A New Fuzzy Logic Approach for Selection of Capacitor Installation Locations

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Abstract - **A new fuzzy logic approach for determining of optimal capacitor locations in radial distribution networks is presented in this paper. The locations are chosen on the bases of real power loss sensitivity on load changes, node electrical distances from the source point, and relative nodal loads. This procedure is simple and efficient.**

Keyword - **capacitor placement, fuzzy logic, distribution network**

I. Introduction

Many papers and professional books are dedicated to reactive power compensation in transmission [1, 2], as well as distribution networks [3, 4, 5]. Reactive power compensation is reactive power control for improvement of electric energy supply quality in electric power networks. Techniques and some of the compensation aims in load neighborhood (in distribution networks), are meaningfully different from those for large transmission networks. The basic aims of reactive power load compensation in distribution networks are:

- Real and reactive power loss reduction,
- Voltage profile improvement,
- Improvement of network efficiency due to voltage increase,
- Line and equipment capacity discharge,
- Reduction and elimination of investment cost.

Reactive power compensation of industrial load realizes by means of capacitors. Determining of capacitor number and sizes depends on economic reasons. Therefore, the objective function, which consists of peak power costs, consumed real and reactive power costs and capacitor investment cost should be minimized.

The method for capacitor allocation in transmission networks using nonlinear programming is presented in [2]. Authors in [4] apply the search method. However, stochastic procedures for the problem solving, require a lot of computer time, because they take into account locations known as unfavorable. Selection of capacitor installation places depends on effects that they can produce. One of the subproblems of reactive power compensation in complex networks is determining of optimal capacitor locations. A simple and efficient procedure which considers a few practical fact connected with capacitor location selection is given in this paper. It is based on fuzzy logic, and can be applied for radial lines and distribution networks with laterals.

Typical distribution networks have different nonuniformly distributed loads. If the loads are uniformly distributed, capacitor should be on two-thirds of the line length, causing minimum real power losses. Based on this fact, the membership function, which presents criterion for capacitor placement convenience, is introduced. It prefers the nodes on two-thirds from the source. On the other hand, the largest reduction of losses is achieved by capacitor installation at the nodes with the largest losses sensitivity on reactive load. By rule, these nodes are of the longest electrical distance. Besides, the fact that capacitors are usually placed at nodes with the largest load is to be accepted. Considering the three mentioned facts, a new fuzzy logic criterion for selection of capacitor locations, is formed by min-max principle.

The procedure is illustrated on an example of a simple middle voltage distribution network. Several variants with different load distribution are considered. The results are compared with the results of basic example with uniformly distributed load. Solving is straightforward, without searching of all possible shunt capacitor locations.

II. Methodology

Total real power losses in a network are equal to the sum of the branch losses. However, the load current of the node j, influences on real power losses only of those branches that connect j^{th} node with source one. These branches form path j, which is illustrated in Fig. 1. The path is defined along branches of the tree to the source node. The number of paths is equal to the node number.

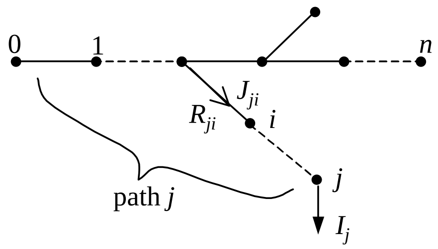

Fig. 1. Forming the paths of radial network

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It is necessary to know voltages and load flows for calculation of real power loss sensitivities on a nodal load. After load flow iterative procedure is finished, real power loss belonging to path *j*, is calculated as:

$$\Delta P_j = \sum_{i \in j} R_{ji} J_{ji}^2 \qquad (1)$$

where

R_{ij} – resistance of branch *i* on path *j*,

J_{ji} – current of branch *i* on path *j*.

According to Eq. (1), partial derivative of total network real power losses (ΔP) with respect to load current of j^{th} node can be expressed as

$$\frac{\partial \Delta P}{\partial I_j} = 2\sum_{i \in j} R_{ji} J_{ji} \ , \qquad (2)$$

while total real power loss sensitivity on reactive load of node *j* is

$$\frac{\partial \Delta P}{\partial Q_j} \cong \frac{\partial \Delta P}{\partial I_j}\frac{\partial I_j}{\partial Q_j} \ . \qquad (3)$$

As the influence criterion for the capacitor placement at a node on a total real power loss reduction, sensitivity of the losses on reactive load of this node, can be used. The larger the sensitivity, the better the effects are achieved by capacitor installation, and vice versa. Therefore, the membership function $\mu_S(j)$ is linear function of sensitivity, and it is shown in Fig. 2. It is defined in the following way

$$\mu_S(j) = \begin{cases} \dfrac{S(j)}{S_{\max}} & , \ S(j) < S_{\max} \\ 0 & , \ \text{otherwise} \end{cases} \qquad (4)$$

where

S(i) – sensitivity of total real power losses on reactive load variation at node *j*,

S_{max} – maximal sensitivity in network.

