Optimal Capacitor Placement to reduce losses in Distribution System

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Abstract: - Distribution system provides a final link between the high voltage transmission system and the consumers.To improve the overall efficiency of power system, the performance of distribution system must be improved. An important method of controlling bus voltage is by shunt capacitor banks at the buses at both transmission and distribution levels along lines or substation and loads. The problem of capacitor allocation in electric distribution systems involves maximizing "energy and peak power (demand) loss reductions" by means of capacitor installations. As a result power factor of distribution system improves. A 10 bus radial distribution system is taken as model. The load flow program is executed using Fuzzy Logic toolbox of MATLAB. Fuzzy logic based technique is used for determination of suitable location of capacitor placement. Shunt capacitors to be placed at the nodes of the system will be represented as reactive power injections. Fuzzy techniques have advantages of simplicity, less computations & fast results.

Key-Words: - Power System, shunt capacitor banks, bus voltage control, Capacitor Placement.

1 Introduction

An important method of controlling bus voltage is by shunt capacitor banks at the buses at both transmission and distribution levels along lines or at substations and loads. Essentially capacitors are a means of supplying vars at the point of installation. Capacitor banks may be permanently connected, but as regulator of voltage they may be switched on and off the system as changes in load demand. Switching may be manually or automatically controlled either by time clocks or in response to voltage or reactive-power requirements. When they are in parallel with a load having a lagging power factor, the capacitors are the source of some or perhaps all of the reactive power of the load. Thus, capacitors reduce the line current necessary to supply the load and reduce the voltage drop in the line as the power factor is improved. Since capacitors lower the reactive requirement from generators, more real-power output is available [1].

The power loss in a distribution system is significantly high because of lower voltage and hence high current, compared to that in a high voltage transmission system [2]. The pressure of improving the overall efficiency of power delivery has forced the power utilities to reduce the loss, especially at the distribution level. In this paper a radial distribution system is taken because of its simplicity. The same technique can be applied to other types of feeders. Reconfiguring the network can reduce the power loss in a distribution system. The reconfiguration process changes the path of power flow from the source to the loads. The loss can also be reduced by adding shunt capacitors to supply a part of the reactive power demands [2]. Shunt capacitors not only reduce the loss but also improve the voltage profile, power factor and stability of the system. The active power demands at all nodes and losses must be supplied by the source at the root node, as distribution system is mainly radial. However, addition of shunt capacitors can generate the reactive power and therefore it is not necessary to Supply all reactive power demands and losses by the source. Thus, there is a possibility to minimize the loss associated with the reactive power flow through the branches.

Distribution system accounts for a major portion of power system losses. The power loss in a distribution system is significantly high because of lower voltage and hence high current, compared to that in a high voltage transmission system [2]. The pressure of improving the overall efficiency of power delivery has forced the power utilities to reduce the loss, especially at the distribution level. In this paper a radial distribution system is taken because of its simplicity. The same technique can be applied to other types of feeders.

Capacitors are used widely to reduce the distribution system loss [2]. In addition, shunt capacitors could also accommodate voltage regulation and VAR supply. For capacitor placement, general considerations are [3]:

(1) The number and location;
(2) Type (fixed or switched);
(3) The size;

When capacitors are placed power loss is reduced & also energy loss is reduced. Both these factors contribute in increasing the profit. Cost of capacitors decreases this profit. So profit is weighted against the cost of capacitor installation [1]. Whole saving can be given as follows [4].

$$S = K_P \Delta P + K_E \Delta E - K_C C \tag{1}$$

where,

K_P: Per unit cost of peak power loss reduction ($/KW)
K_E: Per unit cost of energy loss reduction ($/KWh)
K_C: Per unit cost of capacitor ($/KVar)
Δp: Peak power loss reduction (KW)
ΔE: Energy loss reduction (KWh)
C: Capacitor size (KVar
S: Saving in money per year ($/year)

Voltage constraint must be satisfied. Voltage (pu) should be between min (0.9) to max (1.1).i.e.

