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Optimal Allocation of Distributed Generation, Capacitor Banks and D-STATCOM in Distribution Systems

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Abstract
This paper demonstrates the problem of simultaneous optimal allocation of distributed generations (DGs), shunt capacitor banks (CBs), and distribution FACTSs based D-STATCOMs in distribution network for the improvement of the entire system performance. Here, two objectives, total power loss minimization, and overall voltage stability index (VSI) maximization are considered. In general, minimization of power loss is the primary objective, and VSI is considered for improved voltage stability. VSI must be positive to obtain a stable operation and a higher VSI value represents better stability of the RDS. These objectives are solved subject to constraints related to power balance, DGs, CBs, D-STATCOM powers, bus voltages, and VSI. Here, single objective problem is solved using Particle swarm optimization (PSO), and the multi-objective problem is solved using multi-objective PSO (MO-PSO). Standard 33 bus RDS is considered for solving this problem. The results obtained show that proposed optimization has improved the voltage profile and overall VSI of the RDS and minimized the system power losses.

Keywords- Distributed generation, Shunt compensation, Voltage stability, Power loss, Evolutionary algorithms.

1. Introduction

The use of distributed generation (DG) has been growing rapidly in the distribution systems during the last decade. The maturity in renewable energy sources (RESs) has significantly reduced the installation and maintenance costs. In recent years, all the countries are moving toward the large-scale penetration of RESs. Due to the reduced cost of RESs and also land availability in the countries like the USA and Australia have attracted the RESs investments. As the RESs are sustainable, economical, and environmentally friendly sources of energy, all the governments are developing plans and investments for the large-scale penetration of RESs and their utilization as much as possible (Kola, 2018; Sampangi and Jayabarathi, 2020). The incorporation of renewable-based DGs that as wind turbines, solar PV plants, and biomass plants leads to economic, technical, and environmental benefits.

To enhance the performance of existing distribution networks, distributed generations (DGs), shunt capacitor banks (CBs), and distribution FACTs based D-STATCOM are used in this work. The CBs and D-STATCOMs are used to control the voltage levels in radial distribution system (RDS) by supplying the reactive power. These units help to prevent voltage instabilities and to improve the power quality (PQ) of RDS by maintaining the voltages within the allowable limits (Mistry and Roy, 2014). By installing these devices, the amount of reactive power consumption from the utility grid can be minimized as they provide local support. The installation of these devices leads to the reduction in bus voltage deviations, power losses, operational costs as well as pollution. Voltage stability is also considered as an important tool for optimal operation of RDS. Voltage stability refers to the ability of network to maintain good level of voltages under stressed operating conditions (Sampangi and Thangavelu, 2020). By the simultaneous installation of DGs, CBs, and D-STATCOM leads to the improvement in voltage stability.

1.1 Literature Review

Various methods and algorithms have been proposed in the literature to find the optimal operation of DGs, D-STATCOM, and CB units. An approach for network reconfiguration (NR) considering the heuristic methods and fuzzy based multi-objective technique is proposed in Das (2006). Tanwar and Khatod (2017) proposes an optimal allocation of non-schedulable (solar and wind energy) and schedulable (biomass energy) renewable DG units in an RDS. A multi-objective optimization (MOO) problem considering economic, environmental, and technical indices that is power loss, maximum capacity of line current, and voltage deviation has been developed in Bahar et al. (2018). Hassan et al. (2020) examines an optimal allocation of DGs that optimizes the power loss and voltage stability. An approach to efficiently optimize the power losses within the RDS by optimally placing and sizing of DG units with the reconfiguration of the system is proposed in Abd El-Salam et al. (2018). Nguyen et al. (2019) proposes a chaotic stochastic fractal search technique for optimal sizing and placement of DGs power loss reduction objective subjected to DG penetration and capacity, branch current, power balance, and bus voltage limits.

Various evolutionary-based algorithms are proposed in recent years. A fuzzy-based Ant Colony Optimization (ACO) technique with different fuzzy weights for finding the solution of shortest path problem is proposed in Caprio et al. (2022), with fuzzy arc weights has been proposed in Ebrahimnejad et al. (2016). A Particle swarm optimisation (PSO) technique for evaluating the problems of shortest path with mixed fuzzy arc weights is proposed in Ebrahimnejad et al. (2015). A binary artificial algae algorithm is proposed in Poria et al. (2021), a modified artificial bee colony algorithm is proposed in Ebrahimnejad et al. (2021), a multi-objective artificial bee colony algorithm is presented in Alrezaamiri et al. (2020), efficient improved ant colony optimization algorithm in Kalantari et al. (2020a), and an elite artificial bees' colony is proposed in Sori et al. (2020). A fuzzy inference-based methodology to find multi-objective-based constrained shortest path problems has been proposed in Ali et al. (2020). A dynamic software rejuvenation using whale optimization is proposed in Kalantari et al. (2020b) and by using a fuzzy artificial chemical reaction optimization is proposed in Alrezaamiri et al. (2019).

