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Application of Fuzzy Logic – Particle Swarm Optimization for Reactive – Power Compensation of Radial Distribution Feeders

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Electric distribution systems are becoming large and complex leading to higher system losses and poor voltage regulation. This has stressed the need for an efficient and effective distribution network The objective of this work is to determine optimal location and size of the capacitor to be placed in radial distribution feeders to improve the voltage profile and to reduce the energy loss. This problem of capacitor placement is solved using fuzzy expert system and sizing is solved using particle swarm optimization method.

Firstly, an efficient load flow solution for the radial feeder is obtained by forward sweeping algorithm. Voltage and real power loss index of distribution system nodes are modeled by fuzzy membership function. Then, a fuzzy inference system containing a set of heuristic rules is designed to determine candidate nodes suitable for capacitor placement in the distribution system. Capacitors are placed on the nodes with highest sensitivity index. The sizing is found by using Particle Swarm Optimization (PSO). The proposed method is tested on IEEE –11kV, 12 bus system (without lateral) and an existing 15 bus system (with lateral) in India.

Keywords: *Radial Distribution Feeders, Fuzzy Expert System, Capacitor Placement, Particle Swarm Optimization*

1.0 INTRODUCTION

The installation of shunt capacitors on radial distribution feeders is essential for power flow control, improving system stability, power factor correction, voltage profile management, and reduction in active energy losses. Therefore, it is essential to find the optimal location and size of capacitors required to maintain good voltage profile and to reduce feeder losses. The solution techniques for the capacitor allocation problem can be classified into four categories[12]: analytical, numerical programming, heuristic and artificial intelligence based (AI based). AI based methods such as genetic algorithms (GAs), simulated annealing, expert systems, artificial neural networks, fuzzy set theory, and fuzzy logic are the recently used techniques for solving capacitor allocation problem. In this paper the combination of fuzzy – particle swarm optimization method is used to solve the problem for the location of capacitor and its sizing.

In India all the 11kV rural distribution feeders are radial and too long[3][15][16]. The voltages at the far end of many such feeders are very low with very high voltage regulation [2]. Many of these practical rural distribution feeders have

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failed to converge while using Newton Rapshon (NR) and Fast Decoupled Load Flow (FDLF) algorithms [14 -17]. The load flow solution in this paper is obtained by forward sweeping method (FS). Computationally, the proposed method is very efficient [1-3].

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, releases the kVAR capacities of distribution apparatus, and also improves the system voltage profile [6][18]. 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. Reference [11] presents a new algorithm to determine the exact optimal solution for capacitor allocation in radial distribution using fuzzy heuristic strategies by varying some parameter in the membership function to obtain better results. There have been analytical approaches, numerical programming methods, and AI-based techniques devised to solve this capacitor problem [9][12]. Although these previous methods to solve the capacitor allocation problem have various merits, their effectiveness depends entirely on the goodness of the data used. Fuzzy Sets Theory (FST) provides a remedy for any lack of or uncertainty in the data. Furthermore, fuzzy logic has the advantage of including heuristics and representing engineering judgments into the capacitor allocation optimization process [4][5].Many of the previous strategies for capacitor allocation in the literature are also limited for application to planning, expansion, or operation of distribution systems. Very few of these capacitor allocation techniques have the flexibility of being applicable to more than one of the above activities. Hence, this paper presents a Fuzzy Expert System (FES) approach to determine suitable locations for capacitor placement that also has the versatility of being applied to the planning, expansion and operation of distribution systems.

2.0 FRAMEWORK OF THE APPROACH

The entire framework of this approach to solve the optimal capacitor allocation problem includes the use of numerical procedures, which are coupled to the FES [4]. First, a load flow program calculates the power loss reduction by compensating the total reactive load current at every node of the distribution system

The loss reductions are then linearly normalized into a [0,1] range with the largest loss reduction having a value of 1 and the smallest one having a value of 0.

These power loss reduction indices along with the per-unit node voltages are the inputs into the FES, which determines the node most suitable for capacitor installation by fuzzy inferencing. Finally, a numerical procedure is used to determine the optimal size of capacitor to be placed at the chosen node for the most economic savings. The savings function, S, maximized by this capacitor sizing algorithm is given by [4]:

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

where,

ΔL_p, ΔL_e are the loss reductions in peak demand and energy due to capacitor installation. C is the size of capacitor in kVAR. K_p, K_e, K_c, are the costs of peak demand, energy and capacitors per kVAR respectively. Alternate form of the objective function, which minimizes the cost due to energy loss is described in 4.0.

