Multiobjective optimal sizing of battery energy storage in grid-connected microgrid

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Abstract: This work proposes a new multiobjective framework for the sizing of Battery Energy Storage (BES) for grid-connected microgrid. A combined Particle Swarm Optimization and Technique for Order of Preference by Similarity to Ideal Solution (PSO-TOPSIS) approach is explored to solve the formulated problem. A grid-connected microgrid consisting of various renewable sources and BES is considered as a test system. The results obtained are found to be promising. A trade-off between the formulated objectives is presented and analysed.

Nomenclature

| Symbol | Description |
|--------|-------------|
| MT, FC | Microturbine, Fuel cell |
| PV, WT | Photovoltaic, Wind turbine |
| DERs | Distributed Energy Resources |
| DG | Distributed Generator |
| BES | Battery Energy Storage |
| TCPD | Total cost/day of BES |
| r_i, l | Interest rate, lifetime of BES |
| FC | Fixed cost of BES |
| MC | Maintenance cost of BES |
| ES | Size of BES |
| T_i, t | Time horizon of 24 h, Hour index |
| Δt | Time interval of one hour |
| SOC_i | State of charge of battery at time t |
| η_d, η_c | Discharging and Charging efficiency of BESS respectively |
| TC | Total daily operation cost of microgrid |
| P_{nc}, P_{nd} | Charging and discharging power of BES |
| P_{grid,t}, P_{DG,t} | Output power of DG units, BES and exchanging power from the utility grid respectively t h hour |
| C_p, C_m, C_{grid} | Exchange power to/from grid utility at t h hour |
| p_{min}, p_{max} | Minimum, maximum output power limit |
| u_{i,t}, u_{i,new} | Unit status of the both the renewable and non-renewable DG units and BES respectively |
| SUC_i, SDC_i | Startup and shutdown cost of the DG units respectively |
| U, S | Total no. of DG units and total no. of BES respectively |
| C_1 and C_2 | Acceleration coefficients in PSO |
| w | Linearly decreasing inertia weight |
| P_{best}, G_{best} | Personal best position of the particle, Global best position of the particle |
| R_1, R_2 | Random numbers between 0 and 1 |
| Δt | Time step equals to 1 |
| v_{new}, S_n | Updated or new velocity and position of the particle in swarm |
| v_{old}, S_{n,old} | Previous/old velocity and position of the particle in swarm |
| iter, iter_max | Current iteration and maximum iterations in PSO algorithm |
| PIS, NIS | Positive ideal solution and negative ideal solution respectively |
| f_{ij} | Objective function |
| w_{ij} | Weightage assign to an objective |
| RCI | Relative closeness index |

