Optimum Placement of Battery Energy Storage Systems and Solar PV Units in Distribution Networks Using Gravitational Search Algorithm

Preetham Goli[1(✉)], Srikanth Yelem[1], Kiran Jasthi[2], Srinivasa Rao Gampa[2], and D. Das[3]

[1] University of Missouri Kansas City, Kansas City, MO, USA
golip@umkc.edu
[2] Seshadri Rao Gudlavalleru Engineering College, Gudlavalleru 521356, A.P., India
[3] IIT Kharagpur, Kharagpur 721302, West Bengal, India

Abstract. This paper proposes the optimum sizing and placement of photovoltaic (PV) units and battery energy storage systems using the Gravitational Search Algorithm (GSA) to minimize the burden on the substation. The solar PV units are allocated for daytime peak load reduction and the evening load is compensated with battery energy storage systems. Optimum placement and sizing of solar PV units and shunt capacitors is carried out to minimize the real and reactive powers drawn from the substation to a predefined value, minimize the active power losses, and improve the distribution system's voltage profile. The BESS capacity required for nighttime is also estimated by considering similar objectives. Simulation results have been presented using a 69 bustest system to demonstrate the significance of the proposed methodology.

Keywords: Battery energy storage system (BESS) · Gravitational search algorithm (GSA) · Solar Photovoltaic (PV) units · Distribution systems · Shunt capacitors

1 Introduction

The uncertain nature of renewable energy sources mandates the installation of energy storage systems to provide continuous power supply to customers and overcome the deficiency of fossil fuels. Solar PV units can be used to compensate for the daytime peak load and the load during the evening can be supplied from battery energy storage systems. The batteries can be charged either from the solar photovoltaic units or the power grid during the off-peak period. The optimum placement of solar PV and BESS units is required to reduce the energy losses and enhance the voltage profile.

The distribution system reinforcement using energy storage systems has attracted the research community for the past several years. Reference [1] proposed a Genetic Algorithm (GA) based optimization method for the placement of energy storage devices along with wind turbines. Goli et al. [2] developed ANT colony optimization to achieve the

V. E. Balas et al. (Eds.): AITEES 2022, AHIS 3, pp. 113–123, 2023.
https://doi.org/10.2991/978-94-6463-074-9_11

predetermined performance of distribution systems. Wong et al. [3] applied a whale meta-heuristic algorithm for optimal battery energy storage systems allocation. Bineetha and Das [4] proposed a multiobjective reconfiguration approach for substations installed with DGs and BESS units. Novoa et al. [5] proposed a mixed-integer linear program-based technique for efficient placement of energy storage systems considering transformer limits. Das et al. [6] proposed a chaotic artificial bee colony optimization methodology for optimum energy storage systems allocation for power quality improvement. Yuan et al. [7] applied a novel Cayote optimization-based algorithm to size and allocate BESS in distribution systems and Lim et al. [8] developed a GA-based optimization technique to minimize the energy demand at residential locations.

Farrokifar et al. [9] developed a stochastic mixed-integer linear programming technique for optimum energy management in the residential sector using battery systems. The GA-based methodology was proposed by authors in reference [10] for the allocation of battery storage systems to minimize the effects of solar energy curtailments. Saini and Gidwani [11] proposed a GA-based techno-economical methodology with BESS placement. Anuradha et al. [12] proposed a voltage and loss sensitivity analysis based technique and Thokar et al. [13] used a moth search algorithm for allocating BESS to enhance the DG capacity. Ahmadi et al. [14] proposed a multi-verse optimization algorithm-based approach for optimum coordination of BESS with DGs. Pederson et al. [15] developed a multi-period optimal power flow based approach to minimize distribution system expansion costs by the optimal placement of BESS units. This paper proposes a GSA-based optimization method to optimally size and allocate solar DGs and BESS units for managing the peak load with improved power quality of the distribution network.

2 Multiobjective Function

Optimum allocation of BESS and DGs is considered using GSA to minimize the burden on the substation along with active power loss reduction and improvement of node voltages. The mathematical expressions describing the objective functions are explained in the following sections.

2.1 Substation Real Power Index

The substation real power index is represented mathematically by the following equation

$$J_{SDGP/BESSP} = \left| \frac{SSRP^{SDGP/BESSP} - \alpha\, SSRP^{Base}}{SSRP^{Base}} \right| \tag{1}$$

where $J_{SDGP/BESSP}$ is the substation real power index. $SSRP^{SDGP/BESSP}$ is the real power drawn from the substation by considering DGs/BESS and SCs and $SSRP^{Base}$ is the base case real power supplied by the substation.

