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A Novel Method of Network Reconfiguration for the Compensated Network

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This paper delineates a novel method of network reconfiguration for the compensated network. A two-stage methodology is used to reduce the losses and to improve the voltage profile of the balanced radial distribution networks. In the first stage, capacitors are placed optimally for the reactive power compensation of the original network. Fuzzy approach is used to find the optimal capacitor locations and Particle Swarm Optimisation (PSO) method is used to find the sizes of capacitors. In the second stage, an improved fuzzy multi-objective algorithm is used for the network reconfiguration of the compensated network. The proposed method is tested on 33-bus and 69-bus test systems and the results are presented.

Key words: *novel method, compensated network, fuzzy approach, PSO method, network reconfiguration, fuzzy multi-objective algorithm*

1.0 INTRODUCTION

Optimal capacitor placement and network reconfiguration are two important methods of reducing power losses of radial distribution systems. When the power factor of a system is low, shunt capacitors are very commonly used for the reactive power compensation in distribution systems. The consequential benefits from shunt capacitors are power factor improvement, reduction in line losses, voltage profile improvement and decrease in kVA loading on the equipment. Maximum benefits can be achieved by optimally placing the capacitors, when the power factor of a system is low. But optimal capacitor placement alone cannot effectively reduce the power losses caused by the overloads of some feeders.

Distribution networks are reconfigured for reducing power losses, load balancing among different feeders and improving the voltage profile, by changing the open/closed status of some tie-switches and sectionalising switches. Network reconfiguration is effective, if there is unequal loading on the feeders of the network. However, due to some heavy reactive power loads in the system, network reconfiguration alone cannot effectively reduce the power losses caused by reactive power flow.

Similarly, if the power factor of the system is low and feeders are unequally loaded, then by using the hybrid methods, the power losses can be reduced effectively. A hybrid method is the combination of two or more loss reduction methods. Better results can be obtained by combining the optimal capacitor placement and the network reconfiguration methods, instead of using them separately. Network reconfiguration for the compensated network is a hybrid method for the loss reduction in distribution systems.

Optimal capacitor placement is a well-researched optimisation problem and a variety of methods have been proposed in the literature for solving

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it [1-6]. Network reconfiguration is also a complicated optimisation problem and various research papers have been proposed for it [7-10]. But very little research has been carried out in the area of network reconfiguration for the compensated network [11-13].

Ng, H N *et al.* [5] proposed the capacitor placement problem by using fuzzy approximate reasoning. Voltage and power loss indices of the distribution system nodes are modelled by membership functions and a Fuzzy Expert System (FES) containing a set of heuristic rules used to determine the capacitor placement suitability index of each node. Capacitors are placed on the nodes with the highest suitability.

In the first stage, the method proposed by Ng, H N *et al.* [5] is adapted to determine the optimal capacitor locations for the original network using fuzzy logic. To find the sizes of the capacitors, Particle Swarm Optimisation method is used.

In the second stage, an improved fuzzy multi-objective algorithm is used for the reconfiguration of the compensated network. This algorithm is based on the heuristic rules [9] and fuzzy multi-objective approach [10]. The proposed method was tested on 33-bus [8] and 69-bus [1] test systems.

2.0 PROBLEM FORMULATION

The main objective of the proposed method is to reduce the power losses in the distribution systems. The power losses in the distribution systems are real power loss and reactive power loss.

The total real power loss (I^2R loss) in a balanced distribution system consisting of b branches can be written as:

$$P_{Lt} = \sum_{i=1}^{b} I_i^2 R_i \tag{1}$$

Where I_i is the branch current and R_i is the resistance of the i^{th} branch of the original network.

$$I_i = I_a + j\, I_r \tag{2}$$

The branch current I_i, active part of the branch current I_a and reactive part of branch current I_r in the original network can be obtained from the load flow solution of the original network. The total I^2R loss P_{Lt} can be separated into two components P_{La} and P_{Lr} based on the active and reactive parts of branch currents. The power loss components can be written as:

$$P_{La} = \sum_{i=1}^{b} I_{ai}^2 R_i \tag{3}$$

$$P_{Lr} = \sum_{i=1}^{b} I_{ri}^2 R_i \tag{4}$$

Where P_{La} is the loss associated with the active part of the branch currents and P_{Lr} is the loss associated with the reactive part of the branch currents in the original network.

In the first stage, the reactive power can be generated in the system by adding shunt capacitors. P_{Lr}, the power loss associated with the reactive part of branch currents can be minimised by reducing the reactive power flow through the branches. The best method of reducing this component of the loss is by optimally placing the capacitors.

