International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Research Article

Fuzzy Logic Based Optimal Capacitor Placement and Loss Reduction in Radial Power System

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Accepted 03 July 2016, Available online 11 July 2016, **Vol.6, No.4 (Aug 2016)**

Abstract

A fuzzy technique based decision maker is developed and incorporated in this study in order to determine suitable candidate nodes for optimal capacitor placement and sizing in radial distribution systems for the purpose of reducing power loss and improving voltage profile in order to achieve reliability of entire system. The solution methodology is divided into two main parts. The first part is a fuzzy expert system that selects suitable candidate buses to locate capacitor in distribution feeder and the second part is to calculate the reduction in loss in terms of cost. Power flow analysis of the radial distribution system is performed using NR load flow analysis. The proposed method in this paper is simulated in PWS environment and verified on standard IEEE 14 bus radial distribution system. Results show that the proposed method ensures reduction in power loss and improvement in voltage profile at various busses.

Keywords: *Capacitor placement, radial power system, fuzzy expert system, fuzzy optimization techniques, PWS (Power World Simulator)*

1. Introduction

The expenditure and the quality of electrical energy is always one of the priority topics in power systems. Transmission and distribution losses are one of the important parameter which directly affects the cost of electrical energy. The main source of these losses is the heat, which is caused because of overloading of the entire system and harmonics. Increasing opulence with development of social life has promoted usage of appliances such as coolers, ventilations and HVAC system which demands more reactive power from the utility. As a consequence of increasing demand in the reactive power, the line current of entire system is increased and therefore the active power loss and voltage sag in the line are observed. It is obvious that the overloading of the line due to increased reactive power should be avoided in order to prevent system from unhealthy operations. If the power losses decrease, the system acquires a longer operating life with increased performance thereby becoming more reliable system. Therefore, shunt capacitors are widely used in distribution systems in order to release reactive power burden on main generating stations. In addition to reduction in total power loss and enhancement of voltage profile, power factor correction is also ensured with placement of shunt capacitors in radial distribution feeders. However, in order to attain these advantages, it is necessary to determine proper location and sizing of shunt capacitor. In recent years, a majority of researchers have concentrated on solving optimal capacitor location problem in distribution networks and proposed a wide range of methodologies based on analytical methods (Yesim A. Baysal *et al,*2015), numerical programming methods (S. M. Kannan *et al,*2008), heuristic methods (V .J. Shetty *et al,*2015), and artificial intelligence techniques (S .F. Mekhamer *et al,*2003). In this paper, fuzzy expert system is preferred in order to solve the optimal location of capacitor because of its advantages such as ease, fewer computations and quick results. The solution procedure involves in two main stages. At first, power loss indices (PLI) and per unit bus voltages as inputs of fuzzy expert system (FES) are used to identify best locations of shunt capacitor (Yesim A. Baysal *et al,* 2015).

The used objective function aims to maximize annual net savings in terms of power loss with voltage limit constraints. In order to calculate the objective function, NR load flow analysis is performed due to its suitability for radial distribution systems and effectiveness in speeding up the computing time without difficulties in getting converged solutions. In this work, it is assumed that the entire distribution system is balanced, effect of harmonic is neglected and loads are represented by constant power. The proposed method is executed in Power World

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Simulator environment and applied to IEEE 14 bus radial distribution test system.

2. Framework of the approach

The entire framework of this approach is to solve the optimal location of capacitor problem includes the use of numerical procedures, which are coupled to the FES (S .F. Mekhamer *et al*,2003). First, a load flow program calculates the power loss and voltage profile at each individual bus. The same extracted data is used as power loss index and voltage index and fuzzy rules are formed.

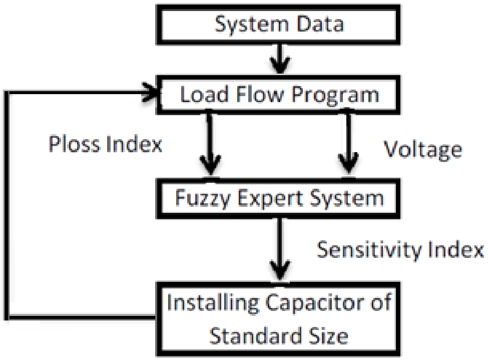

Fig.1. Frame work of the approach

These power loss reduction indices along with the per-unit node voltages are provided as inputs into the Fuzzy Expert System, which determines the candidate node most suitable for capacitor installation in order to achieve the objective function. Finally, a numerical procedure is used to determine the size of capacitor to be placed at the chosen node.