1 Introduction

The growing smart grid concept and environmental concern lead the idea of microgrid under the paradigm of distributed generation. Microgrid is a small scale grid installed in distribution network or low voltage side of the system, deployed with the combination of renewable and non-renewable DGs and storage balancing the local load while taking various technical, socio-economic and environmental concerns into the account. The microgrid acts as a self-controlled entity and manages the local load while maintaining the uncertain power outputs and demand of the renewable DGs and consumer respectively. BES is a pivotal component of the microgrid. The salient features of BES could bring economic benefits to the microgrid owner when it is operated optimally i.e. co-ordinated charging/discharging of power to the utility grid. Apart from this, BES may also be beneficial in decreasing the carbon emissions from different generating units installed in microgrid such as Fuel cell (FC), Microturbine (MT), small scale diesel turbine etc. by discharging available power optimally at different instants of time. Thus, to optimally operate the microgrid, sizing of BES plays an important part in the microgrid. The single objective problem of BES sizing in microgrid is addressed in the literature. A sizing problem of BES is considered where the idea of microgrid under the paradigm of distributed generation. Microgrid is a small scale grid installed in distribution network or low voltage side of the system, deployed with the combination of renewable and non-renewable DGs and storage balancing the local load while taking various technical, socio-economic and environmental concerns into the account. The microgrid acts as a self-controlled entity and manages the local load while maintaining the uncertain power outputs and demand of the renewable DGs and consumer respectively. BES is a pivotal component of the microgrid. The salient features of BES could bring economic benefits to the microgrid owner when it is operated optimally i.e. co-ordinated charging/discharging of power to the utility grid. Apart from this, BES may also be beneficial in decreasing the carbon emissions from different generating units installed in microgrid such as Fuel cell (FC), Microturbine (MT), small scale diesel turbine etc. by discharging available power optimally at different instants of time. Thus, to optimally operate the microgrid, sizing of BES plays an important part in the microgrid. The single objective problem of BES sizing in microgrid is addressed in the literature. A sizing problem of BES is considered where the objective is to optimize the total operating cost of the microgrid for a day [1–3]. Thongchart Kerdpno et al. addresses the battery sizing problem to reduce the cost for a standalone microgrid [4]. Mohammad Reza Aghamohammadi and Haja Abdolahinia consider the battery sizing problem for the primary frequency control in the standalone microgrid [5]. An optimal battery sizing is obtained considering interruptible load in standalone microgrid [6]. Some metaheuristic techniques such as PSO, Grey Wolf Optimization (GWO), Elephant Herding Optimisation (EHO), and Modified Elephant Herding Optimisation (MEHO) for the battery sizing problem are very well explored in literature and found to be promising [7–9]. However the multi-objective problem for optimal BES sizing considering the cost of microgrid and demand response is presented [10], it has been noticed that very less work is reported in literature for multiobjective optimal BES sizing in microgrid. To the best of author(s) knowledge multiobjective problem formulation and analysis of BES sizing in the microgrid considering the cost of the microgrid and environmental aspects are not considered in literature properly. Moreover, the combined Particle Swarm Optimization and Technique for Order of Preference by Similarity to Ideal Solution (PSO-TOPSIS) approach is not explored in the literature for the discussed problem. Following are the major contributions of the work:

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1. A new multiobjective problem formulation for optimal BES sizing in the grid-connected microgrid is proposed.
2. A combined PSO-TOPSIS approach is proposed to solve the formulated problem.

2 Modelling of battery energy storage

In this work, Lithium-ion BES is considered. These BESs are a most popular type of storage system for microgrid application due to its best energy to weight ratio, low steady-state losses and negligible toxic emissions as compared to other type of battery energy storages such as NiMH and lead acid.

The SOC status after charging and discharging of the BES at a particular time instant can be updated as:

Charging: $\text{SOC}_{i+1} = \text{SOC}_i + (\Delta t \times P_{\text{in},i}) \eta_i$ \hspace{1cm} (1)

Discharging: $\text{SOC}_{i+1} = \text{SOC}_i - (\Delta t \times P_{\text{out},i}) \eta_d$ \hspace{1cm} (2)

The total investment cost per day of BES is given by:

$$\text{TCPD} = \frac{1}{365} \left[ \frac{r(1+r)^j}{(1+r)^j - 1} FC \times ES + ES \times MC \right]$$ \hspace{1cm} (3)

3 Problem formulation

The optimal sizing of BES aims to reduce the total cost of the microgrid and the total emissions from the generating units installed in microgrid as well as the power exchange from the utility grid for a finite time horizon $T$.

$$\min f_1 = \sum_{t=1}^{T} \left[ \sum_{i=1}^{I} \left[ u_i (P_{\text{in},i} \times C_i) + \text{SUC}_{i,t} + \text{SDC}_{i,t} \right] + \sum_{n=1}^{S} \left[ u_n C_n \right] \right] + \text{TCPD}$$ \hspace{1cm} (4)

$$\min f_2 = \sum_{t=1}^{T} \left[ \sum_{i=1}^{I} \left[ P_{\text{grid},i} \times C_{\text{grid},i} \right] \right]$$ \hspace{1cm} (5)

$$F = \text{Optimal}[f_1, f_2]$$ \hspace{1cm} (6)

s.t.