The above procedure is repeated until no additional savings from the installation of capacitors are achieved. The capacitor sizing procedure also takes into account the discrete nature of the capacitor sizes and the piecewise cost function for capacitors. Fig. 1 illustrates the flow of data through the individual components of this system.

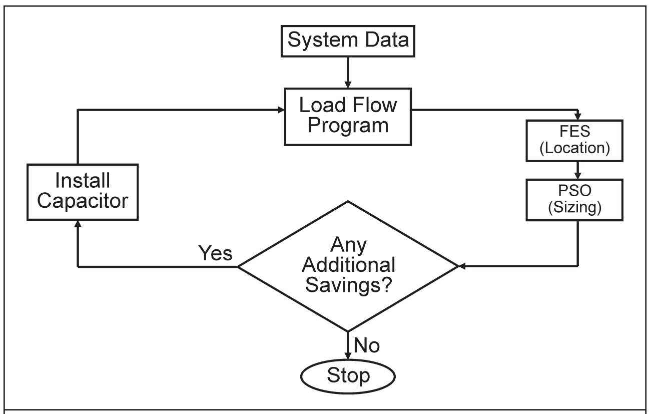

FIG. 1 FRAMEWORK OF THE APPROACH

3.0 DISTRIBUTION SYSTEM POWER FLOW

Power flows in a distribution system obey physical laws (Kirchoff's law and Ohm's law), which become part of the constraints in the capacitor placement problem. In the proposed solution algorithm for the capacitor placement problem, the distribution system power flow solution is to be used as a subroutine in every iteration. Therefore it is essential to have a computationally efficient and numerically robust method for solving the distribution system power flow [1].

In this section, the new power flow equation for radial distribution systems is presented [1][2]. The general case for any radial distribution system is considered in this approach. To simplify the presentation, the system is assumed to be balanced 3-phase system.

4.0 RADIAL MAIN FEEDER

Consider a distribution system consisting of a radial main feeder only [3]. The one line diagram of such a feeder comprising a branch / node is shown in Fig. 2.

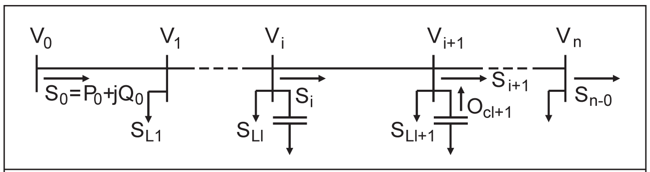

FIG. 2. ONE LINE DIAGRAM OF A MAIN DISTRIBUTION FEEDER

In Fig. 2, V_o represents the substation bus voltage magnitude and is assumed to be constant [3]. Lines are represented by a series impedance $z_1 = r_1 + jx_1$ and loads are treated as constant power sinks, $S_L = P_L + jQ_L$. Shunt capacitors to be placed at the nodes of the system, will be represented as reactive power injections.

With this representation, the network becomes a ladder network with nonlinear shunt loads. If the power supplied from the substation, $S_o = P_0 + jQ_0$ is known, then the power and the voltage at the receiving end of the first branch can be calculated as follows:

$$S_1 = S_0 - S_{loss1} - S_{L1} = S_0 - Z_1|S_0|^2 / V_0^2 - S_{L1}$$

$$V_1\angle\theta_1 = V_0 - Z_1I_0 = V_0 - Z_1S_0^*/V_0$$

Repeating the same process yields the following recursive formula for each branch on the feeder[1][3].

$$P_{i+1} = P_i - r_{i+1}\,(P_i^2 + Q_i^2)/V_i^2 - P_{L_{i+1}} \tag{2}$$

$$Q_{i+1} = Q_i - x_{i+1}(P_i^2 + Q_i^2)/V_i^2 - Q_{L_{i+1}} + Q_{c_{i+1}} \tag{3}$$

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

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_{ci} : reactive power injection from capacitor to node i.

Reference [1-2] presents the algorithm adopted for the power flow solution given by the equations (2-4)

5.0 INTRODUCTION TO FUZZY LOGIC

5.1 Fuzzy Expert System

There exist many applications of ES's to power systems. Some of these applications include: system security assessment and restoration, load management, scheduling, planning and forecasting, substation control, and fault detection. In addition, a number of ES's containing heuristic rules and technical literature expertise have been built to optimally allocate capacitors in distribution systems. These conventional knowledge-based systems contain a set of rules, which assign appropriate actions for given system conditions [4][8][13]. They are systems based upon binary logic; whereby, rules can only be fired if the inputs completely match the predefined conditions. Conventional ES's require exact information and fail to represent such real information. Approximate reasoning by the use of a FES improves the above mentioned deficiencies of conventional knowledge-based systems. Successful applications of FES's have been developed for fault location, reconfiguration, and load forecasting. Related to the capacitor allocation problem, the use of approximate reasoning has also been applied to area of VAR and voltage control.

