changed after making an allowance for DES to be coupled to distribution systems, to maintain bidirectional power flow in distribution networks. Past research work has witnessed the importance of optimal placement of DES to delivering power during network disturbances [6], consequently minimizes loss of energy supplied to unaffected customers. An approach for improving reliability of distribution system using ESS without cost benefit analysis was included in [3] that justify the necessity of BESS in distribution networks. Mathematical formulation for sizing of backup battery storage to expedite the reliability targets were described in [1]. It is difficult to determine customers Willingness To Pay (WTP) for reliability improvement. So, the cost of interruption for different customer types are represented in terms CDF which represents cost of interruption as a function of time duration of interruption. The CDF for different customer types are taken as in [5]. To evaluate the reliability of BESS in RDSs, reliability indices like interruption cost, also called as ECOST and EENS are taken from [4]. The optimization has been performed using PSO algorithm because of its simplicity and high convergence rate [2].

The primary challenge is to optimally allocate the BESS, minimize the installation cost of BESS and to improve the reliability of Power System networks. Further, market margin price variation throughout the day with and without BESS is presented in this paper.

Organization of this paper as follows. In section II, PSO algorithm for sizing of BESS and reliability indices are discussed. In section III, discussed the study area of 33-bus RDS. In section IV, optimization results and reliability assessment results are discussed. Conclusion of this paper is presented in section V.

## 2. METHODOLOGY

At the first, power flow analysis is to be performed to know the current state of the network parameters. As the contingency exists, the fault section is isolated from the system and the isolated system is assumed to form island for optimal allocation of BESS. It is assumed that batteries are fully charged during the normal state of the network and are not permitted to charge during island mode. The problem is to identify the power rating of battery to be installed to meet the load in the island. The power delivered by the BESS during contingency is calculated using Eqn. (1) and this equation is used as fitness function in PSO algorithm.

$$P_{DSi} = \sum_{j=1}^{N} V_i \times V_j \times Y_{ij} \times \cos(\theta_{ij} + \delta_j - \delta_i) - [P_{Gi} - P_{Di}(1 - P_{SH})] \qquad \text{… Eqn. (1)}$$

where,
- N – no. of buses
- V – Bus voltage
- $i, j$ – System bus indices
- $\delta$ – Bus voltage angle
- $\theta$ – Admittance angle
- $P_{DS}$ – Power demanded by BESS
- $P_{SH}$ – Portion of load shed
- $P_D$ – Total load

### A. BESS Optimization using PSO

PSO is used for minimizing the fitness function Eqn. (1). Swarm movement is an evolutionary process that search for optimal parameters in sample space. It starts with finite particles and finds optimal parameters by updating generations. For each generation, particle updates two parameters as $P_{best}$ and $G_{best}$. The particle updates its velocity (V) and position ($x$) using Eqns. (2 & 3).

$$V_{k+1} = V_k + c_1 r_1 (P_{best} - X_k) + c_2 r_2 (G_{best} - X_k) \quad \text{… Eqn. (2)}$$

$$X_{k+1} = V_{k+1} + X_k \quad \text{… Eqn. (3)}$$

where, $k$ – Iteration number

$p$ – Particle number

$V_k$ – Velocity of particle at iteration '$k$'

$X_k$ – Position op particle at iteration '$k$'

$P_{best}$ – Particle best at iteration '$k$'

$G_{best}$ – Global best

$r_1, r_2$ – Correction factor [o 1]

$c_1, c_2$ – Learning factors

The flow chart for optimal sizing of BESS is shown below:

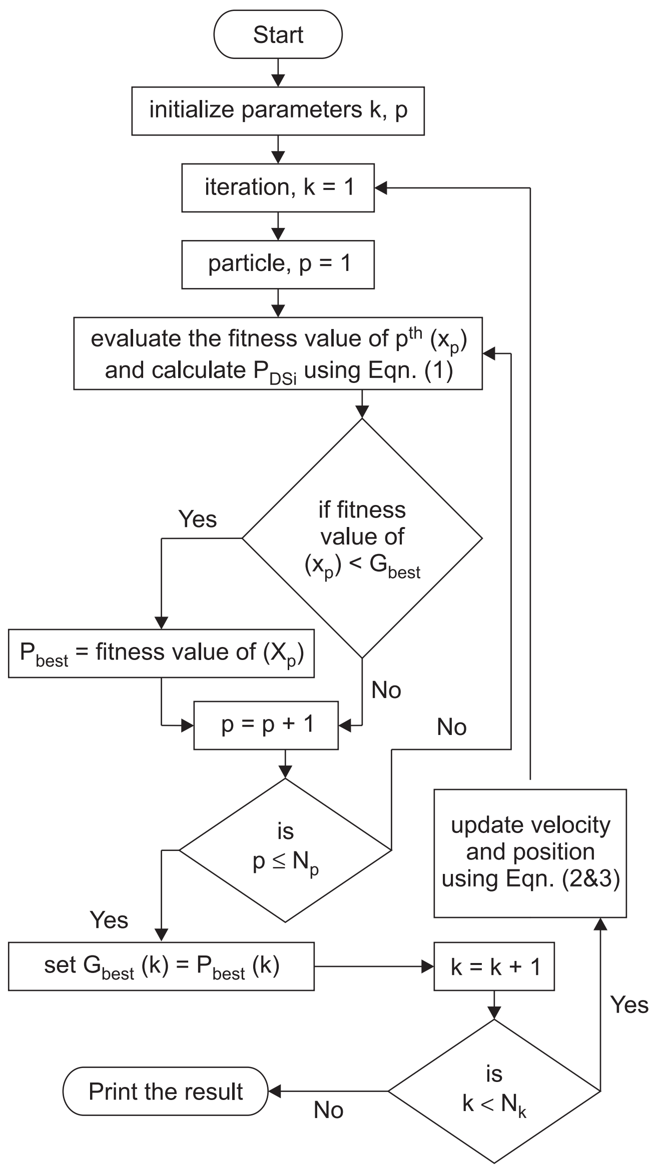


**Figure 1: PSO flow chart for BESS optimal sizing**

### B. Reliability Assessment

When the allocated BESS will not meet the load demand in the formed island it results in customer economic loss and it is represented in CDF. This CDF is used to evaluate the ECOST index using Eqn. (4). Further EENS to the customers during contingency is evaluated using Eqn. (5).

$$\text{ECOST} = \frac{1}{\text{Ny}} \sum_{j=1}^{N} \sum_{t=1}^{Td} \text{CDF}(f_d) \times P_{\text{Shi}} \times P_{\text{D}i,t} \qquad \text{… Eqn. (4)}$$

$$\text{EENS} = \frac{1}{\text{Ny}} \sum_{t=1}^{8760+\text{Ny}} \sum_{t=1}^{N} P_{\text{Shi}} \times P_{\text{D}i,t} \qquad \text{… Eqn. (5)}$$

Then the ECOST function is used to find the total cost spent on BESS for installation and maintenance using Eqn. (6).

$$\sum_{i=1}^{N} \{(C_P + C_M) \times S_{DS} + C_E \times E\} + \text{CDF} \qquad \text{… Eqn. (6)}$$

where, $N_y$ – Study period

N – Total no. of system buses

$T_d$ – interruption in hours

$C_P$ – Annual capital power cost

$C_M$ – Annual capital maintenance cost

$C_E$ – Annual capital energy cost

$S_{DS}$ – Installed BESS power size

$E_{DS}$ – Installed BESS energy size

## 3. CASE STUDY

The area under study is a 33-bus radial distribution system. The distribution system contains a mix of 70% residential customers and 30% small industrial and commercial customers with financial parameter as 5% interest rate [7].

Four types of storage technologies like Lead-Acid battery (LA), Compressed air in vessels (CAS), Sodium-Sulfur (Na/S) battery and Vanadium Redox (VR) battery were selected to store the energy because of their charging/discharging time capacities are feasible for the system under study. It is assumed that battery storage is available in discrete sizes in steps of 100 kVA/kWh. The annual capital and maintenance costs for BESS technologies for four storage types over the assumption of 30-years life cycle is taken from [7-8].

The parameters used in PSO algorithm are taken as shown in Table 1.

**Table 1**
**PSO parameters**

| *S.No.* | *Parameter* | *Count* |
|---|---|---|
| 1 | Swarms | 18 |
| 2 | Iterations | 30 |
| 3 | Learning factor | 1 |
| 4 | Correction factor | 2 |

## 4. RESULTS

### A. BESS Optimal Allocation Results

As an example, shown in Figure 2, for a contingency occurred between buses 1 and 2, two BESS are optimally allowed at buses 16 and 32 in the formed island using PSO as described in section II. Load points 22 and 29 are tripped to avoid the over loading of the BESS.