In the second stage, P_{La} can be minimised by re-routing the active power flow through the reconfiguration process, after the reactive power compensation. The objective is to find a new radial configuration of the network so that the loss associated with the active part of the branch currents has the minimum value, while supplying the demand in full.

3.0 OPTIMAL CAPACITOR PLACEMENT FOR THE ORIGINAL NETWORK

The objective of the optimal capacitor placement is to determine the best locations and sizes of capacitors on radial distribution feeders.

3.1 Identification of optimal capacitor locations using fuzzy approach

This paper presents a Fuzzy Inference System (FIS) approach to determine suitable locations for capacitor placement. For the capacitor placement problem, approximate reasoning is employed in this manner: when losses and voltage levels of a distribution system are studied, an experienced planning engineer can choose locations for capacitor installations, which are probably highly suitable. For example: A section in a distribution system with high losses and low voltage is highly ideal for placement of capacitors; whereas a low loss section with good voltage is not ideal for capacitor placement. A set of fuzzy rules has been used to determine suitable capacitor locations in a distribution system.

In the first step, load flow solution for the original system is required to obtain the basecase total real power loss, $P_L^{(Basecase)}$. Again, load flow solutions are required to obtain the power loss reduction by compensating the total reactive load at every node of the distribution system. The loss reductions are then, linearly normalised into a [0, 1] range with the largest loss reduction having a value of 1 and the smallest one having a value of 0. Power Loss Index (PLI) value for n^{th} node can be obtained using equation (5):

$$PLI_{(n)} = \frac{(LR_{(n)} - LR_{(\min)})}{(LR_{(\max)} - LR_{(\min)})} \tag{5}$$

Where LR(n) = Loss Reduction on n^{th} node

LR(max) = maximum Loss Reduction

LR(min) = minimum Loss Reduction

These power loss reduction indices along with the p.u. nodal voltages are the inputs to the Fuzzy Inference System (FIS), which determines the node more suitable for capacitor installation. In this present work, Fuzzy Logic Toolbox in MATLAB7 is used for finding the Capacitor Suitability Index (CSI).

3.2. Particle Swarm Optimisation (PSO) method to find the capacitor sizes

3.2.1 Particle Swarm Optimisation

The PSO technique evolved from the motion of a flock of birds searching for food. It uses a number of particles that constitute a swarm. Each particle traverses the search space looking for the global minimum. In a PSO system, particles fly around in a multidimensional search space. During flight, each particle adjusts its position according to its own experience and the experience of neighbouring particles, making use of the best position encountered by itself and its neighbours. The swarm direction of a particle is defined by the set of particles neighbouring to the particle and its history of experience.

Let x and v denote a particle's coordinates (position) and its corresponding flight speed (velocity) in a search space, respectively. The best previous position of a particle is recorded and represented as *pbest*. The index of the best particle among all the particles in the group is represented as *gbest*. Each particle knows the best value so far (*pbest*) and best value in the group (*gbest*). The particle tries to modify its position using the current velocity and the distance from *pbest* and *gbest*.

The modified velocity and position of each particle can be calculated using the following formulae [6]:

$$v_i^{k+1} = K.\,[w.\,v_i^k + c_1.rand_1.(pbest_i - x_i) + c_2.rand_2\,.(gbest_i - x_i)] \tag{6}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{7}$$

Where K is constriction factor

v_i^k = velocity of particle i in k^{th} iteration

w = inertia weight parameter

c_1, c_2 = weight factors

$rand_1$, $rand_2$ = random number between 0 and 1

x_i^k = position of particle i in k^{th} iteration

Suitable selection of inertia weight w provides a balance between global and local explorations. In general, the inertia weight w is set according to the following equation:

$$w = w_{max} - ((w_{max} - w_{min}).\ t \,/\, T) \tag{8}$$

Where w is an adjustable parameter between w_{max} and w_{min}

t = current iteration number

T = maximum number of iterations

In the iterative process, the particle velocity is limited by some maximum value v_i^{max}. The parameter v_i^{max} determines the resolution or fitness, with which regions are to be searched between the present position and the target position. This limit enhances the local exploration of the problem space and it realistically simulates the incremental changes of human learning. If v_i^{max} is too high, particles might fly past good solutions. If v_i^{max} is too small, particles may not explore sufficiently beyond local solutions. In many experiences with PSO, v_i^{max} was often set at 10%–20% of the dynamic range of the variable on each dimension.