1.2 Contributions of this Paper

Literature review reveals that very few research works were performed with simultaneous sizing and placement of DGs, CBs, and D-STATCOMs, and also many of them solved the problem as a single objective optimization (SOO) type. But in practical systems, these objectives must be solved simultaneously. The main contribution of this work is to solve optimal allocation problem of RDS by considering the multiple DGs, CBs, and D-STATCOMs by simultaneously optimizing all the objectives. In the present work, two conflicting objectives (power loss minimization and overall voltage stability index (VSI) maximization) are considered. Here, PSO is selected for the optimization of SOO, and multi-objective PSO (MO-PSO) is selected for multiple objectives.

2. Distribution Load Flow (DLF)

The circuit of a branch in a RDS with load demand, DG, CB, and D-STATCOM is shown in Figure 1. Here, the DLF proposed in the references Tolabi et al. (2015), Tolabi et al. (2014) is used. The current in the distribution line (ab) that is connected between nodes a and b can be represented by Salkuti (2021a),

$$I_{ab} = \frac{|V_a|\angle\delta_a - |V_b|\angle\delta_b}{R_{ab} + jX_{ab}} = \frac{P_b - jQ_b}{(|V_b|\angle\delta_b)^*} \tag{1}$$

Active and reactive power losses are evaluated by Salkuti and Battu (2021),

$$P_{a,b}^{loss} = \left(\frac{P_{a,b}^2 + Q_{a,b}^2}{|V_a|^2}\right) \times R_{a,b} \tag{2}$$

$$Q_{a,b}^{loss} = \left(\frac{P_{a,b}^2+Q_{a,b}^2}{|V_a|^2}\right) \times X_{a,b} \quad (3)$$

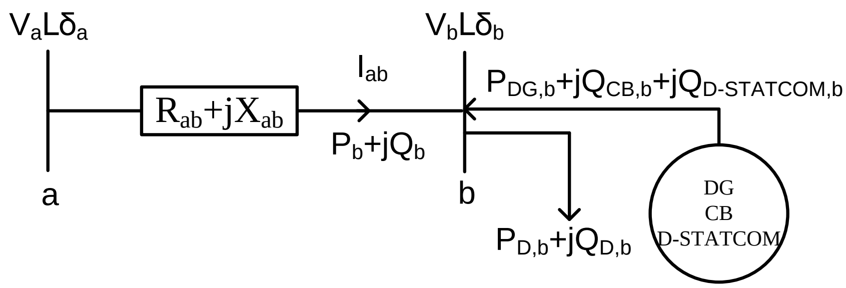

Figure 1. Representation of RDS with DG, CB, and D-STATCOM units.

Active and reactive power from a D-STATCOM is represented by using Gupta and Kumar (2016),

$$P_{D-STATCOM} = \frac{V_a V_b}{X_{ab}} sin(\delta_a - \delta_b) \quad (4)$$

$$Q_{D-STATCOM} = \left(\frac{V_a^2}{X_{ab}}\right) - \frac{V_a V_b}{X_{ab}} cos(\delta_a - \delta_b) \quad (5)$$

3. Problem Formulation

The proposed problem described in this paper is solved by considering the two objectives and they are described next.

3.1 Objective 1: Total Active Power Loss Minimization

Total power losses (P_T^{loss}) in the entire RDS can be represented by Rao et al. (2011),

$$P_T^{loss} = \sum_{a=1}^{N_B} \left(\frac{P_{a,b}^2+Q_{a,b}^2}{|V_a|^2}\right) \times R_{a,b} \quad (6)$$

This objective function is formulated as Sanjay et al. (2017),

$$J_1 = minimize\ \left(P_T^{loss}\right) \quad (7)$$

3.2 Objective 2: Overall Voltage Stability Index (VSI_o) Maximization

The VSI at a particular node in an RDS (Figure 1) is represented by Kola and Jayabarathi (2019),

$$VSI_b = |V_a|^4 - 4\left(P_{D,b}X_{ab} - Q_{D,b}R_{ab}\right)^2 - 4\left(P_{D,b}X_{ab} + Q_{D,b}R_{ab}\right)|V_a|^2 \quad (8)$$