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: It is intutive that 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. Following the idea of the above example, an entire set of fuzzy rules has been created to determine suitable capacitor locations in a distribution system. These fuzzy rules will be discussed in detail in the next sections.

5.2 Fuzzy Expert System (FES) Implementation

The FES contains a set of rules, which are developed from qualitative descriptions. In a FES, rules may be fired with some degree using fuzzy inferencing; whereas, in a conventional ES, a rule is either fired or not fired. 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 has 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 [4].

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. The membership functions are graphically shown in Figs. 3-5.

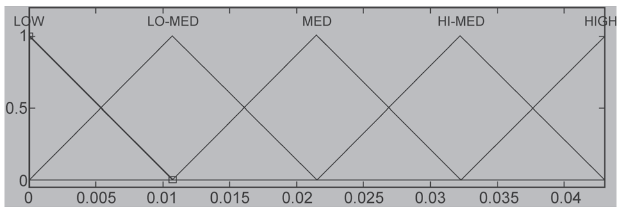

FIG. 3 MEMBERSHIP FUNCTION FOR POWER LOSS INDEX

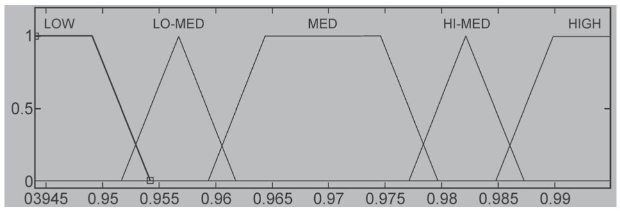

FIG. 4 MEMBERSHIP FUNCTION FOR BUS VOLTAGE

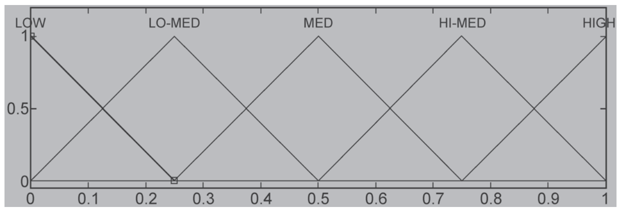

FIG. 5 MEMBERSHIP FUNCTION FOR SENSITIVITY INDEX

TABLE 1

DECISION MATRIX FOR DETERMINING SUITABLE CAPACITOR LOCATION

AND		Voltage				
		Low	**Low Normal**	**Normal**	**High Normal**	**High**
Power Loss Index	Low	Low Medium	Low Medium	Low	Low	Low
	Low Medium	Medium	Low Medium	Low Medium	Low	Low
	Medium	High Medium	Medium	Low Medium	Low	Low
	High Medium	High Medium	High Medium	Medium	Low Medium	Low
	High	High	High Medium	Medium	Low Medium	Low Medium

6.0 IMPLEMENTATION OF PARTICLE SWARM OPTIMIZATION FOR CAPACITOR SIZING

Particle Swarm Optimization (PSO) is a population based optimization technique developed by R.C. Eberhart and J. Kennedy in 1995 [7]. PSO is considered as one of the most powerful methods for solving the non-smooth global optimization problems and has many advantages such as derivative–free technique, easy in its concepts and coding implementation, less sensitive to the nature of the objective function, has limited number of parameters, can generate high-quality solutions within shorter calculation time and stable convergence characteristics. Compared with GA, all the particles tend to converge to the best solution quickly even in the local version in the most cases [10].

The objective function is to place the optimal value of capacitor at best location, which minimizes the cost due to energy loss, and hence maximizes net saving in the distribution system.

A. Steps in algorithm

Step 1: Initialize a population of particles with random positions.

Step 2: Calculate the fitness value for the given objective function for each particle.

Step 3: Set present particles as “Pbest”.

Step 4: Add velocity to initial particles in order to obtain new set of particles.

Step 5: Find fitness value for each new set of particles.

Step 6: Compare each particle’s fitness value to find new “Pbest” between the two set of particles.

Step 7: Find minimum fitness value by comparing two set of particles and corresponding particle is “Gbest”.

Step 8: Update velocity for next iteration using the below formula,

v = w * [a (Pbest - pp) + b (G best- pp)];

pp = pp+v;

Step 9: The iteration is repeated until the convergence is made.