1. Power balance constraints:

$$P_{\text{grid},i} - P_{\text{load},i} = 0$$ \hspace{1cm} (7)

2. Power limiting constraints of DG units, BES and grid

$$P_{\text{in},i} \leq P_{\text{nom},i}, P_{\text{out},i} \leq P_{\text{nom},i}, P_{\text{grid},i} \leq P_{\text{grid},i}$$ \hspace{1cm} (8)

3. SOC constraints of the battery:

$$\text{SOC}_{\text{min},i} \leq \text{SOC}_{i} \leq \text{SOC}_{\text{max},i}$$ \hspace{1cm} (9)

4 Proposed methodology

The multi-objective optimal problem is a complex optimization problem due to the imposition of various system constraints and dynamic/coupling BES constraints. To solve the multiobjective optimal sizing problem of BES in grid-connected microgrid, an efficient combined PSO-TOPSIS approach is explored. PSO is a most popular swarm intelligence technique in literature having potential to solve the various type of complex optimization problems whereas TOPSIS is a multi-criteria decision analysis method based on Euclidean geometry in which optimal solution is selected based on its optimal Euclidean distance from Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) [7,9]. The TOPSIS approach comprises of the following mathematical steps:

1. Normalized Decision Matrix

This matrix is used to change all dimensional quantitates into non dimensional quantities and can be given by (10)

$$N_{ij} = \frac{f_j}{\sum_{i=1}^{n} f_j}$$ \hspace{1cm} (10)

2. Weighted Normalized Decision Matrix

This matrix is used to assign the weightage to the objectives if required otherwise it can be skipped if all objectives are of the same weightage.

$$W_{ij} = w_{it} \times N_{ij}$$ \hspace{1cm} (11)

3. Calculation of PIS and NIS

PIS and NIS are the vectors containing the best and worse solutions of the objectives respectively.

$$\text{PIS} = [W_{1t}, W_{2t}, W_{3t}, \ldots, W_{ht}]$$ \hspace{1cm} (12)

$$\text{NIS} = [W_{1t}, W_{2t}, W_{3t}, \ldots, W_{ht}]$$ \hspace{1cm} (13)

4. Calculation of Euclidean distance

In this step Euclidean distance of each alternative solution from PIS and NIS can be calculated using (13).

$$D_i^+ = \sqrt{\sum_{j=1}^{h} (W_{ij} - W_{j})^2}$$ \hspace{1cm} (14)

5. Calculation of Relative closeness index

The solution corresponding to the highest valued RCI corresponding represents the best compromising solution.

$$RCI = \frac{D_i^-}{D_i^- + D_i^+}$$ \hspace{1cm} (15)

PSO is a swarm based intelligence technique in which the particles in swarm moves with a certain velocity to reach the optimal solution by updating their present positions. The equation to update the velocity and position of particles are given by (16) (17).

$$v_{i}^{(t+1)} = w \times v_{i}^{(t)} + c_1 \times r_1 \times (P_{\text{best},i} - v_{i}^{(t)}) + c_2 \times r_2 \times (P_{\text{grid},i} - S_{\text{new},i})$$ \hspace{1cm} (16)

Where,

$$w = \left( w_{\text{max}} - w_{\text{min}} \right) \left( \frac{\text{iter}_{\text{max}} - \text{iter}}{\text{iter}_{\text{max}}} \right) + w_{\text{min}}$$ \hspace{1cm} (17)

$$S_{\text{new},i} = S_{\text{old},i} + v_{i}^{(t)}$$

In this work, the combination of PSO and TOPSIS is implemented to solve the formulated problem. The objectives are evaluated by assigning equal weightage, the acceleration coefficients in PSO are set to 2, the maximum and minimum value of inertia weight is taken as 0.9 and 0.4, respectively, the PSO is implemented with the maximum range of 50 kWh and the maximum number of iteration is set to 30. Fig. 1 shows the flowchart of the technique implemented.