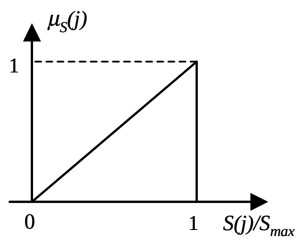


Fig. 2. Membership function $\mu_S(j)$

In the case of uniformly distributed load in radial line, most favorable is to install capacitor on two-thirds of line length. When the load is nonuniformly distributed, optimal location will be closer to the beginning, or to the end of the network, depending on load distribution and branch impedances. In this paper, as a criterion for remoteness, electrical distance is used. It is defined by the sum of branch resistances from the source to the observed node. The selection of capacitor installation place depends on nodal electrical distance, which is included in the function $\mu_D(j)$ that is shown in Fig. 3. This function can be presented analytically in the form:

$$\mu_D(j) = \begin{cases} 2 \cdot r_E(j) & , \ r_E(j) \in [0, \ 1/2) \\ 1 & , \ r_E(j) \in [1/2, \ 5/6) \\ 6 \cdot (1 - r_E(j)) & , \ r_E(j) \in [5/6, \ 1] \end{cases}, \qquad (5)$$

where $r_E(j) = R_E(j)/R_{E\max}$. The electrical distance of node *j*, $R_E(j)$, is equal to the sum of resistances on path *j*. The largest electrical distance of a node in the network is denoted by $R_{E\max}$.

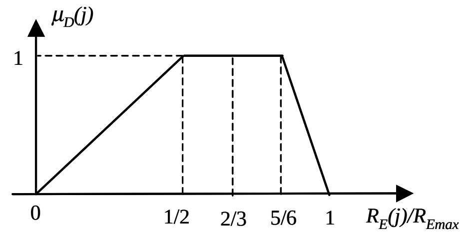


Fig. 3. Membership function $\mu_D(j)$

It is common to install capacitor at the nodes with the largest reactive load, so the new criterion for location selection, $\mu_Q(j)$, is introduced. This membership function is linear, and it is shown in Fig. 4. Analytic expression for membership function $\mu_Q(j)$ is

$$\mu_Q(j) = \begin{cases} \dfrac{Q_L(j)}{Q_{L\max}} & , \ Q_L(j) < Q_{L\max} \\ 0 & , \ \text{otherwise} \end{cases}, \qquad (6)$$

where

$Q_L(j)$ – reactive load of j^{th} node,

Q_{Lmax} – the largest reactive load in the network.

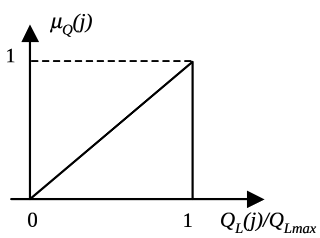


Fig. 4. Membership function $\mu_Q(j)$

Taking into account the above membership functions, the criterion for shunt capacitor location selection is made. The most favorable place for capacitor installation from the viewpoint of the largest loss sensitivity on reactive load, optimal electrical distance from the source node and the value of reactive load is determined by the expression:

$$U = \max_{j} \left\{ \min\left(\mu_S(j), \mu_D(j), \mu_Q(j) \right) \right\} \qquad (7)$$

In this way, three membership functions are taken with the same importance. In the case of economical justification of capacitor installation on *n* locations, the functions

$$\mu(j) = \min\left\{ \mu_S(j), \mu_D(j), \mu_Q(j) \right\} \qquad (8)$$

are sequenced from the largest to smallest one. The first *n* functions and, therefore, the corresponding nodes, are selected for capacitor installation.

III. CALCULATION RESULTS

The suggested approach of capacitor placement can be applied to radial line, as well as to networks with laterals. Here is presented a simple example of radial network without laterals with nine branches that feed three-phase symmetrical loads. The source node voltage is 10.5 kV. All branches have the same resistances and reactances: 1 and 0.5 Ω, respectively. Initial real power load of the nodes is P_L=100 kW, while reactive loads are varied in correlation with power factor which is given in the range from 0.8 to 0.95. Several examples where the load distribution along the line is varied, are considered. The results are compared with basic example results, where the load is uniformly distributed along the line.