In general, VSI must be positive to obtain the stable operation of RDS. VSI varies between 0 and 1. A higher VSI value represents better stability of the RDS. VSI is zero at the voltage collapse point and VSI is one at no-load operating condition. Maximization of overall VSI (VSI_o) of the RDS is considered as another objective and it is formulated as,

$$J_2 = maximize\ (VSI_o) = maximize\ \left(\sum_{j=2}^{N_{Bus}} VSI_j\right) \quad (9)$$

The voltage stability of the RDS can be improved by increasing VSI_o value. The maximization of VSI_o the objective can be expressed as the minimization function and it is formulated as Kola and Jayabarathi (2019),

$$J_2 = minimize\ \left(\frac{1}{VSI_o}\right) \quad (10)$$

The proposed problem has been solved by satisfying the following constraints.

3.3 Constraints

3.3.1 Constraints on Power Balance

These are the equality constraints, and they are expressed as Devabalaji and Ravi (2016),

$$P_{SS}^{Grid} + \sum_{i=1}^{N_{DG}} P_{DG,i} = P_T^{loss} + \sum_{k=1}^{N_{Bus}} P_{D,k} \quad (11)$$

$$Q_{SS}^{Grid} + \sum_{i=1}^{N_{DG}} Q_{DG,i} + \sum_{j=1}^{N_{CB}} Q_{CB,j} + \sum_{d=1}^{N_{D-STATCOM}} Q_{D-STATCOM,d} = Q_T^{loss} + \sum_{k=1}^{N_B} Q_{D,k} \quad (12)$$

P_{SS}^{Grid} and Q_{SS}^{Grid} are real and reactive powers from the main grid or substation.

3.3.2 Constraints on DG Power

Active and reactive powers generated from the DGs are restricted by Salkuti et al. (2018),

$$P_{DG,i}^{min} \leq P_{DG,i} \leq P_{DG,i}^{max} \qquad i = 1,2, \dots, N_{DG} \quad (13)$$

$$Q_{DG,i}^{min} \leq Q_{DG,i} \leq Q_{DG,i}^{max} \qquad i = 1,2, \dots, N_{DG} \quad (14)$$

3.3.3 CBs and D-STATCOM Constraints

The reactive power output from a CB is limited by,

$$Q_{CB,i}^{min} \leq Q_{CB,i} \leq Q_{CB,i}^{max} \qquad i = 1,2, \dots, N_{CB} \quad (15)$$

The reactive power output from a D-STATCOM is limited by El-Ela et al. (2018),

$$Q_{D-STATCOM,i}^{min} \leq Q_{D-STATCOM,i} \leq Q_{D-STATCOM,i}^{max} \qquad i = 1,2, \dots, N_{D-STATCOM} \quad (16)$$

Reactive power output from CBs (Q_{CB}^{total}), D-STATCOM ($Q_{D-STATCOM}^{total}$) and DG units (Q_{DG}^{total}) must be less than the reactive power demand (Q_D^{total}) of RDS, and it can be expressed as,

$$Q_{DG}^{total} + Q_{CB}^{total} + Q_{D-STATCOM}^{total} < Q_D^{total} \quad (17)$$

3.3.4 Bus Voltage Constraints

This constraint at each bus can be expressed as Jung and Salkuti (2020),

$$0.95 \leq V_i \leq 1.05 \qquad i = 1,2, \dots, N_{Bus} \quad (18)$$

3.3.5 Voltage Stability Index (VSI) Constraints

The VSI at each bus can be expressed as,

$$VSI_j > 0 \qquad j = 2,3, \dots, N_{Bus} \quad (19)$$

4. Solution Methodology

In this work, PSO Abido (2002), Singh et al. (2016) is considered for solving the proposed single objective optimization (SOO) problem Naderi et al. (2019), Korab et al. (2021) of RDS, and the multi-objective PSO (MO-PSO) is selected for the solution of multi-objective optimization (MOO) problem f RDS. The description of MO-PSO is described in references Kamal et al. (2021), Jiang et al. (2020), Abido (2009). The implementation procedure of the SOO problem is presented next:

Step 1: Initialize the particles with a population size of N. Read line data and bus data. Execute the power flow.
Step 2: Evaluate power loss for each particle. Determine the value of fitness function.
Step 3: Update velocity (v) and position (P) of i^{th} particle by using Naderi et al. (2019),

$$v_i^{t+1} = \omega v_i^t + c_1 r_1 \left(P_{best,i}^t - P_i^t\right) + c_2 r_2 \left(P_{best,global}^t - P_i^t\right) \tag{20}$$
$$P_i^{t+1} = P_i^t + v_i^{t+1} \tag{21}$$

Update position best and global best values.
Step 4: Determine best fitness, i.e., value of objective function.

