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Analysis of Optimal AVR Placement in Radial Distribution Systems using Discrete Particle Swarm Optimization

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Abstract

Voltage Regulator has always been considered as an integral part of the distribution system response. There are several factors, which contribute to voltage collapse such as increased loading on distribution feeders, reactive power constraints, on load tap changer dynamics and load characteristics. The proposed DPSO method is suitable for voltage regulator placement in radial distribution systems. This paper focuses on achieving optimal voltage control with voltage regulators and then to decrease the total cost and losses, to obtain the maximum net savings. Proposed method makes the initial selection, installation and tap setting of the voltage regulators to provide a smooth voltage profile along the network.

Keywords: Automatic Voltage Regulator, load flow, Radial Distribution Systems, DPSO

1. Introduction

Voltage Regulator (VR) or Automatic Voltage Booster (AVB) is essentially an auto transformer consisting of a primary or existing winding connected in parallel with the circuit and a secondary winding with taps connected in series with the circuit. Taps of series winding are connected to an automatic tap changing mechanism. Voltage regulators are also considered a tool for loss reduction and voltage control. When a voltage regulator is installed at a node, it causes a sudden voltage rise at its point of location and improves the voltage at the nodes beyond the location of voltage regulator. The percentage of voltage improvement is equal to the setting of percentage boost of voltage regulator. The increase in voltage in turn causes the reduction in losses in the lines beyond the location of voltage regulator. Multiple units can be installed in series to the feeder to maintain the voltage within the limits and to reduce the line losses. It can be removed and relocated easily whenever it is required.

When Voltage regulators are properly applied, can compensate for voltage drops and keep customer voltage within permissible limits. Single-phase voltage regulators can be applied on three-phase systems [1]. The capabilities of the regulator systems are affected by the system design. The paper will review the characteristics of the closed delta and wye applications, and discuss the advantages and disadvantages of each application scheme. The impact of the regulator connection on the over current protection scheme will also be reviewed. In [2,3,4] deals with the determination of the optimal locations and real-time control (tap positions) of a minimum voltage regulator number, in order to minimize the peak power and energy losses and provide a smooth voltage profile along a distribution network. In [5], the voltage regulation is initially attempt by changing the tap positions at the substation and solving again the capacitor problem. If the desirable voltage regulation is not achieved in this way a voltage regulator placed at the main feeder, next to node where the sub feeder with the heaviest load is connected and then the proper tap position of this voltage regulator is determined. In [10] presented a neural network controller for controlling shunt capacitor banks and feeder voltage regulator in electric distribution systems is presented. The objective of neural controller is to minimize total I^2R losses and maintain all node voltages within standard limits. The seven points [9] are extremely critical to the understanding of the failure profile of the single-phase voltage regulators on the operating system of this electric utility. A computer algorithm [6] for optimal voltage control with voltage regulator is suitable for large radial distribution network. An objective function concerning the total cost of the voltage regulators (investment and maintenance cost) as well as the cost of losses of the examined networks is developed and constitutes the base of the algorithm. This algorithm makes the initial selection, installation and tap setting of the voltage regulators, which provide a smooth voltage profile along the network. Yoshikazu Fukuyama [7] presents a practical distribution state estimation method and an optimal setting method for voltage regulators in distribution systems using heuristic techniques. In [8] proposes a method considers nonlinear characteristics of the practical equipment and actual measurements in distribution systems.

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The method can estimate load and distributed generation output values at each node by minimizing difference between measured and calculated state variables.

The proposed method deals with selection of voltage regulator nodes by using Power Loss Index (PLI) and Discrete Particle Swarm Optimization (DPSO) is used for tap setting of the voltage regulators, which provides a smooth voltage profile along the network. Throughout the optimization process tap setting of the voltage regulator and its location are being treated as discrete variables. The main objective is to minimize the number of voltage regulators which intern reduces the overall cost. The proposed algorithm is tested with two systems of 15-node and 33-node RDS.

2 Load Flow Solution

In any radial distribution system, the electrical equivalent of a branch 1, which is connected between nodes 1 and 2 having impedance Z_1 is shown in Figure. 1.