B. Constraints

1. Voltage at the bus
2. Total Line Loss

C. Objective Function for capacitor sizing

Case 1: Without voltage constraint

$$S = k_e \sum_{j=1}^{L} T_j P_j + \sum_{i=1}^{ncap} (k_{cf} + k_c Q_{ci}) \quad (5)$$

Case 2: With voltage constraint

$$S = k_e \sum_{j=1}^{L} T_j P_j + \sum_{i=1}^{ncap} (k_{cf} + k_c Q_{ci}) + \lambda (V_{\min}^{1} - V_{\min}^{s})^2 \quad (6)$$

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.

Qci = Reactive power injection from capacitor to node i

λ = Constant multiplier (1×10^6)

V^1_{min} = Minimum voltage limit at the bus

V^s_{min} = System Minimum Voltage limit (0.97 p.u)

Ploss = Real Power loss

S = Savings in '$'

T_j = Load duration

ncap = Number of capacitor locations

L = Number of load level

K_e = Capacitor energy cost of losses (0.06$/kWh)

K_{cf} = Capacitor installation cost (1000$)

K_c = Capacitor marginal cost (3$/kVAr)

7.0 APPLICATION OF THE METHOD

IEEE Standard 11kV,12 bus system

Radial feeder :11kV,12 bus system

Load :1.0pu

No.of Load level (L) :1

Load duration (T) :6760 hours (42 weeks)

No. of capacitor locations(ncap) :1

The line and load data for the test system is given in Appendix (A). One conventional method of determination of capacitor size is described in Appendix (B).

8.0 RESULTS AND DISCUSSION

Table 2 shows the output from FES for the test system. Tables 3–9 shows the comparison of results obtained before and after placing capacitor at bus number 8. Using PSO method, the capacitor size without voltage constraint is 11.96kVAr and with voltage constraint is 17.48kVAr. Tables 3–9 show the comparative results of voltage profile and power loss for the 11 kV, 12 bus main feeder test system after capacitor placement for case 1 and case 2. From these tables, it is concluded that the voltage profile of the system is improved and power loss is reduced. Table 9 shows the saving in cost due to capacitor placement and sizing based on Particle Swarm Optimization Technique. Table 10 shows the overall comparison of the test feeder system. The analysis is also carried out for an existing 15 bus system [3] with capacitors placed at different buses as given in Table 9. The results shows an improvement over the conventional methods.

TABLE 2

TEST SYSTEM 11kV, 12 BUS MAIN FEEDER (BEFORE CAPACITOR PLACEMENT)

Bus No.	Output from Load Flow Program		Output from FES (Sensitivity Index)
	Real Power Loss (in p.u)	Voltage Mag (in p.u)	
1	0.034170	0.994332	0.154
2	0.027467	0.989030	0.092
3	0.039806	0.980578	0.250
4	0.042206	0.969823	0.500
5	0.011483	0.966536	0.250
6	0.009062	0.963749	0.246
7	0.022774	0.955309	0.541
8	**0.015729**	**0.947277**	**0.618**
9	0.003680	0.944461	0.343
10	0.000710	0.943563	0.272
11	0.000052	0.943354	0.252

TABLE 3

CASE–1 COMPARATIVE RESULTS FOR LINE LOSS (WITHOUT VOLTAGE CONSTRAINT)

Section No.	P_{loss} Before Capacitor Placement	P_{loss} After Capacitor Placement
1-2	0.0342	0.0319
2-3	0.0275	0.0254
3-4	0.0398	0.0365
4-5	0.0422	0.0380
5-6	0.0115	0.0102
6-7	0.0091	0.0080
7-8	0.0228	0.0216
8-9	0.0157	0.0146
9-10	0.0037	0.0033
10-11	0.0007	0.0006
11-12	0.0001	0.0001

TABLE 4

CASE–1 COMPARATIVE RESULTS FOR VOLTAGE (WITHOUT VOLTAGE CONSTRAINT)

Bus No.	Voltage Before Capacitor Placement	Voltage After Capacitor Placement
1	1.0000	1.0000
2	0.9943	0.9945
3	0.9890	0.9895
4	0.9805	0.9814
5	0.9697	0.9712
6	0.9664	0.9682
7	0.9636	0.9656
8	0.9552	0.9578
9	0.9471	0.9506
10	0.9443	0.9482
11	0.9434	0.9476
12	0.9432	0.9476

TABLE 5

CASE–1 COMPARATIVE RESULTS FOR TOTAL LINE LOSS (WITHOUT VOLTAGE CONSTRAINT)

Placement	Total Loss (p.u)
Before Capacitor Placement	0.2072
After Capacitor Placement	0.1882