**Table 2**
**Optimal BESS allocation**

| Fault location | BESS Location | BESS Size |
|---|---|---|
| Bus 1-2 | Bus- 32,16 | 100,100 kWh |

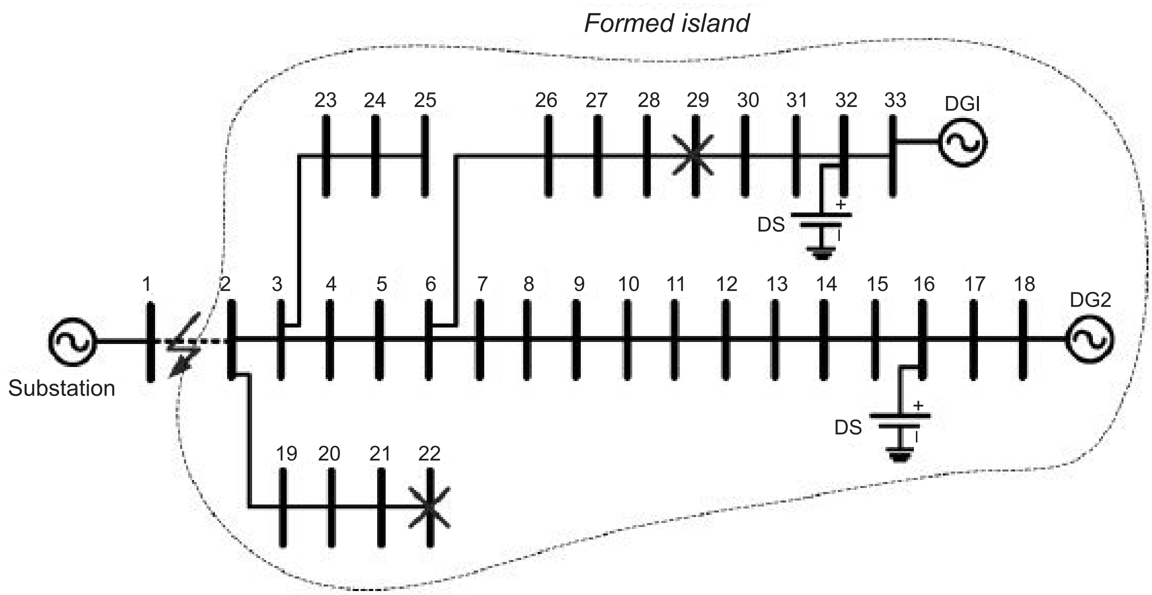


**Figure 2: Graphical representation of BESS allocation for disturbance occurred between buses 1 and 2**

### B. Reliability Assessment Results

By using Eqn. (5), ECOST has evaluated. The ECOST for base case is ₹ 49.4 million and for different storage types is equal to ₹ 16.25 million and the comparison for base case with different storage types are shown in Figure 3.

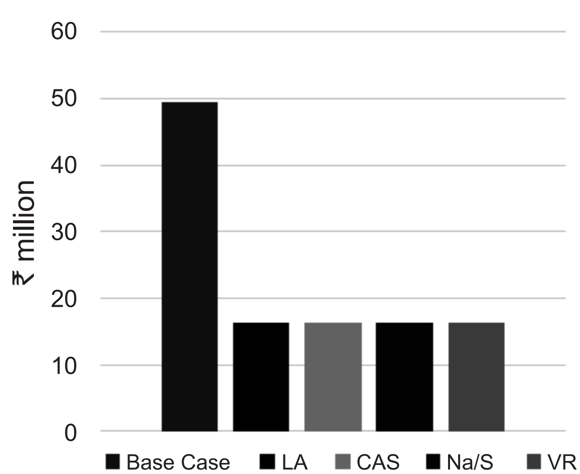


**Figure 3: Total annual ECOST variation**

It is observed that ECOST is same for any type of storage system. But, the energy storage cost varies for different storage techniques. This is because of the installation cost, operational and maintenance costs vary for each type of storage [7]. In Figure 4, presented the total annual cost (ECOST and storage cost) for different storage technologies. It is confirmed that Lead Acid (LA) type technology provides the least storage cost over the study period.