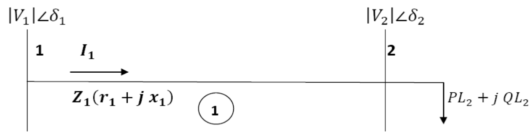

Figure. 1 Electrical equivalent of a typical branch '1'

The voltage at source node is taken as 1.0 p.u. The voltage at node 2 is given by

$$V_2 = V_1 - I_1 Z_1$$

In general $V_{n2} = V_{n1} - I_j Z_j$ -------- (1)

where 'n1' and 'n2' are sending and receiving ends of branch 'j' respectively.

By using Eqn. (1), the voltage at any node (except node 1) can be calculated.

In most of the test systems, the loads are taken as constant power loads, and at each bus, the real and reactive power loads are specified. The load current at node 'i' is calculated by

$$IL_i = \left(\frac{PL_i + jQL_i}{V_i}\right)^*, \text{ for } i = 2,3, \text{----}, nn \qquad \text{-------} \ (2)$$

Where,

PL_i = Real power load at node i

QL_i = Reactive power load at node i

nn= Number of nodes

The real and reactive power losses of branch 'j' can be calculated as

$$LP_j = I_j^2 \ r_j \qquad \text{-------} \ (3)$$

$$LQ_j = I_j^2 x_j \quad \text{for } j=1, 2, \text{----}, nb. \qquad \text{-------} \ (4)$$

where nb= Number of branches

The current in each branch is calculated by applying KCL at node '2' shown in Figure 1 the branch current equation obtained is as follows

$$I_1 = I_2 + I_5 + I_7 + IL_2 \qquad \text{-------} \ (5)$$

From the above, the current can be calculated in any branch. By following the above procedure i.e., branch current calculations in backward walk and the voltage at each node are calculated in the forward walk. Initially, a flat voltage profile is assumed at all nodes i.e., 1.0 p.u. Load currents are computed iteratively with the updated voltages at each node. In the proposed load flow method, current summation is done in the backward walk and voltages are calculated in the forward walk. The maximum difference of voltage magnitudes in successive iterations is taken as convergence criteria, and 0.0001 is taken as tolerance value.

2.1 Algorithm for load flow solution of radial distribution system

Step 1: Read line and load data of radial distribution system. Assume initial node voltages 1 p.u, set $\varepsilon = 0.0001$.

Step 2: Start iteration count, c =1.

Step 3: Calculate load currents at each node by using Eqn. (2)

Step 4: Initialize real power loss and reactive power loss vectors to zero.

Step 5: Using the node currents calculated in Step 3, calculate branch currents.

Step 6 :Calculate node voltages, real and reactive power loss of each branch using Eqns. (1), (3) and (4) respectively.

Step 7: Check for convergence i.e., $|\Delta V_{max}| \leq \varepsilon$ in successive iterations. If it is converged go to next step otherwise increment iteration number and go to Step 3.

Step 8: Calculate total real power and reactive power losses for all branches.

Step 9: Print voltages at each node, real and reactive power losses and number of iterations.

Step 10: Stop.

3. Mathematical Formulation

The voltage regulator problem consists of two sub problems, that of optimal placement and optimal choice of tap setting. The first sub problem determines the location and number of voltage regulator to be placed and the second sub problem decides the tap positions of voltage regulator.

3.1. Objective Function

To obtain the optimal location for placing voltage regulators that maintain the voltages within the limits of the radial distribution system so as to maximize an objective function, which consists of capital investment and capitalized energy loss costs.

The objective function is formulated as maximizing the cost function,

$$\text{Maximize } F = K_e \times P_{lr} \times 8760 \times Lsf - K_{VR} \times N(\alpha + \beta) \qquad \text{----- (6)}$$

Where

P_{lr} = Reduction in power losses due to installation of VR

K_e = Cost of energy in Rs./kWh

Lsf = Loss factor $= 0.2Lf + 0.8Lf^2$

Lf = Load factor

N = Number of VRs

K_{VR} = Cost of each VR

= The rate of annual depreciation charges for VR

= Cost of installation of VR.

