International Journal of Electrical and Electronics Research ISSN 2348-6988 (online)
Vol. 7, Issue 3, pp: (16-22), Month: July - September 2019, Available at: www.researchpublish.com

Application of fuzzy logic for capacitor placement suitability in distribution system

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Abstract: **Electrical power is transmitted at high voltages to reduce the transmission losses and increase the transmission efficiency. Studies reveal that transmission and distribution(T&D) losses are around 33% of total power generated which is causing huge revenue loss to the electrical utility companies. In order to make profit the utilities has to reduce the T&D losses to 22%. Reactive currents account for a portion of losses. The losses produced by reactive currents can be reduced by the installation of shunt capacitors in the distribution system. A proper placement of fixed and switched shunt capacitors reduces energy and peak power losses, release additional KVA capacity from distribution apparatus and improve the system voltage profile. In this work optimal capacitor placement in a 34-bus system is achieved by using fuzzy expert system. Capacitor banks are placed on the nodes with highest suitability.**

Keyword: **Distribution losses, Capacitor Placement, Fuzzy system, weak bus, voltage profile.**

I. INTRODUCTION

The distribution system represents the final stage in the transfer of power to the individual customers. The distribution system is fed through distribution substation. Each distribution substation normally serves its own load area, which is a subdivision of the area served by the distribution system. At the distribution substation the sub transmission voltage is reduced for general distribution throughout the area. The substation designs are based on the consideration such as load density, high side voltage, low side voltage, reliability, voltage drop, cost and losses. Primary feeders supply small industrial consumers. Small generating plants located near the load are often connected to the sub transmission or distribution directly. Most of the losses occur in line often termed as line losses (I2R losses). The factors that contribute line losses in primary and secondary distribution system are feeder length, location of distribution transformer and over rated distribution transformers.

Most of the industrial load is inductive in nature. As the load increases current drawn from the supply increases, voltage drop increases, line losses increases, reactive power consumption increases. Shunt reactors, shunt capacitors, series capacitors, synchronous condensers and static VAR compensators are some of the sources of reactive power compensation. Most commonly shunt compensation is preferred compared to other methods because of advantages like less power loss, less voltage drop, increased life of equipment, causes less strain on the excitation system, Increase in the ability of generators to meet the system peak demand due to the released capacity.

To achieve the benefits from the shunt capacitor, it has to be selected in optimal manner. The amount of reactive power compensation is linked with the location and size of the capacitors. It has been observed from literature that most of the papers are specific about optimal capacitor allocation or placement in the distribution system. The solution techniques for the capacitor placement can be categorized into Analytical, Numerical Programming, heuristics and artificial intelligence based. Draw back with analytical methods is the calculated capacitor sizes may not match with the available standard sizes and the calculated locations may not coincide with the physical node locations in the distribution system. The results need to be rounded up or down to the nearest practical value and may result in an over voltage situation or a loss savings less than calculated.

The data preparation, and interface development for numerical techniques may require more time than for analytical methods. One must also determine the convexity of the capacitor placement problem to determine if the results yielded by a numerical programming technique are a local or global extremism. Furthermore, in formulations that include the released kVA benefits and load growth effects, it may be difficult to assign economic values to such quantities. Heuristic methods are intuitive, easy to understand, and simple to implement as compared to analytical and numerical programming methods. However, the results produced by heuristic algorithms are not guaranteed to be optimal.

The recent popularity of Artificial Intelligence has led many researchers to investigate its use for power engineering applications. In particular, Genetic algorithms, Expert systems, Artificial Neural Networks, and Fuzzy Logic have been implemented in the optimal capacitor placement problem [9]. The capacitor allocation problem can be solved by all these methods, all have various merits, and their efficacy relies entirely on the goodness of the data used. Fuzzy Logic provides a remedy for any lack of or uncertainly in the data. The effectiveness of Fuzzy Logic has been demonstrated in many power-engineering applications. Furthermore, fuzzy logic has the advantage of including heuristics and representing engineering judgments into the capacitor allocation optimization process [1-2].

S. F. Mekhamer et.al developed a new algorithm for determining the optimal solution for allocating a capacitor in radial distribution feeder [3]. M.S.Nagraja et.al developed an approach for reactive power control of a radial distribution system using fuzzy logic, studied the economic benefits of relocating the capacitor in the feeder [4]. Various fuzzy decision forms were applied to the fuzzy model to get solution which is close to optimal. S.K.Bhattacharya et.al analyzed the performance of few methods of fuzzy based capacitor placement, discussed about the limitations and suggested improvements. Also developed a new method for solving the capacitor placement problem [5]. S.M.Kannan tested three radial feeders, from the load flow solution, the power loss and voltage profile at each node were obtained. From the heuristic fuzzy inference system, set of rules were framed to obtain the nodes with highest sensitivity index. The results were obtained using MATLAB [6].