5 Simulation results and discussion

A grid-connected microgrid consisting of MT, FC, PV, WT and BES is considered as a test system [11,12]. The fixed cost, maintenance cost and the lifetime of BES is assumed as 465 €ct/kWh, 15 €ct/kWh and 3 years respectively. Also, the charging and discharging efficiency of the BES is considered as 0.9. The initial SOC of BES is equal to its full capacity and the minimum of SOC is considered as 10% of its full energy rating. The maximum range for sizing of BES is considered as 1700 kWh and each size is taken with the increase in step size of 100 kWh [1]. It is assumed that the
The unit status of the WT and PV is always equal to one. The daily load demand and the generated power from wind and PV are shown in Figs. 2 and 3 respectively. Table 1 shows the power limits, bids and emissions of different DGs, BES and utility grid market price; while Table 2 shows the market price which varies hourly. The multiobjective sizing of BES is solved for the considered test system and a detailed analysis is performed and discussed.

The total cost and emission for the considered test system are obtained after minimizing both the objectives individually for each size of the BES is shown in Figs. 4 and 5, respectively. It can be clearly seen from the results that the obtained optimal size of BES is 300 kWh with TC 923.06 €ct, in case when only TC is minimized; However, if emission is merely minimized, the optimal size of BES is 800 kWh with total emissions of 621.78 kg/MWh.

The curve showing a relation between the size of BES and the optimal solutions after minimizing the total cost and emissions of the microgrid simultaneously is shown in Fig. 6. The optimal size of BES for the multiobjective problem is 700 kWh, which is obtained as the best compromising solution having highest RCI index value in all the optimal solutions obtained after solving the formulated objectives simultaneously. The total cost obtained for the optimal size of BES is 1123.13 €ct and the emission is 776.09 kg/MWh. It has been observed from the optimal solution curve that after 700 Kwh, TC is increasing continuously while the emission remains approximately the same for further BES sizes. This is due to the fact that TC is increasing with TCPD, which is continuously increasing with the increase in the size of BES by 51.77 €ct while the emissions are dependent on the output of the generating sources, BES and the utility grid. Thereby, a trade-off between the two objectives is noticed. Fig. 7 shows the scheduling of the microgrid for the obtained best compromising size of the BES.

| S. No | Type | Min power (kW) | Max power (kW) | Bid (€ct/kWh) | Start-up/shut-down cost (€ct) | CO₂ (kg/MWh) | SO₂ (kg/MWh) | NOₓ (kg/MWh) |
|-------|------|----------------|----------------|---------------|-----------------------------|--------------|--------------|--------------|
| 1     | MT   | 6              | 30             | 0.457         | 0.96                        | 720          | 0.036        | 0.1          |
| 2     | FC   | 3              | 30             | 0.294         | 1.65                        | 460          | 0.03         | 0.0075       |
| 3     | PV   | 0              | 25             | 2.584         | 0                           | 0            | 0            | 0            |
| 4     | WT   | 0              | 15             | 1.073         | 0                           | 0            | 0            | 0            |
| 5     | BES  | -30            | 30             | 0.38          | 0                           | 10           | 0.02         | 0.01         |
| 6     | Grid | -30            | 30             | –             | 1072                        | –            | 0.6          | 7.0          |

![Flow chart of PSO-TOPSIS](image1)

![Load demand](image2)

![Renewable Power Generation](image3)
to the utility grid however the negative values of power from BES means the battery storage is in charging mode

### Conclusions

A multiobjective problem for optimal sizing of BES in microgrid is formulated and solved. A combined PSO-TOPSIS multiobjective technique is successfully explored and the results show a trade-off between the two objectives which validates that the proposed technique is able to solve the formulated problem in an efficient manner. A detailed analysis is performed in which the significant impact of sizing of BES on the operating cost and emission of microgrid is noticed.

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