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Strategic Siting of Automatic Voltage Regulators and Distributed Generators in Distribution Systems using PSO



Abstract- Distributed Generation (DG) penetration in distribution networks has increased dramatically in recent years as power markets have improved. Aside from serving loads locally, the installation of DG has a number of technical advantages, including improved voltage profile and lower network loss. Using an Automatic Voltage Regulator (AVR) in conjunction with DGs maximizes technological benefits. This study investigates the influence of DG and AVR placement with the purpose of decreasing network losses. The Particle Swarm Optimization (PSO) solves the optimization problem. The effectiveness of the proposed approach is proven with a standard IEEE 69-bus distribution network.

Keywords: Distributed Generation, Automatic Voltage Regulator, Particle Swarm Optimization.

1 INTRODUCTION

Industrial growth, rapid urbanization, and increased electric gadget affordability are all contributing to a lack of energy generation to meet expanding demand. To maximize economic gains while also conserving energy, generated electricity must be used efficiently. Power losses at the distribution level are mostly caused by low voltages, high currents, and overload conditions. Energy conservation through network reconfiguration, capacitor allocation, and reconductoring is becoming more significant. However, its effectiveness is limited because it only injects reactive power into the network. The usage of Distributed Generation (DG) for loss reduction has risen in popularity as a result of the restructuring of the electric power system [1].

Various analytical and meta-heuristic strategies have been used by researchers to solve the problem of DG and capacitor allocation. Prasad optimally selects conductors and places capacitors to minimize system costs using the Harmony Search Algorithm, analysing both annual energy loss and investment costs. Implemented on an 85-bus system, this approach effectively reduces losses, lowers costs, and improves the voltage profile [2]. Renewable distributed generation (RDG) deployment has increased due to environmental concerns, offering benefits like loss reduction, improved voltage profile, and reduced line loading [3]. Meta-heuristic techniques, including the Artificial Bee Colony (ABC) algorithm [4], Harmony search algorithm (HSA) [5], Flower pollination algorithm [6], Grey Wolf Optimizer [7], and improved teaching learning-based optimization algorithm [8], were used to solve the DG allocation problem and reduce active power loss. Das [9] employed the Fuzzy-GA approach and Plant Growth Simulation program to tackle the shunt capacitor allocation problem. Bhattacharya and Goswami [10] employed a Fuzzy approach to detect locations and Simulated Annealing to optimize capacitor sizes, reducing

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both loss and capacitor costs. A few authors investigated the influence of DG location and capacitors in distribution systems.

The goal of this research is to use GA to determine the ideal sizes and positions for DGs, as well as the optimal tap settings and placements for AVRs in a radial distribution network. Ravindra proposes an improved Pareto multi-objective backtracking search algorithm for optimal DG and AVR allocation in distribution systems [11]. The optimal allocation problem is solved within the restrictions of maximum DG penetration limit, thermal limit of branches, tap position of AVRs, injected active and reactive power limits of distributed generators, and allowable bus voltage limits [12-13]. Finally, it suggests using NSGA-II optimization for DG, capacitor, and AVR allocation to improve voltage, minimize losses, and enhance network reliability, with testing on IEEE 33 and 69-bus systems [14]. Here the proposed approach is applied to find out optimal placement of DG and AVR for different scenarios for minimizing the objective functions power loss and voltage deviation.

2 PROBLEM FORMULATION

The primary objective of this project is to reduce active power losses directly contributes to an improvement in bus voltage levels. By optimizing the power flow across branches, we aim to achieve a significant reduction in network power loss.

To accomplish this, the strategic placement of Distributed Generators (DGs) and Automatic Voltage Regulators (AVRs) is a key focus. DGs help to decentralize power generation, thereby reducing the distance power must travel, which in turn minimizes losses. Meanwhile, AVRs work to maintain voltage levels within optimal ranges, ensuring consistent and efficient power delivery. This coordinated approach not only minimizes active power loss but also contributes to reduce voltage deviation in distribution network.

2.1 Objective function

The primary objective of this study is to achieve loss reduction in the power distribution network. This goal is quantified using a target function, which is defined as the ratio of the network's power loss with the integration of Distributed Generators (DGs) and/or Automatic Voltage Regulators (AVRs) to the power loss in a base case scenario.