$$V_{\min} \le V \le V_{\max} \tag{2}$$

In this paper shunt (fixed) capacitors are used. 10 bus radial distribution system is taken as the model. It has only main feeder & no branches. So it was a simple model. It's line data & bus data is evaluated. To determine the location & size of capacitors to be installed, a load flow program was executed on MATLAB. This gave the location of capacitor most suitable for capacitor placement. Then by optimizing the profit 'S' due to capacitor placement actual capacitor size is determined i.e. by setting $\partial S / \partial C$=0, and then solving for C, the capacitor size. Shunt capacitors to be placed at the nodes of the system have been represented as reactive power injections [4]. Fuzzy techniques are applied in distribution system for determination of optimal values of capacitor.

A fuzzy inference model is presented in this paper for optimal capacitor placement in distribution system. The paper is organized as follows: Section 2 briefly discusses fuzzy modeling. Section 3 presents the fuzzy inference model for determination of suitable location of capacitor placement and its size is done. Section 4 demonstrates the simulation and discusses the results obtained. Section 5 draws the conclusion.

2 Fuzzy Modeling

Fuzzy models in a broad sense are of two types. The first category of the model proposed by Mamdani is based on the collection of if-then rules with both fuzzy-antecedent and consequent predicates. The advantage of this model is that the rule base is generally provided by an expert, and hence, to a certain degree, it is transparent to interpretation and analysis. Because of its simplicity, the Mamdani model is the most widely used technique for solving many real world problems. The second category of the fuzzy model is based on Takagi-Sugeno-Kang (TSK) method of reasoning. These types of models are formed by if-then rules that have a fuzzy antecedent part and functional consequent. It is generally implemented in two forms, depending upon the type of consequent. If the consequent is a linear function, then it is called a first order TSK model, and if consequent is simply a constant, then it is termed as a zero order TSK model. The main advantage of this approach is its computational efficiency [5]. The fuzzy models are also called fuzzy rule based systems, and fuzzy controllers. A fuzzy rule-based system is composed of four parts: fuzzifier, knowledge base, inference engine, and defuzzifier. A typical fuzzy rule based system is depicted in Fig.1.

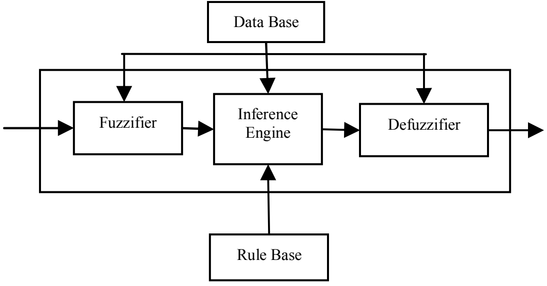

Fig.1 Main elements of a fuzzy rule-based system

The fuzzifier converts real numbers of inputs into fuzzy sets. Fuzzy sets are functions that map a value that might be a member of the set to a number between zero and one indicating its actual degree of membership. A degree of zero means that the value is not in the set and a degree of one means that the value is completely representative of the set. This produces a curve across the members of the set which is known as the Fuzzy membership function. Therefore fuzzy membership functions associate linguistic labels with a particular area of inputs or outputs. Different shapes of the membership functions can be proposed such as triangular, trapezoidal, or Gaussian. The knowledge base includes a fuzzy rule-base and a database. Membership functions of the linguistic terms are contained in the database. The rule base consists of if-then rules, which represents the relationship between input and output variables.

3 Fuzzy Logic Based capacitor placement in distribution system

A 10 bus radial distribution feeder with 23 kV rated voltage system is taken as the main system. 1st bus is source bus and other 9 buses are load bus.