3.2 Candidate Node Identification using PLI

Power Loss Index (PLI) is power loss based approach to determine the suitable location for placement of voltage regulators. After running the load flows for base case system, the total active power loss is given by 60.3482 kW. The Power Loss Index (PLI) are calculated as

$$PLI[j] = \frac{(\text{Loss.reduction}[j] - \text{Min.reduction})}{(\text{Max.reduction} - \text{Min.reduction})} \qquad \text{----- (7)}$$

3.3. Algorithm for Candidate Node Identification using PLI

Following algorithm explains the methodology to identify the candidate nodes, which are more suitable for voltage regulator.

- Read radial distribution system data.
- Run the load flows and calculate the base case active power loss.
- By improving the voltage at each node to maximum voltage limit of 1.05 p.u and run the load flows, to calculate the total active power loss in each case.

- Calculate the power loss reduction and power loss index using Eqn (7).
- Select the candidate node whose PLI>tolerance.
- Stop.

4 Implementation of Discrete PSO for VR Placement

4.1. Overview of the DPSO

DPSO algorithm is developed by simulating human social behavior and individuals of a swarm. Particle swarm optimization has roots in two main component methodologies. Perhaps more obvious are its ties to Artificial life (A-life) in general, bird flocking, fish schooling, and swarming theory in particular. It has been noticed that members within a group seem to share information among them, a fact that leads to increased efficiency of the group. The DPSO algorithm searches in parallel using a group of individuals similar to other AI-based heuristic optimization techniques.

DPSO algorithm searches in parallel using number of individuals. An individual is a swarm approaches to the optimum or a quasi optimum through its present velocity, previous experience, and the experience of its neighbors. In a physical-dimensional search space, the position and velocity of individual are represented as the vectors $X_i=(x_{i1}, x_{i2}, \ldots\ldots, x_{in})$ and $V_i=(v_{i1}, v_{i2}, \ldots\ldots, v_{in})$. Let $Pbest_i = \left(x_{i1}^{Pbest}, x_{i2}^{Pbest}, \ldots\ldots, x_{in}^{Pbest}\right)$, $Gbest_i = \left(x_{i1}^{Gbest}, x_{i2}^{Gbest}, \ldots\ldots\ldots x_{in}^{Gbest}\right)$ respectively, be the best position of individual and best position its neighbors' so far. Using the information, the updated velocity of individual is modified under the following equation in the DPSO algorithm

$$V_i^{k+1} = K\left(V_i^k + C_1 rand_1 \times \left(Pbest_i^k - X_i^k\right) + C_2 rand_2 \times \left(Gbest^k - X_i^k\right) \right) \qquad \text{----- (8)}$$

where

V_i^k Velocity of individual i at iteration k

K Construction factor

C_1, C_2 Weight factors

$rand_1$, $rand_2$ Random numbers between [0,1]

X_i^k Position of individual i at iteration k

$Pbest_i^k$ Best position of individual i up to iteration k

$Gbest^k$ Best position of the group up to iteration k

Each individual moves from the current position to the next one by using the modified velocity.

$$X_i^{k+1} = round\left(X_i^k + V_i^{k+1}\right) \qquad \text{----- (9)}$$

The search mechanism of the DPSO using the modified velocity and position of individual based on eqns. (8) and (9) is illustrated in Figure.2.

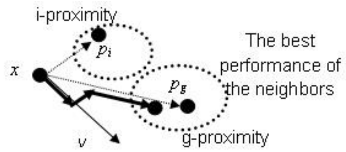

Figure.2. The search mechanism of the discrete particle swarm optimization.

4.2 Initialization of Parameters

Initialize control parameters such as lower and upper bounds of node voltage and tap setting of voltage regulators are selected as parameters. Randomly generate an initial swarm (array) of particles with random positions and velocities.

There exist several parameters to be determined for the implementation of the DPSO. In this paper, these parameters have been determined through the experiments for the 15 node radial distribution system and 33 node system. The procedures and strategies are adopted as follows:

- The values of C_1,C_2 and have the same value, which implies the same weights are given between Pbest and Gbest in the evolution processes.
- Numbers of particles (10-50) are usually sufficient.
- Usually C_1 +C_2=4, no good reason other than empiricism.
- If maximum velocity (V_{max}) is too low the DPSO convergence speed is too slow,

if maximum velocity (V_{max}) is too high, DPSO performance will be unstable.

4.3 Velocity update

To modify the position of each individual, it is necessary to calculate the velocity of each individual in the next stage. In this velocity updating process, the values of parameters such as k, C_1, C_2 should be determined in advance.