In this context, "base case power loss" represents the power loss within the network when no DGs or AVRs are utilized. By comparing the modified network's performance against this baseline, the study can effectively assess the impact of DG and AVR placement on reducing power loss, thereby highlighting the improvements in voltage deviation.

$$f_p = \left(\sum_i^{Nbr} PL_i^{with_DG/AVR} \right) / \left(\sum_i^{Nbr} PL_i^{base} \right) \quad (1)$$

The optimization problem is solved using the following constraints:

(i) Voltage Constraint

$$V_{min} \leq V_i^{with_DG/AVR} \leq V_{max} \quad (2)$$

(ii) Branch current limits (Thermal limits)

$$I_i \leq I_{cap} \quad (3)$$

(iii) DG power capacity constraint

$$P_{DG_min} \leq P_{DGi} \leq P_{DG_max} \quad (4)$$

(iv) Tap settings Constraint for AVR

$$T_{\min} \leq T \leq T_{\max} \tag{5}$$

where $PL_i^{with_DG/AVR}$ represents the total real power loss with DG and/or AVR, PL_i^{base} corresponds to the total real power loss with base case, V_{\min} is the Minimum voltage, V_{\max} is the Maximum voltage, P_{DG_min} is the Minimum DG power capacity, P_{DG_max} is the Maximum DG power capacity, T_{\min} is the Minimum tap setting, T_{\max} is the Maximum allowable tap setting.

2.2 Automatic Voltage Regulator (AVR) model

To assess the influence of Automatic Voltage Regulators (AVRs) on the distribution network, a detailed model is developed [9]. An AVR operates as an autotransformer equipped with a tap-setting control mechanism on its windings, enabling precise regulation of voltages across the distribution network. Positioned strategically between buses A and B, the AVR is initially set with a tap setting denoted as ‘t’ and an internal admittance represented by ‘Y’, as illustrated in Fig. 1.

In this model, the AVR is depicted as a combination of series and parallel admittances, as shown in Fig. 2. This configuration allows for accurate simulation of the AVR’s impact on the network’s voltage profile and power flow. By adjusting the tap setting, the AVR can dynamically maintain voltage levels within desired limits, thereby improving the voltage deviation at each bus in the network.

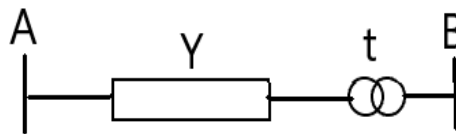


Fig. 1 AVR model in branch

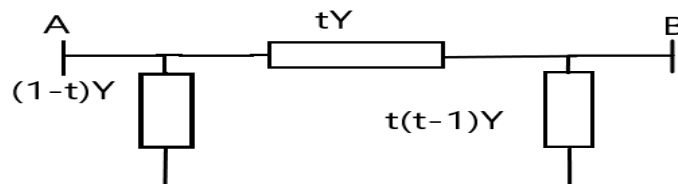


Fig.2 π model representation of AVR

When the tap setting of the autotransformer is adjusted from its initial value t by an increment Δt , the AVR model requires modification, as depicted in Fig. 3. To represent this variation in tap position, an alternative modeling approach involves adjusting the configuration in Fig. 3 by introducing imaginary injection currents, I_A and I_B as shown in Fig. 4.

These fictitious injected currents, defined by equations (6) and (7), enable an accurate simulation of the effects of tap changes on the network without physically altering the transformer setup. By incorporating these injection currents into the model, we can replicate the impact of varying tap positions on the voltage profile and power flow, allowing for a precise analysis of AVR performance in maintaining optimal network conditions.

$$I_A = (1 - (t + \Delta t)) * Y * V_B \tag{6}$$

$$I_A = (1 - (t + \Delta t)) * Y * V_B + ((t + \Delta t)^2 * Y * V_B) \tag{7}$$

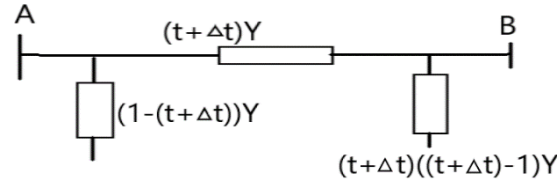


Fig. 3 AVR model including tap position variation

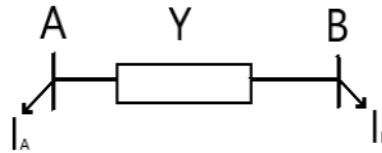


Fig. 4 AVR equivalent with fictitious current injections

2.3 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is an iterative optimization algorithm inspired by the social behavior of birds and fish. It works as follows:

STEP 1: Initialization: Define the objective function to optimize. Randomly initialize a swarm of particles, each with a position and velocity (v) in the search space. Set each particle's personal best to its initial position and identify the global best (g) among all particles.