3.2.2 Algorithm to find the capacitor sizes using PSO Method

After identifying the n number of candidate locations using fuzzy approach, the capacitor sizes in all these n candidate locations are obtained by using the Particle Swarm Optimisation Method (PSOM).

Step 1: Initially [nop x n] number of particles are generated randomly within the limits, where nop is the population size and n is the number of capacitors. Each row represents one possible solution to the optimal capacitor-sizing problem.

Step 2: Similarly [nop x n] number of initial velocities are generated randomly between the limits ($-v_i^{max}$) and ($+ v_i^{max}$). Iteration count is set to one.

Step 3: Placing all the n capacitors of each particle at the respective candidate locations, load flow analysis is performed to find the total real power loss P_L. The same procedure is repeated for the nop number of particles to find the total real power losses. Fitness value corresponding to each particle is evaluated using equation (9) for maximum loss reduction.

Fitness function for maximum loss reduction is given by:

$$F_A = (P_L^{\text{(Basecase)}} - P_L^{\text{(after compensation)}}) \tag{9}$$

The capacitor sizes corresponding to maximum loss reduction are required. For any one particle, the negative F_A value indicates that losses are increasing due to overcompensation and F_A is fixed at F_A (minimum) and capacitor sizes corresponding to that particle are fixed at Q_C (minimum).

Step 4: *pbest* values for all the particles are obtained from the fitness values and the best value among all the *pbest* values (*gbest*) is identified.

Step 5: Maximum fitness and average fitness values are calculated. Error is calculated using equation (10).

Error = (maximum fitness – average fitness) (10)

If this error is less than a specified tolerance, go to step 10.

Step 6: New velocities for all the particles are calculated using equation (11) in the range of ($-v_i^{max}$) and ($+ v_i^{max}$).

$$v_{i,j}^{k+1} = K.\ [w.\ v_{i,j}^{k} + c_1.rand_1.\ (p^{pbest}_{i,j} - p_{i,j}) + c_2.rand_2.(p^{gbest}_{1,j} - p_{i,j})] \tag{11}$$

Where K is constriction factor

$V_{i,j}^{k}$ = velocity of particle i,j in k^{th} iteration

w = inertia weight parameter

c_1, c_2 = weight factors

$rand_1$, $rand_2$ = random number between 0 and 1

$p_{i,j}^{k}$ = particle *i, j* in k^{th} iteration

$p^{pbest}_{i,j}$ = pbest particle *i, j* in k^{th} iteration

$p^{gbest}_{1,j}$ = gbest particle *1, j* in k^{th} iteration

Step 7: The position of each particle is updated using equation (12).

$$p_{i,j}^{k+1} = p_{i,j}^{k} + v_i^{k+1} \quad (12)$$

Step 8: New fitness values are calculated for the new positions of all the particles. If the new fitness value for any particle is better than the previous *pbest* value, then the *pbest* value for that particle is set to present fitness value. Similarly the *gbest* value is identified from the latest *pbest* values.

Step 9: The iteration count is incremented and if iteration count has not reached maximum, go to Step 3.

Step 10: The *gbest* particle gives the optimal capacitor sizes in *n* candidate locations and the results are printed.

4.0 NETWORK RECONFIGURATION FOR THE COMPENSATED NETWORK

In the second stage, an improved fuzzy multi-objective algorithm is used for the reconfiguration of the compensated network. An improved reconfiguration algorithm based on the heuristic rules and fuzzy multi-objective approach is used for network reconfiguration of the compensated network.

Three objectives are considered for the network reconfiguration of the compensated network-minimising real power loss, deviation of nodal voltage and branch current constraint violation, while subject to a radial network structure in which all loads must be energised. These three objectives are modelled by fuzzy membership functions μL_i, μV_i and μA_i respectively. The shapes of these three membership functions are the same and are shown in Fig. 1.