On the bases of the proposed method, for the line with uniformly distributed load, the most favorable place for capacitor installation, is node 7, not node 6 which minimizes the real power losses because it is on three-thirds of the source node. This location displacing occurs due to the influence of real power loss sensitivity on reactive nodal loads. This sensitivity increases with remoteness from the source point. However, although two final buses have large sensitivity, they are not selected because of long electrical distances from the source node that is taken into account by membership function $\mu_D(j)$.

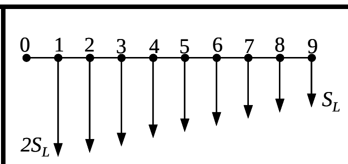
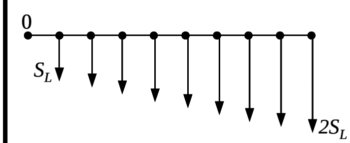
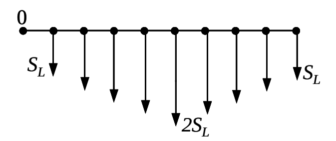
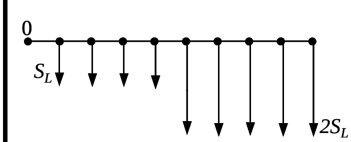
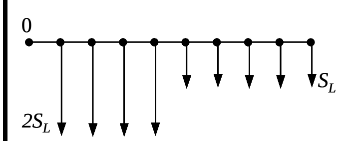
Besides, the influence of load distribution along the line is examined, too. Graphic representation of considered load distribution variants and selected locations in the cases of the same and different branches are shown in Table I.

If the resistances of the branches are same, the most favorable locations are: node 5 for the case of load distribution a), 7 for b), 6 for c), 7 for d) and 4 for e). When the loads are concentrated at the beginning of the line, there is no an important oncoming of capacitor installation place. The cause is relative low sensitivity of real power losses on reactive load in these nodes. On the other hand, in the cases of larger load concentration in the final nodes, more favorable installation place moves to the right, but node index is not larger than 7, due to long electrical distance of the nodes 8 and 9.

The influence of branch resistances on the selection of capacitor locations is examined, too. The same network with different resistances of the first two branches – three times bigger, is taken for illustration. This case is mentioned in the last column of Table 3.1. Increase of the first branch resistances, increases the node electrical distances. The membership function $\mu_D(j)$ will have the values 1, for nodes 3, 4, 5 and 6. In the previous case of the network with the same branches, the function has value 1 for nodes 5, 6 and 7. The function $\mu_S(j)$ increases rapidly compared with previous case, that is shown in Fig. 5 for load distribution from figure e). For this load distribution, $\mu_Q(j)$ has the values close to one for nodes 1, 2, 3 and 4. Therefore, based on criterion (7), the node 4 is selected again as an optimal location for this kind of load distribution. Due to increase of function $\mu_S(j)$, in the considered case of different branches, the optimal location will be closer for load distribution from figures a) and c) and these nodes will be 4 and 5, respectively. For the distributions b) and d), selected node will be seven, due to large electrical distances of the final nodes.

TABLE I

FAVORABLE LOCATIONS FOR DIFFERENT LOAD DISTRIBUTIONS

Load distribution		Capacitor location	
		same branches	different branches
a)		5	4
b)		7	7
c)		6	5
d)		7	7
e)		4	4

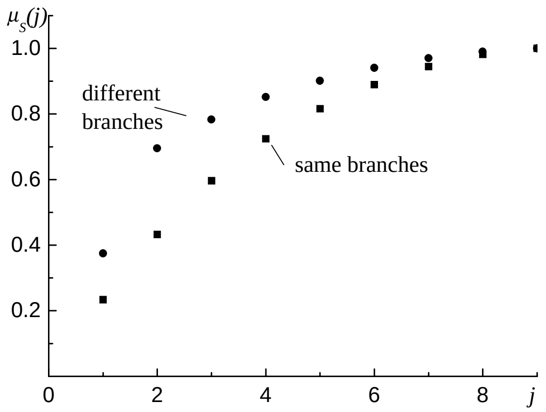


Fig. 5. The change of $\mu_S(j)$ for the same and different branches

IV. CONCLUSION

The new fuzzy logic approach to selection of capacitor installation locations in radial middle voltage distribution networks with nonuniformly load distribution is proposed in the paper. The installation place is selected on the bases of the functions that take into account real power losses, sensitivity of the losses on reactive nodal power and nodal loads. The procedure enables to avoid stochastic methods for capacitor allocation on the bases of experience. Described method is very efficient. After load flow calculation, the solution is straightforward. Further investigations connected to capacitor allocation will take into account cost function minimization, capacitor control and voltage violations.

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