2.2 Substation Reactive Power Index

The objective to minimize the substation reactive power to a fraction of the base case value is represented by the following expression

$$J_{SDGQ/BESSQ} = \left| \frac{SSQP^{SDGQ/BESSQ} - \beta\, SSQP^{Base}}{SSQP^{Base}} \right| \tag{2}$$

where $J_{SDGQ/BESSQ}$ is the substation reactive power index. $SSQP^{SDGQ/BESSQ}$ is the reactive power drawn from the substation with PVDGs/BESS and SCs and is the base case substation reactive power.

2.3 Voltage Deviation Minimization Index

The objective is to improve all the node voltages close to unity. It is formulated as follows

$$J_{VT} = \frac{\sqrt{\sum_{i=1}^{N} (1 - V_i^{SDG/BESS})^2}}{\sqrt{\sum_{i=1}^{N} (1 - V_i^{Base})^2}} \tag{3}$$

where J_{VT} is the voltage deviation minimization index. $V_i^{SDG/BESS}$ is the ith node voltage with PVDGs/BESS and shunt capacitors. V_i^{Base} is the base case value at the ith node.

2.4 Real Power Loss Reduction Index

The real power loss reduction index (J_{RPL}) is mathematically expressed by the following Eq. (4).

$$J_{RPL} = \frac{RPL^{SDG/BESS}}{RPL^{Base}} \tag{4}$$

$RPL^{SDG/BESS}$ is the active power loss in presence of DGs/BESS and SCs and RPL^{Base} is the base case value of active power loss.

The multiobjective function for the optimal allocation and sizing of PVDGs and BESS units is given by Eq. (5).

$$\text{Minimize } J_C = J_{SDGP/BESSP} + J_{SDGQ/BESSQ} + J_{VT} + J_{RPL} \tag{5}$$

3 GSA Search Algorithm

The GSA [16] is a population-based search algorithm developed using newton's law of gravity. It states that gravitational force of attraction exists between any two particles.

In a system with N masses the position of ith mass can be defined in the Euclidian space as

$$X_i = (x_i^1, x_i^2, x_i^3 \ldots x_i^n) \text{ for i } = 1, 2, 3, \ldots \text{N}.$$

The force on mass i due to mass j can be calculated at a given iteration by the following equation.

$$Force_{ij}^d(t) = G(t)\frac{MA_{pi}(t) \times MP_{aj}(t)}{Rd_{ij}(t) + \varepsilon}(x_j^d(t) - x_i^d(t)) \tag{6}$$

where $MA_{ai}(t)$ and $MP_{pj}(t)$ are the active and passive gravitational masses. Rd_{ij} is the Euclidian distance between the two masses i and j. ε is a small constant. $G(t)$ is a constant initialized at the beginning and controlled at every iteration.

The force on the i^{th} mass in $\mathrm{d^{th}}$ dimension is expressed by Eq. (7).

$$Force_i^d(t) = \sum_{\substack{j=1 \\ j \neq i}}^{N} rand_j Force_{ij}^d(t) \tag{7}$$

The acceleration of the $\mathrm{i^{th}}$ agent at time t and in the $\mathrm{d^{th}}$ direction is obtained by Eq. (8).

$$accel_i^d(t) = \frac{Force_i^d(t)}{M_i(t)} \tag{8}$$

The mass of the $\mathrm{i^{th}}$ agent in the population can be defined as

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_j(t)} \tag{9}$$

$$m_i(t) = \frac{fit_i(t) - \mathrm{worst}(fit_\mathrm{i}(t))}{\mathrm{best}(fit_i(t)) - \mathrm{worst}(fit_\mathrm{i}(t))} \tag{10}$$

where $fit_i(t)$ represents the fitness value of agent i, $best\big(fit_i(t)\big)$ and $worst\big(fit_i(t)\big)$ are the minimum and maximum values of the fitness function.

The next generation population can be determined by the following velocity and position equations.

$$v_i^d(t+1) = rand_i \times v_i^d(t) + accel_i^d(t) \tag{11}$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \tag{12}$$

4 Proposed Methodology

The distribution system is reinforced with PVDGs and BESS units to achieve the objectives discussed in Sect. 2.

The optimum size and locations of PVDGs and SCs are determined during the first stage to support the peak load during the daytime. During the second stage, the optimum size of BESS units and SCs are determined to compensate for the evening peak load by allocating them to the exact locations obtained during the first stage.