STEP 2 Evaluation: Calculate the fitness of each particle's position using the objective function.

Update pi if the particle's current position is better than its previous best.

Update g if any particle has achieved a better position than the current global best.

STEP 3: Update Velocity and Position: Adjust each particle's velocity using: Update the particle's position.

STEP 4: Iterate steps 2–3 until convergence criteria are met, such as reaching a maximum number of iterations or achieving a satisfactory fitness value.

2.4 Proposed Approach

Step 1: Define loss as objective function, DG sizes and locations, Tap changers and locations as decision variables. Initialize MWCA parameters and specify the IEEE 69-bus test system line and load data, constraints.

Step 2: Initialize the RM with solution vectors (DG sizes and locations, Tap changers and locations).

$$SV = [DG_1^1 \ DG_2^1 \ \dots \ DG_N^1 \ L_1^1 \ L_2^1 \ L_3^1 \ \dots \ L_N^1 \ T_1^1 \ T_2^1 \ T_3^1 \ \dots \ T_N^1 \ TL_1^1 \ TL_2^1 \ TL_3^1 \ \dots \ TL_N^1] \tag{11}$$

Each solution vector in RM is evaluated by finding the objective function value by running a load flow. Backward-Forward Sweep method is used determine load flows. Sort the solution vectors in RM based on their ascending order of functional values.

Step 3: Determine the best solution from the raindrops.

Step 4: Generate a fresh set of solutions

Step 5: Check the termination criteria and stop.

3 RESULTS

To verify the efficacy of the proposed approach, it is tested on a IEEE 69-bus system which is a 12.66 kV system whose data is taken from [15].

Four scenarios are simulated in this work.

Scenario I: System without DGs and AVRs (Base case)

Scenario II: System with AVRs only

Scenario III: System with DGs only

Scenario IV: System with DGs and AVRs (Proposed approach)

Bus voltage deviations of the system is computed as given in (12)

$$Vdev = \sum_{i=2}^{nbus} (V_i - 1)^2 \quad i = 1,2,3,4,\dots,nbus \tag{12}$$

where *nbus* represents total number of nodes and *V_i* is the *ith* bus voltage.

Table 1. Results of IEEE 69-bus Test System

Planning Cases	DGs placement and rating		AVR locations and Tap ratio				Total Real Power loss (kW)	Minimum bus voltage (p.u)	Voltage deviation
	Bus No.	Ratings (MVA)	Branch no.	Tap ratio	Branch no.	Tap ratio			
Scenario-I	----	----	----	----	----	----	224.98	0.9091	0.0993
Scenario-II	----	----	56 59 61 62	0.9000 1.0875 0.9125 0.9625	----	----	196.82	0.9141	0.0897
Scenario-III	65 26 60 62 61	0.56 0.40 0.59 0.51 0.27	----	----	----	----	14.94	0.9884	0.0036
Scenario-IV (AGA) [16]	21 61 62 63 64	0.441 0.572 0.348 0.539 0.428	5 6 7 8 9 10 11 44	1.0989 1.0938 1.0984 0.9014 1.0906 1.0983 1.0958 1.0509	48 49 55 57 59 66 68	1.0637 1.098 0.9237 1.063 0.9098 0.9305 0.9092	11.87	0.9953	0.00076

Scenario-IV HSA[17]	61	0.76							
	60	0.38		13	1.0813				
	62	0.48		25	0.9125	----	----	10.44	0.9904
	65	0.32		10	0.9188				0.0026
	23	0.38		35	0.9813				
Scenario-IV PSO	20	0.35	0.62	52	0.9058				
	63	1.32		26	1.0278	----	----	11.11	0.9881
	61			23	0.9412				0.0036

In this study, DG penetration is restricted to 50%, with all DG units assumed to operate at a lagging power factor of 0.85. The results for the four scenarios are summarized in Table 1. The total real power loss in the network is 224.98 kW for Scenario I, which decreases to 196.821 kW in Scenario II. In Scenario III, the loss is further reduced to 14.94 kW. For Scenario IV, the loss is 11.87 kW when solved using the Adaptive Genetic Algorithm (AGA) [13], while the proposed PSO achieves a lower loss of 10.44 kW. A comparison of Scenario IV results shows that PSO outperforms AGA in power loss mitigation. Although the proposed Particle Swarm Optimization (PSO) approach provides better voltage deviation performance compared to AGA, it is less effective than PSO in minimizing power loss.