The construction factor, $k = \dfrac{2}{2-\phi-\sqrt{\phi^2-4\phi}}$ and $\phi = C_1 + C_2$ ----- (10)

The values of C_1 and C_2 have the same value, which implies the same weights are given between Pbest and Gbest in the evolution processes.

4.4 Position modification

The position of each individual is modified by eqn. (9). The resulting position of an individual is not always guaranteed to satisfy the inequality constraints due to over/under velocity. If any element of an individual violates its boundary condition due to over/under speed, then the position of the individual is fixed to its maximum/minimum operating point. Therefore, this can be formulated as

$$T_{ij}^{k+1} = \begin{cases} T_{ij}^{k+1} + v_{ij}^{k+1} & \text{if } T_{ij,min} \le (T_{ij}^{k+1} + v_{ij}^{k+1}) \le T_{ij,\max} \\ T_{ij,min} & \text{if } T_{ij}^{k+1} < v_{ij}^{k+1} < T_{ij,min} \\ T_{ij,max} & \text{if } T_{ij}^{k+1} < v_{ij}^{k+1} > T_{ij,max} \end{cases} \quad \text{----- (11)}$$

The aforementioned method always produces the position of each individual satisfying the boundary condition of tie switch position for each loop.

4.5 Update of Pbest and Gbest

The Pbest of each individual i at iteration k+1 is updated as follows

$$Pbest_i^{k+1} = X_i^{k+1} \quad ; \quad \text{if} \quad TC_i^{k+1} < TC_i^k$$

$$Pbest_i^{k+1} = Pbest_i^{k+1} \quad ; \quad \text{if} \quad TC_i^{k+1} > TC_i^k \quad \text{----- (12)}$$

$$Gbest^{k+1} = best(Pbest_i^{k+1})$$

where TC_i, the objective function is evaluated at the position of individual i. Gbest at iteration k+1 is set as the best evaluated position among $Pbest_i^{k+1}$.

4.6 Evaluation of Fitness Function

The fitness function should be capable of reflecting the objective and directing the search towards optimal solution. Since the DPSO proceeds in the direction of evolving best-fit particles and the fitness value is the only information available to the DPSO, the performance of the algorithm is highly sensitive to the fitness values. For each particle or swarm, the voltage regulators are placed at the sensitive nodes and run the load flow to calculate the losses, net savings using Eqn. (6) and these net savings becomes the fitness function of the DPSO (as savings are maximized).

4.7 Optimal Solution

Optimal solution (the best position and the corresponding fitness value) to the target problem. Information of the best position includes the optimal location and numbers of voltage regulators, and the corresponding tap setting value represents the maximizing the total savings of the system. Accordingly, the optimal location and number of voltage regulators with tap setting at each node can be determined.

4.8 Stopping criteria

The DPSO is terminated if the iteration approaches to the predefined maximum number of iterations.