The 24 h distribution system load is classified into three different load factors. Each load factor is considered for eight hours. The load factors considered are: 0.4 for the load between 12 am and 8 am, 1.0 for the load between 8 am and 4 pm, and 0.7 for the load between 4 pm to 12 am. The division of the load is shown in Fig. 1.

4.1 Step by Step Algorithm of GSA

The procedural steps for optimal sizing and allocation of solar PV units and SCs are enumerated as follows.

Step 1**:** Generate the population for PV units and shunt capacitors and their locations.
Step 2: Find the fitness and mass of all the agents in the population.
Step 3: Determine the force on each agent in all the dimensions using Eqs. (6) and (7).
Step 4: Find the acceleration component in each dimension using Eq. (8).
Step 5: Update the velocity and positions of the agents using Eqs. (11) and (12).
Step 6: Incorporate the best solution.
Step 7: If Iter $<$ Iter$_{\text{Max}}$ Go To ***Step 3*** otherwise, Go To Step 8.
Step 8: Store the best solution.

Similar procedure is applied to determine the optimum size of the BESS units at a load factor of 0.7. The BESS units are allocated at the locations obtained for PV DGs.

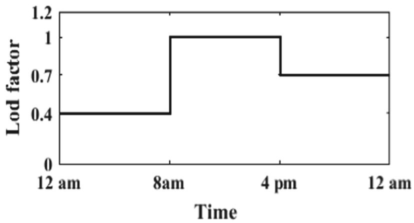

Fig. 1. Load factors in a day

5 Results and Discussions

In this section, the proposed optimization algorithm based on GSA is validated by using a 69 node, 12.66 kV distribution network [17]. Negative PQ load modeling is considered for DGs, BESS units and shunt capacitors [18]. During the first stage, the optimum size of PVDGs and SCs is determined using GSA by minimizing the objective function described by Eq. (5) at peak load.

Two case studies are implemented by considering different values for the predefined factors α and β. The values of α and β in Eq. (5) are considered as 0.25 in the first case and 0.5 in the second case. The optimization problem is solved for 25% and 50% reduction in substation real and reactive powers. In the second stage, the optimum size of the BESS units is determined by allocating them at the locations of the PVDGs by using the GSA-based multiobjective function at a load factor of 0.7. The optimum locations and size of the PVDGs and SCs obtained during the first stage for different values of α and β are shown in Table 1 and Table 2.

In case-1, it is desired to reduce the substation active power to 25% of the base case value, whereas it is 50% in case-2. Therefore, the amount of PV injected is greater in case-1 compared to case-2. Similar explanation can be given for the reactive power supplied by the shunt capacitors. The optimum sizing of BESS units and SCs obtained at 0.7 load factor for different values of α and β are shown in Tables 3 and 4.

Table 1. Case 1-Optimum values of PV units and SCs

$\alpha = \beta = 0.25$			
Node Location	PVs (kW)	Node Location	SCs (kVAr)
64	950.5500	53	370.2234
69	913.7277	56	488.7902
65	676.013	63	304.4430

Table 2. Case 2-Optimum values of PV units and SCs

$\alpha = \beta = 0.5$			
Node Location	PVs (kW)	Node Location	SCs (kVAr)
60	813.0759	23	575.2421
24	405.2954	69	109.3509
65	625.2311	57	286.0122

Table 3. Case 1-Optimum values of BESS units and SCs

$\alpha = \beta = 0.25$			
Node Location	BESS (kWh)	Node Location	SCs (kVAr)
64	7604.5	53	299.2612
69	6680.9104	56	275.6487
65	1099.052	63	206.0512

Table 4. Case 2-Optimum values of BESS units and SCs

$\alpha = \beta = 0.5$			
Node Location	BESS (kWh)	Node Location	SCs (kVAr)
60	4994.9576	23	148.1016
24	2214.9336	69	219.7805
65	4218.36	57	90.9151

Table 5. Performance at peak load with PVDGs and SCs

Peak load	Base Case	With PVs and SCs	
		$\alpha = 0.25$ $\beta = 0.25$	$\alpha = 0.5$ $\beta = 0.5$
Substation real power (kW)	4027.19	1290.775	1994.784
Substation reactive power (kVAr)	2796.77	713.5427	1138.007
Min voltage (p.u)	0.9092	0.9898	0.97865
Real power loss (kW)	225	28.8765	36.1971

It can be inferred from Tables 1, 2, 3 and 4 that the BESS units and SCs are allocated at the exact locations of PVDGs and SCs determined in stage 1. In addition, it has to be noted that the ratings of the SCs are reduced during the second stage since optimization is performed at a load factor of 0.7. The improvement inthe performance of the distribution system in presence of PVs and SCs at peak load is shown in Table 5.