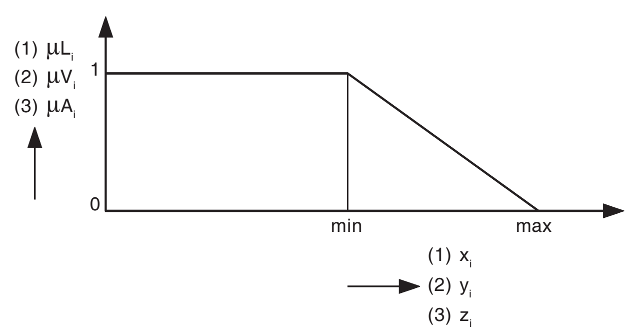

FIG. 1 MEMBERSHIP FUNCTIONS FOR μL_i, μV_i AND μA_i

4.1 Membership function for real power loss reduction (μ L_i)

$$xi = \frac{PLOSS(i)}{PLOSS^0},$$

for $i = 1, 2, \ldots N_k$ (13)

Where N_k is the total number of branches in the loop including tie-branch, when the k^{th} tie-switch is closed, PLOSS (*i*) is the total real power loss of the radial configuration of the system when the i^{th} branch in the loop is opened, and $PLOSS^0$ is the total real power loss before network reconfiguration.

From Fig. 1, μL_i can be written as:

$$\mu L_i = \frac{(x_{max} - x_i)}{(x_{max} - x_{min})},$$

for $x_{min} < x_i < x_{max}$

μL_i = 1 for $x_i \le x_{min}$

μL_i = 0 for $x_i \ge x_{max}$ (14)

4.2 Membership function for maximum nodal voltage deviation (μ V_i)

Let us define,

$$y_i = \max |V_{i,j} - V_s|$$

for $i = 1, 2, \ldots N_k$

$j = 1, 2, \ldots NB$ (15)

Where N_k is the total number of branches in the loop including tie-branch, when the k^{th} tie-switch is closed; NB is the total number of nodes of the system; V_s is the voltage of the substation (in per unit); $V_{i,j}$ is the voltage of node j corresponding to the opening of the i^{th} branch in the loop (per unit).

From Fig. 1, μV_i can be written as:

$$\mu V_i = \frac{(y_{max} - y_i)}{(y_{max} - y_{min})},$$

for $y_{min}<y_i<y_{max}$

$\mu V_i = 1$ for $y_i \le y_{min}$

$\mu V_i = 0$ for $y_i \ge y_{max}$ (16)

4.3 Membership function for maximum branch current loading index (μA_i)

The basic purpose of this membership function is to minimise the branch current constraint violation.

Let us define branch current loading index $= \frac{|I(i,m)|}{I_c(m)}$,

For $i = 1, 2, \ldots N_k$

and $m = 1, 2, \ldots NB-1$ (17)

where N_k is the total number of branches in the loop including the tie-branch when the k^{th} tie-switch is closed; $|I(i, m)|$ is the magnitude of current of branch-m when the i^{th} branch in the loop is opened; $I_c(m)$ is the line capacity of branch-m; NB is the total number of nodes of the system.

Let us define $z_i = \max\{\frac{|I(i,m)|}{I_c(m)}\}$,

for $i = 1, 2, \ldots N_k$

and $m = 1, 2, \ldots NB-1$ (18)

From Fig. 1, μA_i can be written as:

$$\mu A_i = \frac{(z_{max} - z_i)}{(z_{max} - z_{min})},$$

for $z_{min}<z_i<z_{max}$

$\mu A_i = 1$ for $z_i \le z_{min}$

$\mu A_i = 0$ for $z_i \ge z_{max}$ (19)

4.4 An improved fuzzy multi-objective algorithm

A complete algorithm of the improved fuzzy multi-objective algorithm for the network reconfiguration of the compensated network is given below:

Step 1: Read the line data and bus data of the compensated network.

Step 2: Run the load flow program to find the nodal voltages, branch currents and power flows of the compensated network. Also find the total losses of the compensated network.

Step 3: Compute the voltage difference across all the open tie-switches.

Step 4: Identify the open tie-switch across which the voltage difference is maximum.

Step 5: If this voltage difference is greater than $\in_r$, then consider switch "k" first and go to Step 6; otherwise, go to Step 10.

Step 6: Identify the number of branches on HV side of the tie-switch (N_{HV}) and the number of branches on LV side of the tie-switch (N_{LV}). In the present work, only N_{LV} number of branches on the LV side of the tie-switch are considered including the tie-branch when the tie-switch "k" is closed.

Step 7: Open one branch at a time and evaluate the membership value for each objective and also evaluate the overall degree of satisfaction. Compute μL_i, μV_i and μA_i using equations (14), (16) and (19), respectively.

Evaluate: $D_{k,I} = \min\{\mu L_i, \mu V_i, \mu A_i\}$.

Step 8: Obtain the optimal solution for the operation of tie-switch "k" (i.e., $OS_k = \max\{D_{k,i}\}$).

Step 9: Go to Step 2 and repeat the same procedure for all the other tie-switches.