Step 5: Check for termination condition. If satisfied, then output the value of the optimum objective function and sizes ans locations of DGs, CBs, and D-STATCOM. Else, repeat steps 1 to 4.

5. Simulation Results and Analysis

IEEE 33 bus RDS is considered for solving the proposed approach and the system data is is taken from reference Rao et al. (2011). In this system, a maximum of 3 DG units, 3 CBs, and one D-STATCOM are considered. Active, reactive, and apparent power demands are 3715 kW, 2300 kVAr, and 4369.4 KVA. Installed capacities of grid/substation, wind turbine, and solar PV are 25000 kW, 5000 kW, and 1000 kW, respectively (El-Ela et al., 2018; Salkuti, 2021b). The maximum capacities of CBs and D-STATCOMs are 1000 kVAr and 2000 kVAr respectively. In this paper, 6 cases are considered, and they are described next.

5.1 Case 1: Base Case

Base case represents the case without installing the DGs, CBs, and D-STATCOM units, and also considering the standard structure of the RDS (Table 1). The power losses (active and reactive) obtained in this case are 202.66 kW and 135.14 kVAr (Salkuti, 2021a, Salkuti and Battu, 2021). Therefore, the P_{SS}^{Grid} and Q_{SS}^{Grid} in this case are 3917.66 kW and 2435.14 kVAr, respectively. The overall VSI obtained, in this case, is 26.17.

Table 1. Obtained results for Cases 1, 2, and 3.

	Case 1	Case 2	Case 3
DG size (kW) and location (bus number)	---	635.2(13), 928.5(24), 1010.3(30)	560(18), 802.8(24), 855.3(30)
Active power loss (kW)	202.66	75.04	126.92
Overall VSI (VSI_o)	26.17	29.44	29.98
Minimum voltage (bus number)	0.9131(18)	0.9686(33)	0.9548(32)
Loss reduction (%)	---	62.3	37.35

5.2 Case 2: Solving Objective 1 Considering only DG Allocation

In this case, objective 1 is optimized independently by referring only optimal allocation problem of the DG units, and obtained results are depicted in Table 1. Optimization results give an optimal size of 3 DG units 635.2kW, 928.5kW, and 1010.3kW at buses 13, 24, and 30, respectively. The optimum loss obtained is 75.04kW, which is 62.3% less than Case 1. The overall VSI (VSI_o) is calculated by using the equation (9), and the value obtained in this case is 29.44. The voltage profile has been increased compared to Case 1, and low voltage occurred in the entire system is 0.9686 p.u. and it is at bus number 33.

5.3 Case 3: Solving Objective 2 Considering only DG Allocation

In this case, objective 2 is optimized independently by optimally placing the three DGs. The resulted optimum value of VSI_o is 29.98, but the power losses have been moved away from optimum (Table 1). Here, three DG units are situated at buses 18, 24, and 30 with their capacities of 560kW, 802.8kW, and 855.3kW. In this case, the low voltage obtained at bus 32 is 0.9548 p.u.

5.4 Case 4: Solving Objective 1 Considering Simultaneous Allocation of DGs, CBs, and D-STATCOM

Here, objective 1 is optimized independently by simultaneously allocating the DGs, CBs, and D-STATCOM. A maximum of 3 DG units, 3 CBs, and one D-STATCOM can be considered. The results are reported in Table 2, and from results it is clear that 3 DG units are placed at buses 13, 23, and 29 with the capacities of 300kVAr, 460kVAr, and 585 kVAr, respectively. D-STATCOM is located at bus 29 with a capacity of 1259.6 kVAr. Optimum loss obtained is 30.16 kW which is 85.12% less compared to the results of base case. The value of VSI_o resulted in this case is 30.01.

Table 2. Results for Cases 4, 5, and 6.