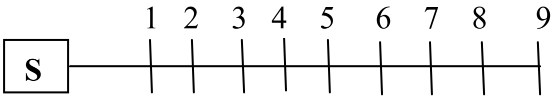

Fig.2 10 bus radial distribution feeder

It's line and bus data are given as follows [6].

line_status = 1 for sectionalizing branch
= 2 for Tie line branch
bus_status = 1 for load bus
= 0 for source bus

TABLE 1
Test data (one feeder radial line network – 10 Bus)

S. No.	From Bus	To Bus	Z = R+jX	Line Status
[1	1	2	0.1233+0.4127i	1;
2	2	3	0.2467+0.6051i	1;
3	3	4	0.7469+1.2050i	1;
4	4	5	0.6984+0.6084i	1;
5	5	6	1.9837+1.7276i	1;
6	6	7	0.9057+0.7886i	1;
7	7	8	2.0552+1.1640i	1;
8	8	9	4.7953+2.7160i	1;
9	9	10	5.3434+3.0264i	1];

TABLE 2
Bus data

Bus No.	S. No.	S = P+jQ	V0	BusStatus
[0	1	(0+0j)	23000	0;
1	2	(1840+(460j))*1000	23000	1;
2	3	(980+340j)*1000	23000	1;
3	4	(1790+(446j))*1000	23000	1;
4	5	(1598+(1840j))*1000	23000	1;
5	6	(1610+(600j))*1000	23000	1;
6	7	(780+(110j))*1000	23000	1;
7	8	(1150+60j)*1000	23000	1;
8	9	(980+130j)*1000	23000	1;
9	10	(1640+(200j))*1000	23000	1];

Reactive currents in an electrical utility distribution system produce losses and result in increased ratings for distribution components [1] Shunt capacitors can be installed in a distribution system to reduce energy and peak demand losses. They release the KVar capacities of distribution apparatus, and also improve the system voltage profile [6]. Thus, the problem of optimal capacitor placement consists of determining the locations, sizes, and number of capacitors to install in a distribution system, such that the maximum benefits are achieved while operational constraints at different loading levels are satisfied. All the process is done according to the flow chart given in Figure 3 [3]. For the capacitor allocation problem, rules are defined to determine the suitability of a node for capacitor installation. Such rules are expressed in the following form:

IF premise (antecedent), THEN conclusion (consequent)

For determining the suitability of capacitor placement at a particular node, a set of multiple-antecedent fuzzy rules have been established. The inputs to the rules are the voltage and power loss indices, and the output consequent is the suitability of capacitor placement. The rules are summarized in the fuzzy decision matrix in Table 3.

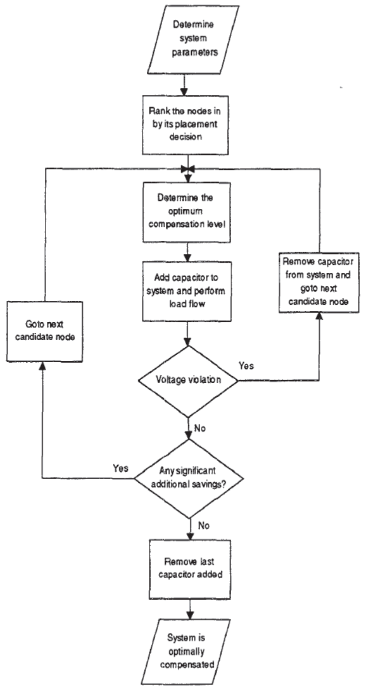

Fig.3 Flow chart of proposed optimal capacitor placement technique

The consequents of the rules are in the shaded part of the matrix. The fuzzy variables, power loss reduction, voltage, and capacitor placement suitability are described by the fuzzy terms *high, high-medium/normal, medium/normal, low-medium/normal* or *low*. These fuzzy variables described by linguistic terms are described by the fuzzy terms *high, high-medium/normal, medium/normal, low-medium/normal* or *low* [2]. These fuzzy variables described by linguistic terms are represented by membership functions. The membership functions are graphically shown in Figs. 3, 4 and 5.

The membership functions for describing the voltage have been created based on Ontario Hydro Standards of acceptable operating voltage ranges for distribution systems [6]. The membership functions for the PLRI and CPSI indices are created to provide a ranking. Therefore, partitions of the membership functions for the power and suitability indices are equally spaced apart.