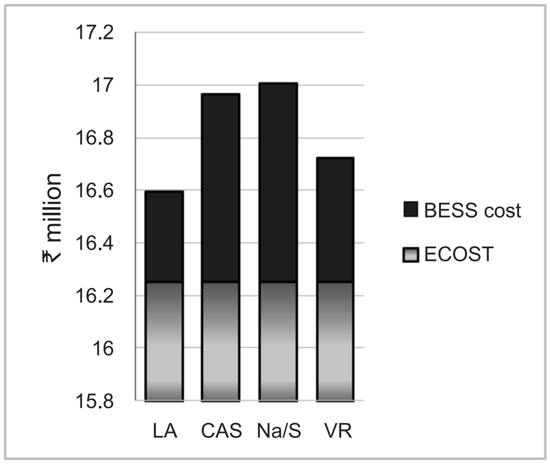


**Figure 4: Total annual cost for different storage types**

The total annual cost spent for interruption and energy storage are not same for all types of customers. The impact of interruption is less for residential customers when compared to industrial and commercial customers. So, that ECOST varies for different scenario of customers and the variation is shown in Figure 5, and it can be observed that more the residential customers then lesser the ECOST.

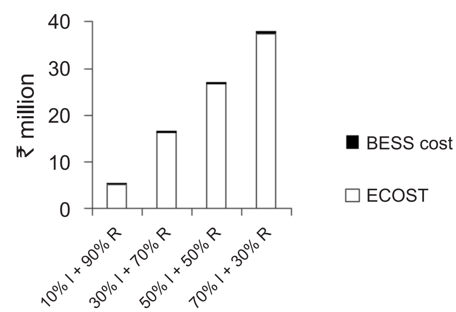


**Figure 5: Total annual cost for various scenarios of customers**

EENS index measures the amount of energy not delivered by the DGs and the BESS to the connected load during contingency. In Figure 6, the reliability measures in terms of EENS are presented. Since, the load shed are same for all types of storage technologies, the same EENS value are sketched in each case.

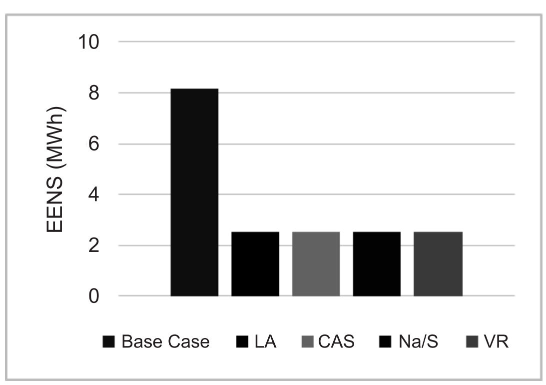


**Figure 6: EENS for the base case and different storage technologies**

### C. BESS Impact on Market Pricing Results

BESS are capable to support peak load by delivering power during peak demand. Further, BESS can charge during off peak demand, there by increases capacity factor of generating units and avoids the high unit cost associated with it.

The highest price of market equilibrium, with and without BESS is shown in Figure 7. It is noticed that the market pricing is leveled during off peak and peak demand duration with the integration of BESS. The price is increased during off peak hours due to charging of batteries and the prices are decreased during peak hours due to battery discharge.

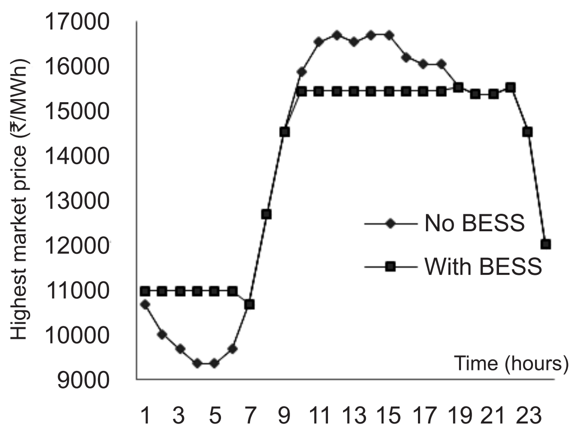


**Figure 7: Highest market price with and without BESS**

The charging and discharging rate of power from BESS throughout the day as a percentage is shown in Table 2.