	Case 4	Case 5	Case 6
DG size (kW) and location (bus number)	543.4(13), 760.4(23), 805.9(29)	596.3(8), 800.5(13), 753.6(24)	535.0(13), 816.4(23), 837.9(29)
CB size (kVAr) and location (bus number)	300(13), 460(23), 585(30)	300(16), 385(18), 535(29)	332(17), 540(18), 600(30)
D-STATCOM size (kVAr) and location (bus number)	1259.6(29)	1152.5(30)	1250(30)
Active power loss (kW)	30.16	72.95	55.98
Overall VSI (VSI_o)	30.01	30.88	30.42
Minimum voltage (bus number)	0.9698(31)	0.9672(31)	0.9696(30)
Loss reduction (%)	85.12	64	72.4

5.5 Case 5: Solving Objective 2 Considering Simultaneous Allocation of DGs, CBs, and D-STATCOM

Here, objective 2 is optimized independently with simultaneous placement and sizing of DGs, CBs, and D-STATCOM units. The obtained results are reported in Table 2. Optimum value of VSI_o obtained in this case is 30.88, but the power loss has deviated from the optimum value obtained in Case 4. The optimal locations obtained for DGs are 8, 13, and 24 with capacities of 596.3 kW, 800.5kW, and 753.6kW, respectively. Three CBs are placed on buses 16, 18, and 29 with capacities of 300 kVAr, 385 kVAr, and 535 kVAr. One D-STATCOM is placed at bus number 30 with the sizing of 1152.5 kVAr. Minimum voltage occurred in this case is 0.9672 p.u. and it is at bus 31 with the overall improvement in system voltage profile.

From simulation results, it is clear that results obtained in Case 2 and Case 3 are conflicting with each other. Similarly, the optimum results obtained in Case 4 and Case 5 are also conflicting with each other. Therefore, there is a requirement for obtaining the compromised solution between the power losses and overall ($\boldsymbol{VSI_o}$). In this work, MO-PSO is selected for the solution of power loss and $\boldsymbol{VSI_o}$ objectives simultaneously.

5.6 Case 6: Solving both the Objectives at a Time Considering Simultaneous Allocation of DGs, CBs, and D-STATCOM

Here, two conflicting objectives, i.e., power loss and overall VSI_o are solved simultaneously using MO-PSO algorithm. The results are reported in Table 2. In this case, 3 DGs are placed at buses 13, 23, and 29 with capacities of 535kW, 816.4kW, and 837.9kW, respectively. Here, 3 CBs are placed at buses 17, 18, and 30 with the sizes of 332 kVAr, 540kVAr, and 600kVAr, respectively. One D-STATCOM is located at bus number 30 with a size of 1250kVAr. The fuzzy min-max based best-compromised solution has a total power loss of 55.98kW and overall VSI (VSI_o) of 30.42 and this solution can be seen in Pareto optimal front depicted in Figure 2.

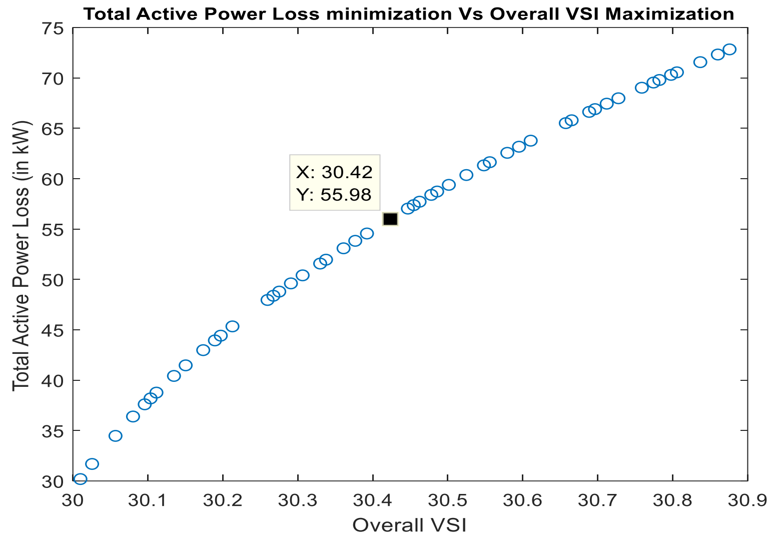

Figure 2. Pareto optimal front of total power loss and overall VSI for Case 6.

6. Conclusions

This paper has considered different combinations of allocations of distributed generations (DGs), shunt capacitor banks (CBs), and distribution FACTSs based D-STATCOMs integration to satisfy technical and environmental aspects of distribution networks. This work addressed technical challenges of distribution network planning and operation by simultaneously placing the various emerging components to improve operating conditions of the radial distribution system (RDS). In this work, two important and conflicting objectives (active power loss and overall voltage stability index (VSI)) are formulated. These objectives are solved individually and simultaneously by using the evolutionary-based PSO and MO-PSO algorithms. The results obtained on 33 bus RDS show that the proposed optimization has improved the voltage profile and overall VSI of the RDS and minimized the system power losses.

Conflict of Interest

The author declares that there is no conflict for this publication.

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