From the above table, it can be observed that the active power supplied by the substation is reduced to 32% and 49.5% and reactive power drawn from the substation is reduced to 28.58% and 40.7% for the two cases considered. Therefore, it can be concluded that the performance of the distribution network has improved in presence of PVs and SCs. The distribution system's performance system with BESSs and SCs at 0.7 load factor is shown in Table 6.

Table 6. Performance at 0.7 load factor with BESS units and SCs

Peak load	Base Case	With BESSs and SCs	
		$\alpha = 0.25$ $\beta = 0.25$	$\alpha = 0.5$ $\beta = 0.5$
Substation Real power (kW)	2766	753.3973	1250.242
Substation Reactive power (kVAr)	1933.9	481.5878	967.9456
Min voltage (p.u)	0.93825	0.996	0.98512
Real power loss (kW)	104.535	14.9096	17.2406

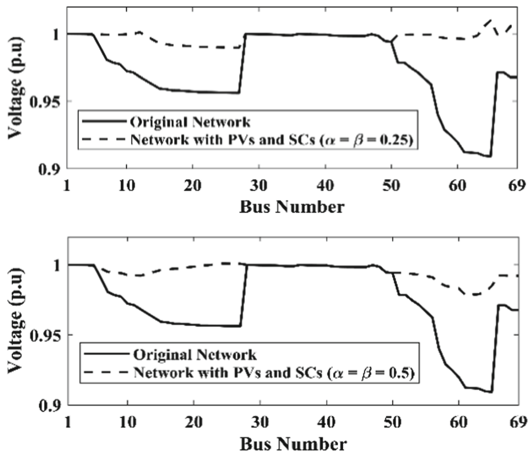

Fig. 2. Voltage profile with PVs and SCs

From the above table, it can be inferred that the active power drawn from the substation is reduced to 27.2% and 45%, and the reactive power drawn from the substation is reduced to 24.9% and 50%.

Figures 2 and 3 depict the node voltage profile of the distribution system with the addition of PVs and BESS units. The figures show that the voltage profile is improved with the presence of PVs during the daytime and the BESS units during the evening for different values of the predefined factors α and β.

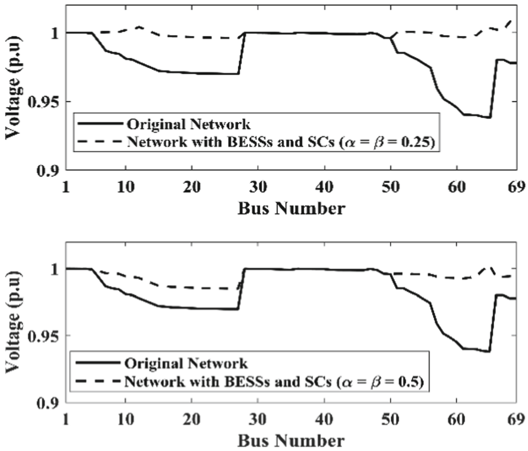

Fig. 3. Voltage profile with BESS units and SCs

6 Conclusions

A two-stage optimization algorithm based on the Gravitational Search Algorithm (GSA) has been presented in this paper for the optimum sizing of PVDGs and BESS units to minimize the power drawn from the substation and improve the performance of the distribution network. PVDGs and SCs support the peak load during the daytime and the load during the evening is compensated by BESS units and SCs. The BESS units can be charged from the grid during the off-peak period or by installing additional PVDGs. Simulation results demonstrate the efficacy of the proposed algorithm to improve the performance of the distribution network by installing PVDGs, BESS units and shunt capacitors.