The savings function “S” maximized by this capacitor sizing algorithm is given by:

$$S = K_p \Delta L_p + K_e \Delta L_e - K_c C \qquad (1)$$

where , $\Delta L_p, \Delta L_e$ are the loss reductions in peak demand and energy due to capacitor installation, C is the size of the capacitor in kVAr, Kp, Ke and Kc are the costs of peak demand, energy and capacitors per kVAr respectively. The above procedure is repeated until no additional savings from the installation of capacitors are achieved. Figure.1 explains about flow of data through the individual components of the system.

3. Distribution system power flow

Power flows in a distribution system obey physical laws (Kirchoff's law and Ohm's law), which becomes part of the constraints in the capacitor placement problem. In the proposed algorithm for the capacitor placement problem, the distribution system power flow solution is used as a subroutine for each iteration. Therefore it is essential to have a computationally efficient and numerically robust method for solving the distribution system power flow. In this section, we present the new power flow equation for radial distribution systems (S. M. Kannan *et al*,2008). The formulation is conducive to efficient solution methods. For pedagogic convenience, we first consider a special case where there is only one main feeder. The general case for any radial distribution system is considered next. To simplify the presentation, the system is assumed to be balanced three-phase system.

Consider comprising a branches / node is shown in Fig. 2.

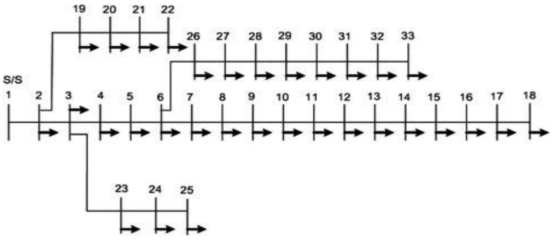

Fig.2 Radial Bus System

Initially substation bus voltage and magnitude are assumed to be constant and represented as V_0. Lines are represented by a series impedance $Z_1 = R_1 + jX_1$ and the loads are treated as constant power sinks, $S_L = P_L + jQ_L$. Shunt capacitors to be placed at the nodes of the radial distribution system will be represented as reactive power source. With this representation, the network becomes a ladder network with nonlinear shunt loads. If the power supplied from the substation, $S_0 = P_0 + jQ_0$ is known, then the power and the voltage at the receiving end of the first branch can be calculated as follows:

$S = S_0 - S - S_{loss1} = S_0 - Z_1|S_0|^2 / V_0 - S_{L1}$
$V_1 \llcorner \theta_1 = V_0 - Z_1 I_0 = V_0 - Z_1 S_0{}^* / V_0$

Repeating the same process yields the following recursive formula for each branch on the feeder,

$$P_{i+1} = P_i - \frac{r_{i+1}(P_i^2 + Q_i^2)}{V_i^2} - P_{Li+1} \qquad (2)$$

$$Q_{i+1} = Q_i - \frac{x_{i+1}(P_i^2 + Q_i^2)}{V_i^2} - Q_{Li+1} - Q_{ci+1} \qquad (3)$$

$$V_{i+1}^2 = V_i^2 - 2(r_{i+1}P_i + x_{i+1}Q_i) + (r_{i+1}^2 + x_{i+1}^2) \times (P_i^2 + Q_i^2) \Big/ V_i^2 \qquad (4)$$

Where,

P_i, Q_i: real and reactive power flows into the sending end of branch i+1 connecting nodes i and i+1.
V_i: bus voltage magnitude at node i.
Q_{cl}: reactive power injection from capacitor to node i.