TABLE 3
Decision matrix for determining optimal capacitor location

AND		Voltage Sensitivity Index(VI)					
		V-Low	Low	Lo-Normal	Normal	Hi-Normal	High
PL RI	Low	Med	Lo-Med	Lo-Med	Low	Low	Low
	Lo-Med	Hi-Med	Med	Lo-Med	Lo-Med	Low	Low
	Med	High	Hi-Med	Med	Lo-Med	Low	Low
	Hi-Med	High	Hi-Med	Hi-Med	Med	Lo-Med	Low
	High	High	High	Hi-Med	Med	Lo-Med	Lo-Med

PLRI: Power Loss Reduction Index

Input 1-Power loss reduction index (PLRI)

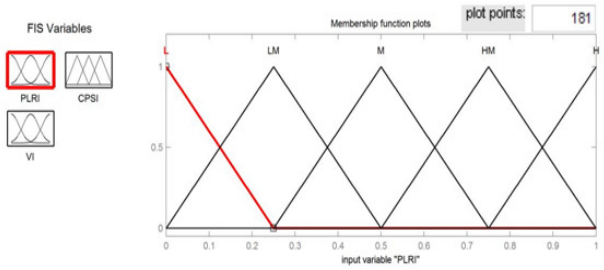

Fig.3 Input 1(PLRI) membership function

Input 2- Voltage sensitivity index (VI)

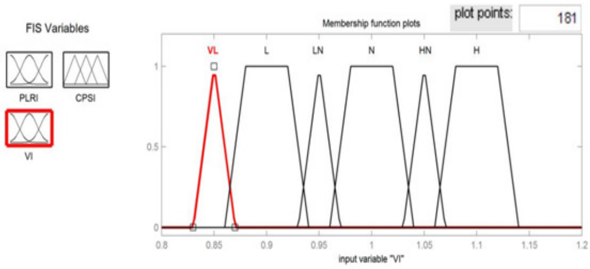

Fig.4 Input 2 (VI) membership function

Output-Capacitor placement suitability index (CPSI)

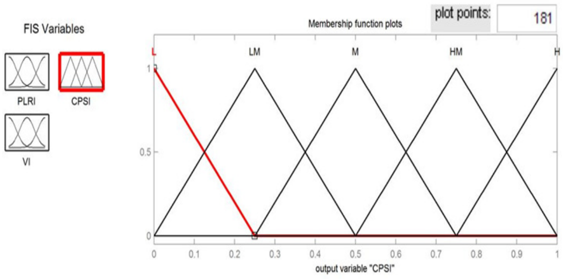

Fig.5 Output membership (CPSI) function

Rule base

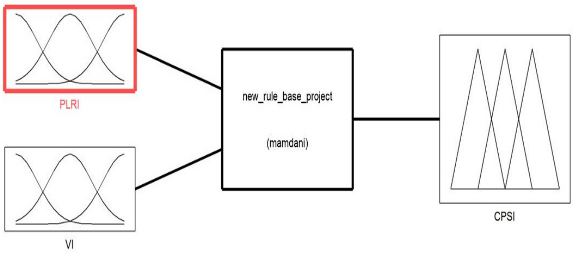

Fig.6 Rule base

Algorithm adopted for load flow solution

The algorithm for capacitor location finding & sizing is as follows:

1. Perform load flow program to calculate bus voltages and segment losses.
2. Find the membership functions of voltage drops, power loss and suitability of capacitor node, and decision for the fuzzy sets of voltage drops, power loss and capacitor nodes.
3. Identify the node having highest suitability ranking.
4. Install a capacitor at optimal node (s). Select capacitor that has the lowest cost and size.
5. Check whether voltage constraint is satisfied. If yes, go to next step, otherwise, go to step- 9.
6. Compute the benefits due to reduction in peak power loss, energy loss and cost of capacitor banks and net savings.
7. Check whether net savings is greater than zero. If yes, go to next step, otherwise, go to step-9.
8. Increment size of capacitor bank and go to step- 2.
9. Reject the installation.