4.9 Flow Chart for Optimal Location & Tap setting of VR

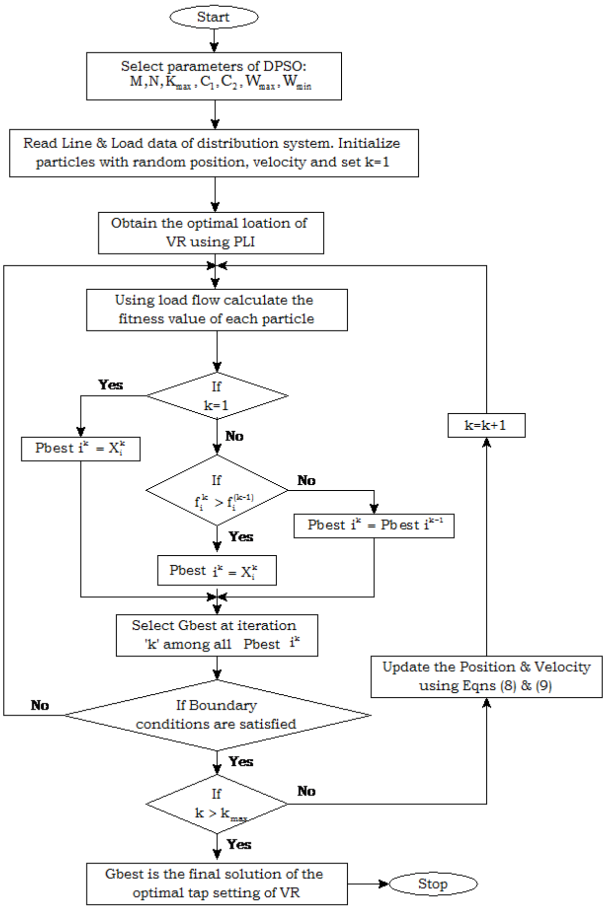

Figure.3. Flow chart for optimal location & tap setting of VR

5 Results and Analysis

The effectiveness of the proposed method is illustrated with two test systems consisting of 15-node and 33-node RDS. The data for 15 node systems are given in [13].The data for 33 node systems is given in [12]. For the positioning of voltage regulators, the upper and lower bounds of voltage are taken as ±5% of base value [10]. The voltage regulators are 11kV, 200MVA with 32 steps of 0.625% each.

5.1 Example-1:

Consider 15-node RDS, and the single line diagram with and without voltage regulators are shown in Figure 4. The voltage values for 15-node RDS with and without voltage regulators are given in Table 1. Observing the voltage levels in second column of Table 1, it is found that most of the node voltages except nodes 1 to 3 & 6 to 10 are violate the lower limit of 0.95 p.u. Ideally voltage regulators are to be installed at all nodes except at node 1 to 3 & 6 to 10. However, in practice, it is not economical to have more number of voltage regulators at all nodes to get the voltages within specified limits. Hence by applying candidate node identification algorithm, the optimal number of voltage regulators that will maintain the voltage profile within limits is determined. The variation of PLI versus node number is shown in Figure 6. The net savings for different PLI tolerance values is given in Table 2. From Table 2, it is observed that the power loss index (PLI) tolerance of

0.3-0.9 is chosen to get maximum net savings. From candidate node identification algorithm, the optimal nodes for voltage regulator placement are 2 and 3. From proposed DPSO algorithm the tap positions are {+12, 0}, at nodes 2 and 3 respectively. At node 2 the voltage regulator is in boost position by 12 i.e. 7.5% and at node 3, the tap position is 0 means that the voltage regulator at node 3 can be omitted.