4. Flow of capacitor placement and sizing based on fuzzy technique

In the radial distribution feeder, the loss reduction improvement is achieved by testing the load and impedance data of the test system. The bus voltages, real power and reactive power magnitudes at the load of the radial distribution system are calculated using PWS software platform. Simulations are run under two cases before and after installation of the capacitor at each bus (C. L. Wadhwa *et al,*2005). The algorithm for finding location of capacitor & size are described by the following procedures.

1. Read line and load data of IEEE 14 bus radial distribution system.
2. To calculate the individual bus voltages and power losses of the distribution system, run the Load-Flow program without any capacitor placement using Power World Simulator.
3. To calculate the Power Loss Index (PLI), take Bus Voltages (BV) of the original system (without capacitor). PLI at each node is determined by using the formula given below:

$$PLI(i) = \frac{X(i)-Y}{(Z-Y)} \qquad for\ i = 2,3,\ldots..n$$

Where,

X (i) = Loss reduction at i^{th} bus.
Y = Minimum reduction.
Z = Maximum reduction.
n = Number of nodes.

4. Bus voltages and power losses index are the input values of Fuzzy Interface System (FIS) for finding the optimal locations of capacitor installation, the output of this controller.
5. After specifying the optimal locations of capacitor installation, the variables of Bus Voltages and the magnitude of load at each level are processed as input variables to the second stage fuzzy controller to find the optimal size of capacitor value in MVAr installed in each pre-specified optimal locations. The optimal value of capacitor represents the output, capacitor sizing, of fuzzy controller (Yesim A. Baysal *et al,*2015). After finding of sizes and optimal locations of distribution system, the load flow program is then performed again to know the impact of proposed solution method on the real power losses reduction and voltage profile improvement (Yesim A. Baysal *et al,*2015).

5. Algorithm adopted for load flow solution

Load flow study is a technique that provides basic calculation procedure in order to determine the characteristics of power system under steady state condition. In this paper load flow study for IEEE 14-bus system is carried by using PWS software as shown in fig.3. Conventional techniques for solving the load flow problem are iterative, using the Newton-Raphson method.

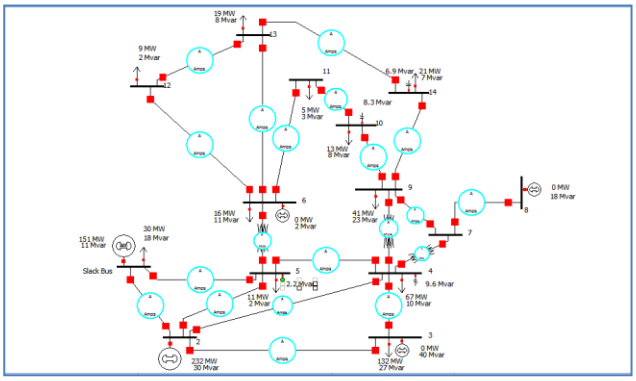

Fig.3. Single line diagram of Test case system

6. Implementation of fuzzy algorithm for capacitor placement

For determining the suitability of capacitor placement at a particular candidate node, a set of multiple-antecedent fuzzy rules have been established. The inputs to the rules are the bus voltages and power loss indices, and the output consequent is the suitability of capacitor placement index. As given in table II, the consequents of the rules are in the shaded part of the matrix (Yesim A. Baysal *et al,*2015). The fuzzy variables, power loss reduction, voltage, and capacitor placement suitability are described by the fuzzy terms as shown in Table-I. These fuzzy variables described by linguistic terms are described by the fuzzy terms high, high-medium/normal, medium/normal, low-medium/ normal or low (Yesim A. Baysal *et al,*2015). These fuzzy variables described by linguistic terms are represented by membership functions. The membership functions are graphically shown in Fig. 4, 5 & 6. The membership functions for the PLI and CSI indices are created to provide a ranking. Therefore, partitions of the membership functions for the power and suitability indices are equally spaced apart.