TABLE 6

CASE–2 COMPARATIVE RESULTS FOR LINE LOSS (WITH VOLTAGE CONSTRAINT)

Section No.	P_{loss} Before Capacitor Placement	P_{loss} After Capacitor Placement
1-2	0.0342	0.0319
2-3	0.0275	0.0254
3-4	0.0398	0.0365
4-5	0.0422	0.0380
5-6	0.0115	0.0102
6-7	0.0091	0.0080
7-8	0.0228	0.0208
8-9	0.0157	0.0139
9-10	0.0037	0.0031
10-11	0.0007	0.0005
11-12	0.0001	0.0000

TABLE 7

CASE–2 COMPARATIVE RESULTS FOR VOLTAGE (WITH VOLTAGE CONSTRAINT)

Bus No.	Voltage Before Capacitor Placement	Voltage After Capacitor Placement
1	1.0000	1.0000
2	0.9943	0.9945
3	0.9890	0.9895
4	0.9805	0.9814
5	0.9697	0.9712
6	0.9664	0.9682
7	0.9636	0.9656
8	0.9552	0.9577
9	0.9471	0.9505
10	0.9443	0.9481
11	0.9434	0.9474
12	0.9432	0.9473

TABLE 8

CASE–1 COMPARATIVE RESULTS FOR TOTAL LINE LOSS (WITH VOLTAGE CONSTRAINT)

Placement	Total Loss (p.u)
Before Capacitor Placement	0.2072
After Capacitor Placement	0.1901

TABLE 9

SAVING COST RESULT

Case	Saving Cost (in $)
1. Without Voltage Constraint	$1049.6
2. With Voltage Constraint Conventional Method (Case 1)	$1212 $1088.4

TABLE 10

OVERALL COMPARISON TABLE

	Output from Load Flow Program		
	Without Capacitor	With Capacitor (without voltage constraint)	With Capacitor (with voltage constraint)
Total real power loss in kW	20.72	18.82	19.01
Total reactive power loss in kVAr	8.04	7.43	7.84
The real power supplied from substation in kW	455.72	453.82	454.01
The reactive power supplied from substation in kVAr	413.04	412.43	412.84
Voltage at last bus in p.u	0.9432	0.9476	0.9473
Saving function in dollar		1049.6	1212

TABLE 11

RESULTS OF 15 BUS SYSTEM[3]

Placement	Total P Loss (p.u)	Average Voltage (p.u)
Before capacitor placement	0.8953	0.9582
After capacitor placement	0.4893	0.9827
% Change	- 45.34	+2.55
Bus No.	4,6,7,11,15 and Total kVAr=1665	
Saving	US$22,878 per annum	

9.0 CONCLUSION

This paper has presented a novel method to determine suitable candidate nodes and size of the capacitor in distribution systems for capacitor installation. The use of a FES determines these nodes by finding a compromise between the possible loss reduction from capacitor installation and voltage levels. In addition, the FES can easily be adapted for capacitor allocation in distribution system planning, expansion or operation. Using Particle Swarm Optimization algorithm, the optimal size of capacitor is obtained for both cases (with and without voltage constraint) and saving in cost realized due to capacitor placement. The time varying characteristics of the load are also considered. Simulation results show the advantages of this approach over the previous capacitor allocation in distribution system planning expansion and operation.

APPENDIX (A)

TABLE A

LINE DATA FOR 11kV, 12–BUS MAIN FEEDER TEST SYSTEM

Branch No.	Sending End	Receiving End	R (Ohms)	X (Ohms)
1	1	2	1.093	0.455
2	2	3	1.184	0.494
3	3	4	2.095	0.873
4	4	5	3.188	1.329
5	5	6	1.093	0.455
6	6	7	1.002	0.417
7	7	8	4.403	1.215
8	8	9	5.642	1.597
9	9	10	2.89	0.818
10	10	11	1.514	0.428
11	11	12	1.238	0.351

TABLE B

LOAD DATA FOR 11kV, 12–BUS MAIN FEEDER TEST SYSTEM

Bus No.	P_l (kW)	Q_l (kVAr)
1	0	0
2	60	60
3	40	30
4	55	55
5	30	30
6	20	15
7	55	55
8	45	45
9	40	40
10	35	30
11	40	30
12	15	15

APPENDIX (B)

In the conventional method, the size of the capacitor is found out using the following relation kVAr (Q) = correction factor * P_{Lj} ; Where P_{Lj} = Load real power at jth bus. The correction factor is calculated based on desired power factor and the value obtained from the correction factor table[18]. Then the saving in cost is determined using the equation (5). The results thus obtained are, Q = 27.94kVAr and Saving function S = $1088, for case 1.

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