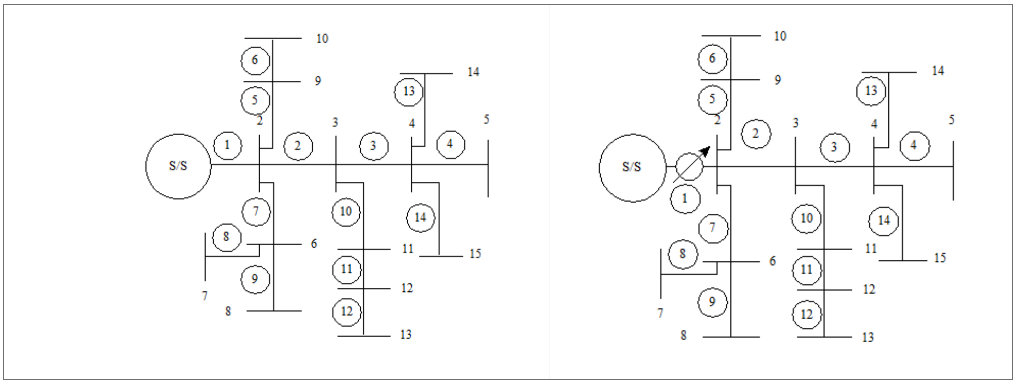

Figure.4. 15-node RDS with and without voltage regulators

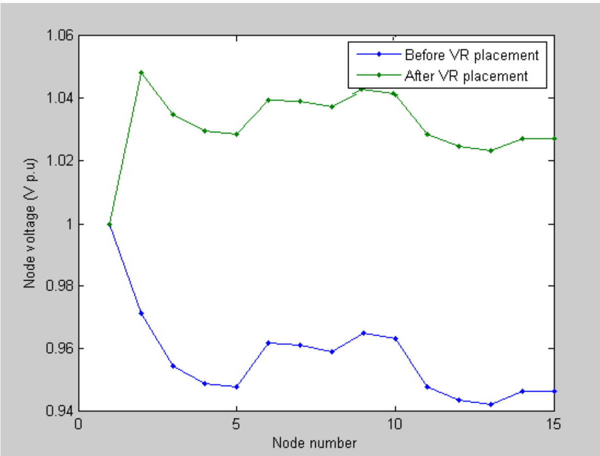

Figure.5 Voltage profile of 15-node RDS before and after VR placement

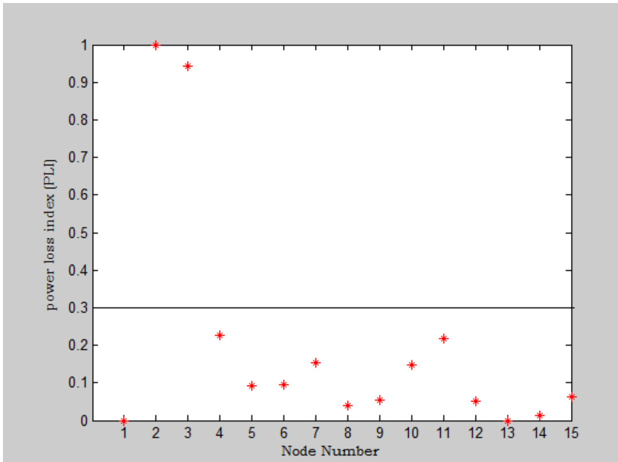

Figure.6 PLI Vs Node number of 15 node RDS for VR placement

The voltage profile before and after placing voltage regulators is shown in Figure.5. Power losses of 15-node RDS with and without voltage regulator are given in Table 3. The variation of net savings versus iteration number is shown in Figure.7. The summary of test results are given in Table 4 which shows that by placement of voltage regulators, reduction in power losses and improvement in voltage profile. It is observed that, with voltage regulators in the system the total active power loss are reduced from 60.3481kW to 45.2756kW i.e. 24.97% reduction and minimum voltage from 0.9423 at node 13 is increased to 1.0000 at node 1. Thus the voltage regulation is reduced from 5.77% to 0% i.e. 100% improvement. The net savings is Rs.6,58,572/- with voltage regulator at optimal locations.

Table 1 Voltage values of 15-node RDS before and after VR placement

Node No	Before VR Placement	After VR Placement at 2 & 3 nodes	Voltage Regulator Tap Position (-16 to+16)
	Voltage (p.u)	Voltage (p.u)	
1	1.0000	1.0000	0
2	0.9712	1.0483	+12
3	0.9547	1.0348	0
4	0.9489	1.0294	0
5	0.9479	1.0285	0
6	0.9618	1.0396	0
7	0.9611	1.0389	0
8	0.9592	1.0372	0
9	0.9651	1.0427	0
10	0.9634	1.0411	0
11	0.9478	1.0284	0
12	0.9437	1.0246	0
13	0.9423	1.0234	0
14	0.9466	1.0273	0
15	0.9464	1.0272	0

Table.2 Net savings for different PLI tolerance values for 15-node RDS

PLI	Nodes	Net Savings(Rs.)
0.2	2,3,4,11	2,88,381/-
0.3-0.9	**2,3**	**6,58,572/-**

Table.3 Power losses of 15-node RDS

Br. No	Sending Node	Receiving Node	Without VR		With VR	
			P_{loss} (kW)	Q_{loss} (kVAr)	P_{loss} (kW)	Q_{loss} (kVAr)
1	1	2	37.7205	36.8954	28.0565	27.4427
2	2	3	11.3380	14.0136	7.5986	9.3917
3	3	4	2.4541	2.4004	2.0841	2.0385
4	4	5	0.0556	0.0375	0.0472	0.0318
5	2	9	1.6093	1.0855	1.3786	0.9299
6	9	10	0.1501	0.1012	0.1286	0.0867
7	2	6	3.0198	2.0368	2.5835	1.7426
8	6	7	0.0386	0.0260	0.0330	0.0223
9	6	8	0.4495	0.3032	0.3844	0.2593
10	3	11	2.1860	1.5475	1.8554	1.3135
11	11	12	0.6043	0.4076	0.5125	0.3456
12	12	13	0.0743	0.0501	0.0630	0.0425
13	4	14	0.2057	0.1387	0.1746	0.1178
14	4	15	0.4417	0.2979	0.3750	0.2529
Total losses			60.3481	59.3421	45.2756	44.0184