References

1. Khaki, B.: Joint sizing and placement of battery energy storage systems and wind turbines considering reactive power support of the system. J. Energy Storage **35** (2021). https://doi.org/10.1016/j.est.2021.102264
2. Goli, P., Makkena, S., Gampa, S.R., Das, D.: Fuzzy ant colony optimization technique for predefined performance of distribution systems considering DGs and shunt capacitors. In: 51st 2019 North American Power Symposium NAPS 2019 (2019). https://doi.org/10.1109/NAPS46351.2019.9000250
3. Wong, L.A., Ramachandaramurthy, V.K., Walker, S.L., Taylor, P., Sanjari, M.J.: Optimal placement and sizing of battery energy storage system for losses reduction using whale optimization algorithm. J. Energy Storage **26** (2019). https://doi.org/10.1016/j.est.2019.100892
4. Mukhopadhyay, B., Das, D.: Multiobjective dynamic and static reconfiguration with optimized allocation of PV-DG and battery energy storage system. Renew. Sustain. Energy Rev. **124** (2020). https://doi.org/10.1016/j.rser.2020.109777

5. Novoa, L., Flores, R., Brouwer, J.: Optimal renewable generation and battery storage sizing and siting considering local transformer limits. Appl. Energy **256** (2019). https://doi.org/10.1016/j.apenergy.2019.113926
6. Das, C.K., et al.: Optimal allocation of distributed energy storage systems to improve performance and power quality of distribution networks. Appl. Energy **252** (2019). https://doi.org/10.1016/j.apenergy.2019.113468
7. Yuan, Z., Wang, W., Wang, H., Yildizbasi, A.: A new methodology for optimal location and sizing of battery energy storage system in distribution networks for loss reduction. J. Energy Storage **29** (2020). https://doi.org/10.1016/j.est.2020.101368
8. Lim, K.Z., Lim, K.H., Bin Wee, X., Li, Y., Wang, X.: Optimal allocation of energy storage and solar photovoltaic systems with residential demand scheduling. Appl. Energy **269** (2020). https://doi.org/10.1016/j.apenergy.2020.115116
9. Farrokhifar, M., Aghdam, F.H., Alahyari, A., Monavari, A., Safari, A.: Optimal energy management and sizing of renewable energy and battery systems in residential sectors via a stochastic MILP model. Electr. Power Syst. Res. **187** (2020). https://doi.org/10.1016/j.epsr.2020.106483
10. Mohamad, F., The, J., Lai, C.M.: Optimum allocation of battery energy storage systems for power grid enhanced with solar energy. Energy **223** (2021). https://doi.org/10.1016/j.energy.2021.120105
11. Saini, P., Gidwani, L.: An environmental based techno-economic assessment for battery energy storage system allocation in distribution system using new node voltage deviation sensitivity approach. Int. J. Electr. Power Energy Syst. **128** (2021). https://doi.org/10.1016/j.ijepes.2020.106665
12. Anuradha, K.B.J., Jayatunga, U., Perera, H.Y.R.: Loss-voltage sensitivity analysis based battery energy storage systems allocation and distributed generation capacity upgrade. J. Energy Storage **36** (2021). https://doi.org/10.1016/j.est.2021.102357
13. Thokar, R.A., Gupta, N., Niazi, K.R., Swarnkar, A., Meena, N.K.: Multiobjective nested optimization framework for simultaneous integration of multiple photovoltaic and battery energy storage systems in distribution networks. J. Energy Storage **35** (2021). https://doi.org/10.1016/j.est.2021.102263
14. Ahmadi, M., Adewuyi, O.B., Danish, M.S.S., Mandal, P., Yona, A., Senjyu, T.: Optimum coordination of centralized and distributed renewable power generation incorporating battery storage system into the electric distribution network. Int. J. Electr. Power Energy Syst. **125** (2021). https://doi.org/10.1016/j.ijepes.2020.106458
15. Pedersen, J., Schachler, B., Heider, A., Pleßmann, G.: Distribution system planning with battery storage using multi period optimal power flow. In: Proceedings of 14th International Renewable Energy Storage Conference 2020 (IRES 2020), vol. 6, no. Ires 2020, pp. 41–48 (2021). https://doi.org/10.2991/ahe.k.210202.007
16. Rashedi, E., Nezamabadi-pour, H., Saryazdi, S.: GSA: a gravitational search algorithm. Inf. Sci. (NY) **179**(13), 2232–2248 (2009). https://doi.org/10.1016/j.ins.2009.03.004
17. Savier, J.S., Das, D.: Impact of network reconfiguration on loss allocation of radial distribution systems. IEEE Trans. Power Deliv. **22**(4), 2473–2480 (2007). https://doi.org/10.1109/TPWRD.2007.905370
18. Hung, D.Q., Mithulananthan, N., Bansal, R.C.: Analytical expressions for DG allocation in primary distribution networks. IEEE Trans. Energy Convers. **25**(3), 814–820 (2010). https://doi.org/10.1109/TEC.2010.2044414