Compensation of each bus' reactive power demand is done by placing capacitor. Calculation of power loss reduction & voltage were done thereafter .Highest power loss reduction was assigned '1' & lowest loss reduction was assigned '0'. All other power loss reductions were placed between 0 &1.Voltage is also given in pu values [7].

Example

First bus is source bus. All the other 9 load buses were fully compensated by placing capacitors. Then power loss reduction in the entire system is calculated by load flow program using MATLAB. Both the power loss reduction index (PLRI) & voltage sensitivity index (VI) is scaled in pu values. Based on these two values capacitor placement suitability index (CPSI) for each bus is determined by using fuzzy toolbox in MATLAB. As shown in Table II. The bus which is in urgent need of balancing will give maximum CPSI. Buses which are already balanced will give lesser values. Bus which gives highest values of CPSI is first considered for capacitor placement. Then value of capacitor to be place is determined.

TABLE 4

Bus location finding for capacitor placement

Bus	PLRI(Input 1)	VI(Input 2)	CPSI(Output)
1	0	0.993	0.08
2	0.031	0.983	0.14
3	0.176	0.960	0.25
4	1	0.953	0.75
5	0.49	0.918	0.73
6	0.084	0.903	0.34
7	0.039	0.884	0.30
8	0.144	0.855	0.64
9	0.246	0.837	0.74

Bus 4 has highest CPSI, so it's selected for capacitor placement. Now value of capacitor is to be found. So equation (1) was used for saving calculation.

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

Where

$K_P = \$120/\text{KW}$

$K_E = \$0.3/\text{KWh}$

$K_C = \$5/\text{KVar}$

Load factor = 0.56 (Main feeder) [8].

From load flow program on MATLAB relevant data is obtained, and a graph between C & S for bus 4 is plotted. S is max for C=3400KVar.So capacitor of this value is installed on bus 4.

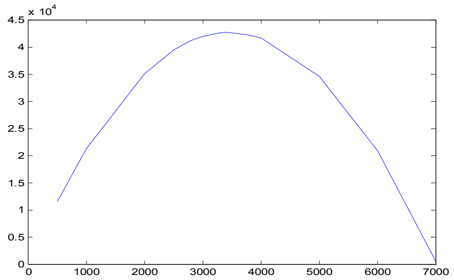

Fig.6 Curve of C Vs S for bus 4.

4 Results

Tables 5, 6, and 7 show results after placement of capacitors.

Savings-As power and energy loss is reduced and power factor improves, so there is a net benefit in installing the capacitors.

TABLE 5

Capacitor location, Capacitor value & saving

S. No.	Capacitor location (Bus No)	Capacitor value (kVar)	Saving($)
1	4	3400	42650
2	5	400	1038
3	9	400	7036
Total saving			50,724/-

Voltage stabilisation-There is a considerable improvement in voltage profile after the compensation of system. It satisfies the voltage constraint.

TABLE 6

Voltage improvement

	Before compensation	After compensation
Minimum voltage(pu)	0.85	0.91
Maximum voltage(pu)	0.990	0.996

Power and Energy loss reduction

As a result of capacitor placement reactive power is compensated as a result power factor of the system improves. So both energy loss & power loss reduces. Data is obtained from load flow programme on MATLAB.

TABLE 7

Power & energy loss reduction

	Before compensation	After compensation
Power loss (KW)	861.4	751.9
Energy loss (KWh)	236866	214594.9

5 Conclusions

An approach incorporating the use of fuzzy sets theory has been presented in this project to determine the optimal number, locations and ratings of capacitors to place in a distribution system. In choosing the ideal locations for capacitor placement, a compromise of the reactive losses and the voltage sensitivity is determined. Application of this method to a sample test system has shown its effectiveness in peak power and energy loss reductions, and improvement in voltage regulation. The same procedure with some additional considerations can be successfully applied to complex systems having sub feeders or system with more buses. In addition, this algorithm can easily he adapted for capacitor allocation in distribution system planning, expansion or operation.

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