**Table 2**
**BESS charging/discharging rate in %**

| *Hours* | *Charging or discharging in %* | *Hours* | *Charging or discharging in %* |
|---|---|---|---|
| 1 | 14.063 | 13 | –8.91 |
| 2 | 15 | 14 | –9 |
| 3 | 15.517 | 15 | –9 |
| 4 | 16.071 | 16 | –8.73 |
| 5 | 16.071 | 17 | –8.64 |
| 6 | 15.517 | 18 | –8.64 |
| 7 | 14.063 | 19 | 0 |
| 8 | 0 | 20 | 0 |
| 9 | 0 | 21 | 0 |
| 10 | –8.55 | 22 | 0 |
| 11 | –8.91 | 23 | 0 |
| 12 | –9 | 24 | 0 |

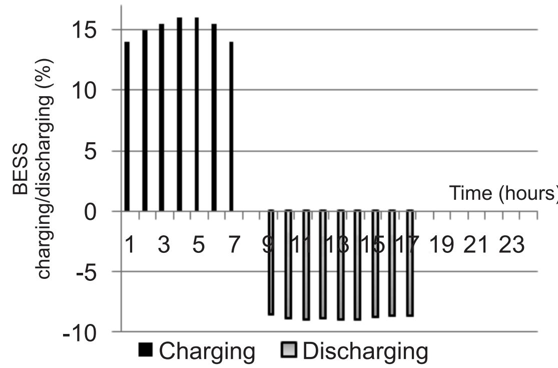


**Figure 8: Optimal BESS dispatch**

Further, in Table III presented the highest market price variation throughout the day without BESS, with 100 kWh and 200 kWh BESS sizes.

**Table 3**
**Highest market price variation for different storage sizes**

| *Hours* | *Highest market clearing price - ₹/MWh* | | |
|---|---|---|---|
| | *No BESS* | *100 kWh BESS* | *200 kWh BESS* |
| 1 | 10699 | 10200 | 10699 |
| 2 | 10031 | 10200 | 10699 |
| 3 | 9696.1 | 10200 | 10699 |
| 4 | 9361.8 | 10200 | 10699 |
| 5 | 9361.8 | 10200 | 10699 |
| 6 | 9696.1 | 10200 | 10699 |
| 7 | 10699 | 10590 | 10699 |
| 8 | 12705 | 12705 | 12705 |
| 9 | 14544 | 14544 | 14544 |
| 10 | 15882 | 15882 | 15882 |
| 11 | 16550 | 16255 | 15882 |
| 12 | 16718 | 16255 | 15882 |
| 13 | 16550 | 16255 | 15882 |
| 14 | 16718 | 16255 | 15882 |
| 15 | 16718 | 16255 | 15882 |
| 16 | 16216 | 16214 | 15882 |
| 17 | 16049 | 16049 | 15882 |
| 18 | 16049 | 15900 | 15882 |
| 19 | 15547 | 15547 | 15547 |
| 20 | 15380 | 15380 | 15380 |
| 21 | 15380 | 15380 | 15380 |
| 22 | 15547 | 15547 | 15547 |
| 23 | 14544 | 14544 | 14544 |
| 24 | 12037 | 12037 | 12037 |

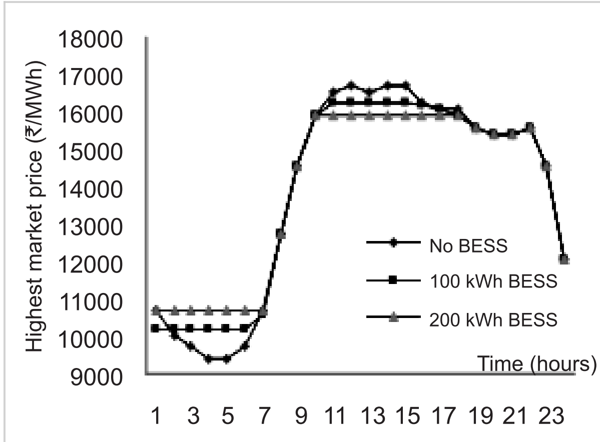


**Figure 9: Highest market price for different storage size.**

From Figure 9, it is observed that with the increase in the size of BESS more power can be exchange with the system. So that the market prices are high during off peak demand period and are settled at low during peak demand periods.

## 5. CONCLUSION

In this paper, PSO algorithm is proposed and is capable to find optimal location and sizing of BESS. Cost effective BESS allocation has performed to benefit both for utility as well as the customers. Under case study, 33-bus RDS is considered and four BESS technologies are compared against base case without BESS. It is clear that LA type BESS technology has suitable application and provided best solution of storage cost of ₹ 0.343 million per year in comparison of other battery technologies. The result shows the incorporation of batteries has reduced firms annual ECOST to ₹ 16.25 million in comparison to base case cost ₹ 49.4 million because of decrease in interruption costs. Further, it is observed that the sizing of BESS has direct impact on market equilibrium.

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