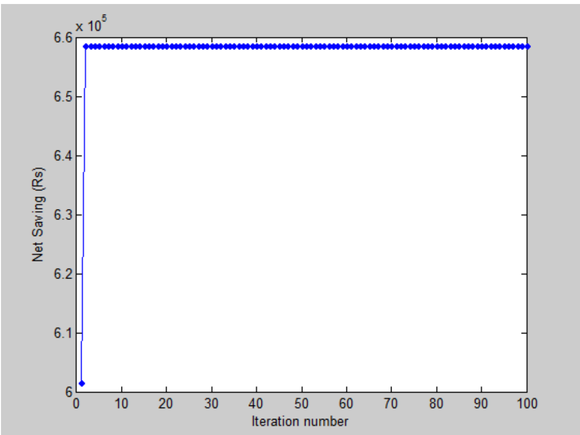

Figure.7 Net saving Vs iteration number of 15-node RDS for VR placement

Table.4 Summary of test results of 15-node RDS

Aspect		**Without VR**	**With VR**			
			Existing [11] Method		**Proposed DPSO Method**	
Optimal locations and Tap Setting of VR			Node	Tap-Set	Node	Tap-Set
			2	+10	2	+12
			3	+2	3	0
Total Active power loss (kW)		60.3481	54.6782		45.2756	
Total Reactive power loss (kVAr)		59.3421	45.9754		44.0184	
Net Savings(Rs.)	Best	0	585982.46		658572.91	
	Worst		78341.01		97438.89	
	Average		238964.27		267904.76	
Percentage loss reduction		-------	9.39%		24.97%	
Min.Voltage(p.u)		0.9423	0.9782		1.0000	
Voltage Regulation (%)		5.77%	2.18%		0	
No. of times best solution occured		-------	31		54	
Execution time (Sec)		-------	27.9863		19.1291	

5.2 Example-2:

Consider 33-node RDS, the single line diagram with voltage regulators is shown in Figure.8. The net savings for different PLI tolerance values is given in Table 5. From Table 5, it is observed that the power loss index (PLI) tolerance of 0.6 is chosen to get maximum net savings. From candidate node identification algorithm, the optimal nodes for voltage regulator placement are 2, 3, 4, 5 and 6. From proposed DPSO algorithm the tap positions are {0, 0, 0, +12, +1}, at nodes 2, 3, 4, 5, and 6 respectively. At node 2,3,4, the tap position is 0 means that the voltage regulator at node 2,3,4 can be omitted and at nodes 5 & 6 the voltage regulator is in boost position by +12 & +1 i.e.7.5%, 0.625%.

The voltage profile before and after placing voltage regulators is as shown in Figure.9. The variation of net savings versus iteration number is shown in Figure.10. The summary of test result in Table 6 shows that by placement of voltage regulators reduction in power losses and improvement in voltage profile. It is observed that, with voltage regulators in the system the total active power loss are reduced from 202.7069 kW to 154.2994 kW i.e. 23.8805% reduction and minimum voltage from 0.9130 at node 18 increased to 0.9714 at node 25. Thus the voltage regulation is reduced from 8.7% to 2.856% i.e. 67.17% improvement. The net savings is Rs. 23,25,011/- with voltage regulators at optimal locations.