Sheeraz kirmani et.al used a novel approach to determine suitable nodes for placing the capacitors in the given system. Also the peak power losses and energy losses were presented [10]. Ahmed Elsheikh et.al addressed particle swam optimization algorithm to determine the optimal location of capacitors, size of the capacitor in a radial distribution system [11]. A.Y.Abdelaziz eta.al proposed a new algorithm for installing capacitors based on power loss index. Also proposed reduced size of the capacitors to reduce the overall cost and this method can be applied for a large system [12].

II. LOAD FLOW ANALYSIS

Load flow analysis for a given power system network is required for determining the node voltages, phase angles and power flow in all the branches. Load flow analysis can be carried out by any of the methods Newton-Raphson, Fast - Decoupled, and Accelerated Gauss - Seidel. They possess different convergent characteristics, and sometimes one is more favourable in terms of achieving the best performance [7-8]. ETAP software is used to perform Load flow analysis for a 34 bus system as shown in fig.1 and Newton Raphson method is selected to get the power flow in all branches. In Power system each bus or node will be associated with four parameters namely voltage, phase angle, Real power and Reactive Power. Depending on the parameters specified the buses in power system are classified into Load bus, Generator bus and Slack bus. At Load bus real power and reactive power will be specified. At generator bus voltage magnitude and real power will be specified. At Slack bus voltage magnitude and phase angle is specified. The other parameters are obtained from load flow solution. Some of the constraints to be satisfied are capacitor limits, bus voltage limits and line flow limits.

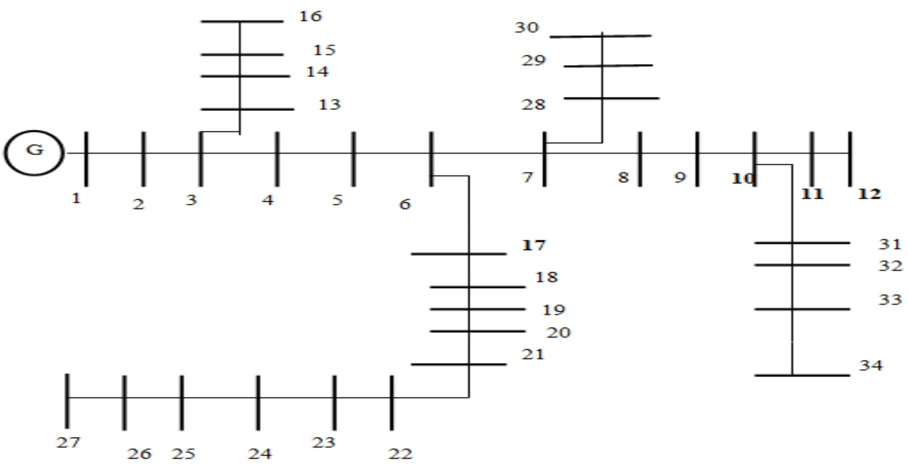

Fig.1 Schematic diagram of a 34-bus distribution network

TABLE I: Data of 34-bus system Distribution network and load flow report

Bus No	Load		Line Impedance		Length (km)	Load Flow Report	
	P (kW)	Q (kVAR)	R (Ω/km)	X (Ω/km)		Bus Voltage (kV)	Reactive Power (kVAR)
1	0.0	0.0	0	0	0	11.000	270
2	230.0	142.5	0.195	0.080	0.60	10.940	2719
3	0.0	0.0	0.195	0.080	0.55	10.889	2569
	230.0	142.5	0.299	0.083	0.55	10.819	2420
5	230.0	142.5	0.524	0.090	0.50	10.719	2274
6	0.0	0.0	0.299	0.083	0.50	10.662	2132
7	0.0	0.0	0.524	0.090	0.60	10.623	739
8	230.0	142.5	0.524	0.090	0.40	10.602	604
9	230.0	142.5	0.524	0.090	0.60	10.577	471
10	0.0	0.0	0.524	0.090	0.40	10.565	339
11	230.0	142.0	0.524	0.090	0.25	10.560	209
12	137.0	84.0	0.524	0.090	0.20	10.559	78
13	72.0	45.0	0.524	0.090	0.30	10.885	140
14	72.0	45.0	0.524	0.090	0.40	10.882	96
15	72.0	45.0	0.524	0.090	0.20	10.881	52
16	13.5	7.5	0.524	0.090	0.10	10.881	8
17	230.0	142.5	0.299	0.083	0.60	10.619	1390
18	230.0	142.5	0.299	0.083	0.55	10.583	1254
19	230.0	142.5	0.378	0.086	0.55	10.497	1103
20	230.0	142.5	0.378	0.086	0.50	10.465	971
21	230.0	142.5	0.378	0.086	0.50	10.437	841
22	230.0	142.5	0.524	0.090	0.50	10.405	711
23	230.0	142.5	0.524	0.090	0.50	10.379	583
24	230.0	142.5	0.524	0.090	0.60	10.354	455
25	230.0	142.5	0.524	0.090	0.40	10.342	328
26	230.0	142.5	0.524	0.090	0.25	10.338	201
27	137.0	85.0	0.524	0.090	0.20	10.336	75
28	75.0	48.0	0.524	0.090	0.30	10.620	134
29	75.0	48.0	0.524	0.090	0.30	10.618	89
30	75.0	48.0	0.524	0.090	0.30	10.617	45
31	57.0	34.5	0.524	0.090	0.30	10.561	129
32	57.0	34.5	0.524	0.090	0.40	10.558	97
33	57.0	34.5	0.524	0.090	0.30	10.556	65
34	57.0	34.5	0.524	0.090	0.20	10.556	32