Table 1 reveals that in Scenario IV (AGA), deploying 5 DGs and 15 AVRs results in a power loss of 11.87 kW. In Scenario IV (PSO), using 5 DGs and 4 AVRs reduces the loss further to 10.44 kW. Meanwhile, Scenario IV (PSO) achieves a power loss of 11.11 kW with 3 DGs and 3 AVRs. These findings demonstrate that the proposed PSO-based method outperforms the AGA-based approach. Additionally, the proposed method achieves the highest percentage of loss reduction, at 95.36%, among all scenarios. Figure 5 further illustrates that the voltage profile of the network has significantly improved, owing to the simultaneous placement of AVRs and DGs in Scenario IV.

4 CONCLUSION

This study explores the simultaneous placement of Automatic Voltage Regulators (AVRs) and Distributed Generators (DGs) in the IEEE 69-bus system, aiming to minimize energy losses in the distribution network. The optimization process is divided into three distinct scenarios: Scenario-I, focusing on optimal DG allocation; Scenario-II, dedicated to optimal AVR allocation; and Scenario-III, addressing the combined allocation of DGs and AVRs. Each scenario addresses specific challenges to improve the overall performance of the power system. Particle Swarm Optimization (PSO) was utilized as the optimization tool to achieve these objectives. This algorithm effectively identified the optimal locations and capacities of DGs and AVRs, providing a comprehensive and efficient solution. Among the scenarios analyzed, Scenario-IV, which involves the simultaneous placement of DGs and AVRs using PSO, achieved the most significant reduction in power losses.

This outcome demonstrates the superiority of the integrated approach compared to standalone deployment strategies, as seen in Scenarios I, II, and III.

Moreover, Scenario-IV resulted in a substantial improvement in the voltage profile of the network. The coordinated deployment of DGs and AVRs not only minimized energy losses but also enhanced voltage stability and system reliability. This study underscores the critical role of simultaneous resource integration in optimizing the performance of modern power distribution systems.

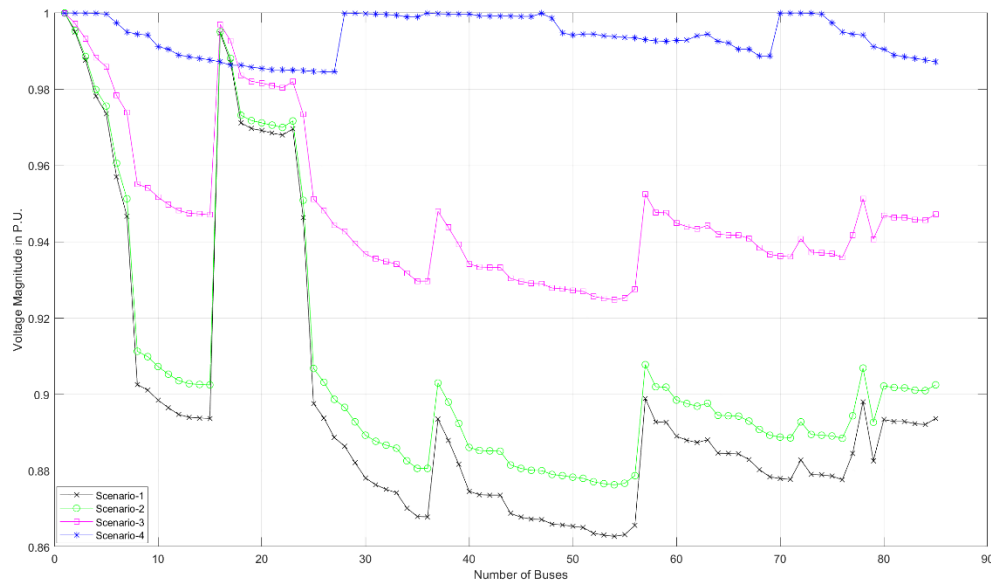


Fig. 5 Voltage profile of 69-bus system

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