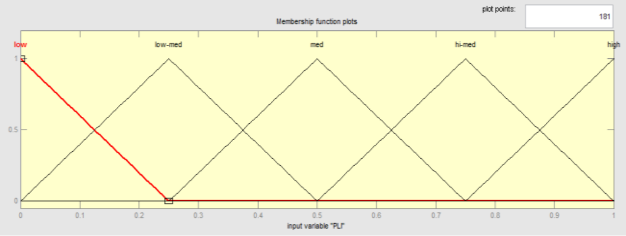

Fig.4. Power Loss Index membership function

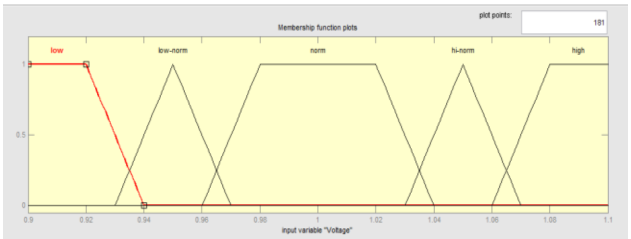

Fig.5. Voltage Magnitude membership function

Table 1 Fuzzy decision matrix

And		**Voltage**				
		Low	**Low-normal**	**Normal**	**High-normal**	**High**
Power loss index (pli)	**Low**	Low-med.	Low-med.	Low	Low	Low
	Low-med.	Med.	Low-med.	Low-med.	Low	Low
	Med.	High-med.	Med.	Low-med.	Low	Low
	High-med.	High-med.	High-med.	Med.	Low-med.	Low
	High	High	High-med.	Med.	Low-med.	Low-med.

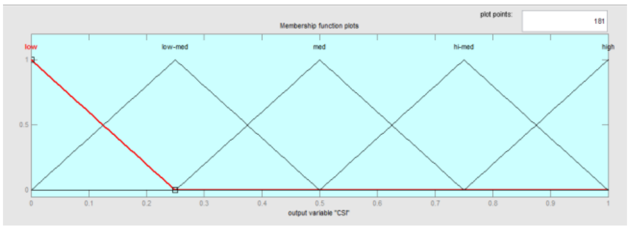

Fig.6. Capacitor suitability Index

Buss having low voltage and high power loss is more appropriate to be selected as the candidate node for allocation of capacitor. Fuzzy decision matrix is formed as in Table 1.

When membership functions for power loss index and bus voltages are examined, it is observed that there are four active rules. Minimum of membership values of input variables is chosen for each active rule using (5) and then capacitor placement suitability index (CPSI) is determined by the center of defuzzification area method expressed in (6).

$$\mu_s = min[\mu_p, \mu_v] \tag{5}$$

Where μ_p, μ_v and μ_s are the membership values of the power loss index, bus voltage and capacitor placement suitability, respectively.

$$CPSI = \frac{\int \mu_S(z).Zdz}{\int \mu_S(z)dz} \tag{6}$$

Where, z is the precise value corresponding maximum membership degree of each membership function. The capacitor placement suitability index (CPSI) is determined for every buses and the bus with the maximum index is selected as the optimal location for installation of capacitor.

7. Capacitor Sizing

Fuzzy optimization techniques are used to find the size of shunt capacitors optimizing the objective function and at the same time to keep the bus voltages in the acceptable voltage ranges. The objective function used in this work is the saving function defined in (1) and aims to maximize net annual saving by minimizing power loss. The size of the capacitor for a particular node is calculated using (7)

$$C= \frac{P*10^6}{2\pi*f*V^2} * \sqrt{\frac{1}{pf^2} - 1} \text{......}\mu F \tag{7}$$

8. Framework of approach

Steps of algorithm used in the study are described as follows.

Step 1: Read the system load and line data.

Step 2: Perform the load flow program to calculate bus voltages, power loss reduction indices and total power loss.

Step 3: Identify membership degree of the capacitor placement suitability using membership degrees of PLI and bus voltages.

Step 4: Calculate capacitor placement suitability index for all the buses.

Step 5: Spot the bus with the maximum index as the best location for installation of capacitor.

Step 6: Select a capacitor from the list available commercially and update reactive power value in best bus as seen in (8).

$$Q_{new\_load} = Q_{load} - Q_c \tag{8}$$

Step 7: Run the load flow with updated Q and calculate new total power loss and bus voltages.