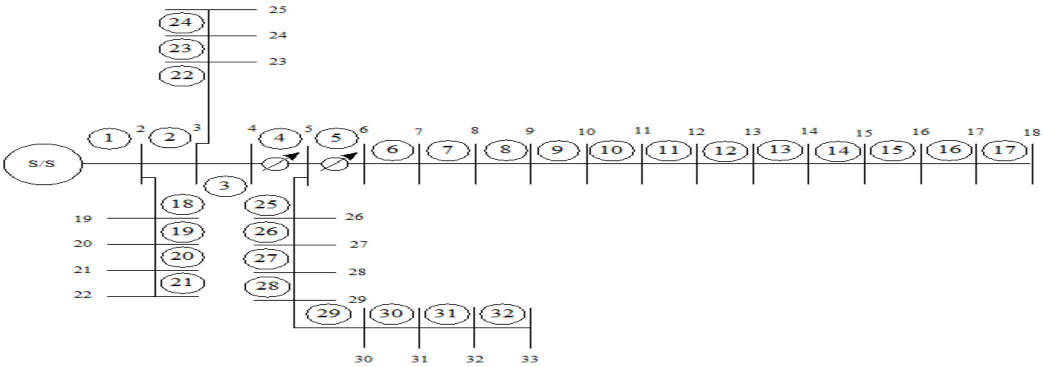

Figure.8 33-node RDS with voltage regulators

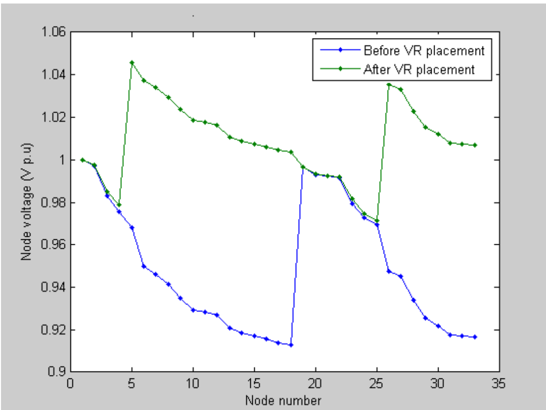

Figure.9 Voltage profile of 33-node RDS before and after VR

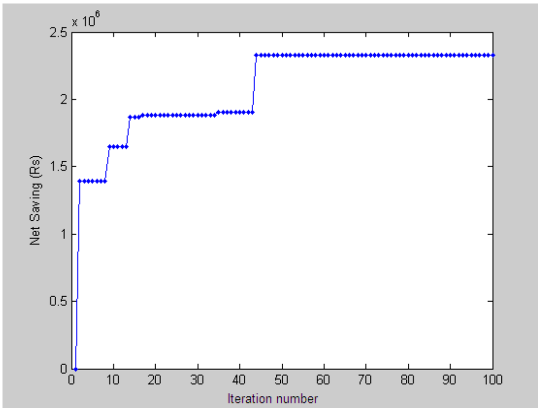

Figure.10 Net savings Vs iteration number of 33-node RDS for VR placement

Table.5 Net savings for different PLI tolerance values for 33-node RDS

PLI	Nodes	Net Savings(Rs.)
0.5	2,3,4,5,6,26,27,28,29	15,11,919/-
0.6	**2,3,4,5,6**	**23,25,011/-**
0.7	3,4,5,6	22,42,460/-

Table.6 Summary of test results of 33-node RDS for VR placement

Aspect		Without VR	With VR			
			Existing [11] Method		Proposed DPSO Method	
Optimal locations and Tap Setting of VR			Node	Tap-Set	Node	Tap-Set
			2	+6	2	0
			3	-9	3	0
			4	0	4	0
			5	+15	5	+12
			6	+2	6	+1
Real power loss(kW)		202.7069	156.4223		154.2994	
Reactive power loss(kVAr)		135.2394	101.2393		103.3696	
Net Savings(Rs.)	Best	0	2247661.21		2325011.44	
	Worst		380600.45		206865.87	
	Average		2003851.02		2071586.93	
Percentage loss reduction(%)		-------	22.83		23.88	
Min.Voltage(p.u)		0.9130	0.9515		0.9714	
Voltage Regulation (%)		8.70	4.85		2.856	
No. of times best solution occured		-------	47		54	
Execution time (Sec)		-------	25.4078		19.1291	

6 Conclusions

DPSO for solving the voltage regulator placement in RDS has been proposed in this paper. In RDS it is necessary to maintain voltage levels within limits at various nodes. This papers aims at discussing the maintenance of voltage levels by using voltage regulators in order to improve the voltage profile and to maximize the net savings. The proposed method deals with initial selection of nodes by using power loss index (PLI) and then Discrete Particle Swarm Optimization (DPSO) has been used for optimal tap setting of the voltage regulators to maintain voltage profile within the desired limits and reduce the losses. The proposed algorithm is tested with two systems consisting of 15 node, and 33 node RDS. From the results, several important observations can be concluded as follows.

- The power losses of distribution system can be effectively reduced by proper placement of voltage regulator.
- In addition of power loss reduction, the voltage profile can be improved as well by the proposed method.

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