Step10: Print the results of network reconfiguration for the compensated network.

5.0 RESULTS

The proposed method is applied to the IEEE 33-bus system [8] and IEEE 69-bus system [1] and the results are presented. A two-stage methodology is used for the network reconfiguration for the compensated network. In the first stage, original network is compensated by optimally placing the capacitors. In the second stage, an improved fuzzy multi-objective approach is used for the reconfiguration of the compensated network.

5.1 Results of 33-bus system

Optimal capacitor locations are identified based on the CSI values. For this 33-bus system, nodes having CSI value greater than 0.5 are considered for optimal capacitor placement. Node 30 is selected for optimal capacitor placement. 1315 kVAr size capacitor is selected by using PSO method at node 30.

Results of network reconfiguration of the compensated network are shown in Table 1.

TABLE 1

NETWORK RECONFIGURATION RESULTS OF THE COMPENSATED NETWORK

Switch operation	Branch closed	Branch opened	Real power loss (kW)
Comp. network	-----	-----	297.9886
1	22-12	9-8	236.9923
2	25-29	29-28	214.0954
3	18-33	33-32	212.1729
4	9-15	15-14	211.9019

The comparative results for the original network, compensated network and after reconfiguration of the compensated network are presented in Table 2.

TABLE 2

COMPARATIVE RESULTS

Description	Value
Total real power loss of the original network in kW	369.2558
Minimum p.u. voltage of the original network (V_{33})	0.8785
Total real power loss in kW (after compensation)	297.9886
Loss reduction after compensation	19.30 %
Minimum p.u. voltage of the compensated network (V_{18})	0.9094
Total real power loss after reconfiguration of the compensated network in kW	211.9019
Loss reduction after reconfiguration for the compensated network	42.61 %
Minimum p.u. voltage after reconfiguration of the compensated network (V_{32})	0.9381

The comparative results of the 33-bus system shown in Table 2 confirm that 42.6% loss reduction is possible by reconfiguring the compensated network.

5.2 Results of 69-bus system

Optimal capacitor locations are identified based on the CSI values. For the 69-bus system, nodes having CSI value greater than or equal to 0.5 are considered for optimal capacitor placement.

Nodes 61 and 64 are selected for optimal capacitor placement. 1123 kVAr size capacitor at node 61 and 207 kVAr capacitor at node 64 are selected by using PSO method. Results of network reconfiguration of the compensated network are shown in Table 3.

TABLE 3

NETWORK RECONFIGURATION RESULTS OF THE COMPENSATED NETWORK

Switch operation	Branch closed	Branch opened	Real power loss (kW)
Comp. network	-----	-----	151.7074
1	50-59	56-55	92.5760
2	46-15	13-12	81.5303
3	27-65	62-61	68.6308

The comparative results for the original network, compensated network and after reconfiguration of the compensated network are presented in Table 4.

TABLE 4

COMPARATIVE RESULTS

Description	Value
Total real power loss of the original network in kW	225.0044
Minimum p.u. voltage of the original network (V_{65})	0.9092
Total real power loss in kW (after compensation)	151.7074
Loss reduction after compensation	32.58 %
Minimum p.u. voltage of the compensated network (V_{65})	0.9314
Total real power loss after reconfiguration of the compensated network in kW	68.6308
Loss reduction after reconfiguration for the compensated network	69.50 %
Minimum p.u. voltage after reconfiguration of the compensated network (V_{61})	0.9690

The hybrid method results of the 69-bus test system shown in Table 4 prove that 69.5% loss reduction is possible for the 69-bus system and voltage profile can be improved significantly by reconfiguring the compensated network.

6.0 CONCLUSIONS

A novel method of network reconfiguration for the compensated network is delineated in this paper. In the proposed two-stage methodology, the original network is compensated by optimally placing the capacitors and then the compensated network is reconfigured. The efficiency of the proposed hybrid method has been proved for the two test systems with the following conclusions:

In the first stage, the power loss of the system is reduced by optimally placing the capacitors at the potential locations of the original network. Fuzzy approach determines the optimal capacitor locations and PSO method determines the optimal capacitor sizes effectively.

In the second stage, the power loss of the system is further reduced and the voltage profile is improved significantly, after the reconfiguration of the compensated network. The proposed reconfiguration algorithm is effective in finding the optimal radial configuration of the compensated network with less computational effort because only LV side branches are considered for branch exchange operation. The final results of the proposed method show that better loss reduction is possible by reconfiguring the compensated network.

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