Step 8: Calculate the power loss reduction using the new total power loss and the total power loss calculated in Step 2 as seen in (9).

$$P_{loss\_reduction} = P_{loss} - P_{new\_loss} \tag{9}$$

Step 9: Calculate the saving function using Eqn. (1).

Step 10: Identify membership value of capacitor selected in Step 6 using fuzzy optimization techniques.

Step 11: Check if the membership value of capacitor is greater than the previous value. If yes, identify capacitor selected in Step 6 as optimal capacitor. Otherwise, go to next step.

Step 12: Check if all of capacitors in the available list are selected. If not, go back to Step 6. Otherwise, go to next step.

Step 13: Check if the saving calculated in Step 9 is greater than zero. If yes, install optimal capacitor identified in Step 11 to the best bus and go back to Step 2. Otherwise, stop the algorithm.

9. Simulation results

IEEE 14 bus radial power system shown in Fig. 2 is taken as the test system. Nominal voltage of the test system is 138 kV. The load data and the line data for the system and commercially available capacitor sizes and their costs are taken. K_p is selected as 60 $/kW.

The minimum voltage and losses of IEEE 14 bus distribution system before and after compensation are given in the Table 2 from which we can infer that there is a considerable improvement in voltage profile and reduction in loss is observed after the compensation of the system without violating the bus voltages thereby satisfies the voltage constraint. The following Fig.7 is described the compare of voltage profile in test system before and after compensation.

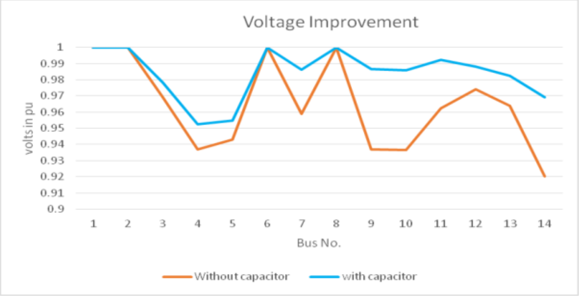

Fig.7. Voltage profile with and without compensating device

Table 2 Bus voltage profile with and without capacitor

Bus no	Without Capacitor	With capacitor
	Voltage in PU	Voltage in PU
1	1	1
2	1	1
3	0.96931	0.97468
4	0.93697	0.94626
5	0.94319	0.95188
6	1	1
7	0.95902	0.97396
8	1	1
9	0.9369	0.96551
10	0.93645	0.96673
11	0.96229	0.97826
12	0.97416	0.97755
13	0.9638	0.97152
14	0.92025	0.95182

Table 3 Comparison of results before and after placement of capacitor

Power Loss before compensation (in MW)	21.71
Power Loss after compensation (in MW)	20.84
Net Loss reduction (in MW)	0.87

From Table 3, It is observed that there is a considerable reduction in loss occurring in the system after placement of compensating device at candidate nodes found using fuzzy expert system.

Table 4 Capacitor cost calculation

Total capacitors installed in kVAr	33356.32kVAr
Cost of Capacitor	$1.2/kVAR
Cost of Capacitor installation (in $)	40027.584
Cost of Capacitor installation (in Rupees)	2601792.96

From Table-IV, it is observed that the entire cost of installation of capacitor comes out to be Rs.2601792.96 in order to achieve the objective.

The calculation of Annual Savings is shown below

$S = K_P\Delta P + K_E\Delta E - K_C C$………$

K_p = $60/kW

K_E = $0.05/kWh

K_c = $1.2/kVAr

S= (60*870) + (0.05*870*24)-(1.2*33356.32)

S= $13216.416 (Rs 792984.96)

From the above calculation it is observed that the annual savings of entire system comes out to be around Rupees 792984.96 and with this the payback period comes out around 4 years including all miscellaneous costs.

Conclusions

In this study, the application of fuzzy technique is used to determine optimal location of shunt capacitors is carried out. Effectiveness of the proposed method is examined on standard IEEE 14 bus radial distribution system. The obtained results demonstrated that the total power loss and the annual cost of the system are reduced and the enhanced voltage profile is achieved.

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