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TABLE II: Reactive Power Compensation and Power Loss reduction

Bus No	Q-injected (kVAR)	Power flow		Power loss reduction		Bus Voltage (kV)	Bus No	Q-injected (kVAR)	Power flow		Power loss reduction		Bus Voltage (kV)
		kW	kVAR	kW	kVAR				kW	kVAR	kW	kVAR	
1	2700	202.9	71.5	0.00	0.00	11.00	18	1250	169.2	62.1	33.70	9.40	10.616
2	2750	196.1	68.4	6.80	3.10	10.952	19	1100	170.8	58.1	32.10	13.40	10.570
3	2600	190.5	66.4	12.40	5.10	10.910	20	1000	171.2	58.4	31.70	13.10	10.534
	2450	182.5	64.2	20.40	7.30	10.849	21	850	173.3	59.3	29.60	12.20	10.498
5	2300	171.0	62.3	31.90	9.20	10.755	22	750	174.7	60.1	28.20	11.40	10.462
6	2150	165.6	60.8	37.30	10.70	10.730	23	600	178.2	61.6	24.70	9.90	10.476
7	750	181.9	65.7	21.00	5.80	10.643	24	450	182.7	63.6	20.20	7.90	10.414
8	600	184.7	66.6	18.20	4.90	10.618	25	350	186.4	65.0	16.50	6.50	10.373
9	500	186.7	67.2	16.20	4.30	10.593	26	200	192.8	67.6	10.10	3.90	10.355
10	350	190.7	68.3	12.20	3.20	10.577	27	100	197.6	69.5	5.30	2.00	10.345
11	200	195.4	68.6	7.50	2.90	10.568	28	150	197.9	70.2	5.00	1.30	10.624
12	70	200.1	70.8	2.80	0.70	10.652	29	100	199.5	70.6	3.40	0.90	10.621
13	150	201.5	70.9	1.40	0.60	10.887	30	50	201.2	71.1	1.70	0.40	10.618
14	100	201.9	71.1	1.00	0.40	10.883	31	150	197.2	70.0	5.70	1.50	10.567
15	50	202.4	71.3	0.50	0.20	10.882	32	100	199.0	70.5	3.90	1.00	10.562
16	10	202.8	71.5	0.10	0.00	10.881	33	100	199.0	70.5	3.90	1.00	10.561
17	1400	169.2	62.1	33.70	9.40	10.651	34	50	200.9	71.0	2.00	0.50	10.558

III. IMPLEMENTATION OF FUZZY LOGIC TO THE 34-BUS DISTRIBUTION SYSTEM

The fuzzy expert system contains a set of rules, which are developed from qualitative description. For determining of capacitor placement at a particular node, sets 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.

TABLE III: Decision Matrix of fuzzy system

And	Voltage				
	Low	**Low-Normal**	**Normal**	**High Normal**	**High**
Powers loss index	Low	Low-Medium	Low	Low	Low
	Low Medium	Medium	Low Medium	Low	Low
	High Medium	High Medium	Medium	Low Medium	Low
	High	High	High Medium	Low Medium	Low Medium

The fuzzy variables power loss reduction, voltage and capacitor placement suitability are described by the fuzzy term high, high-medium/normal, medium/normal, low-medium/normal or low. The membership functions for power loss reduction, voltage and capacitor placement suitability are represented graphically as shown in fig.2, fig.3 and fig.4 respectively.

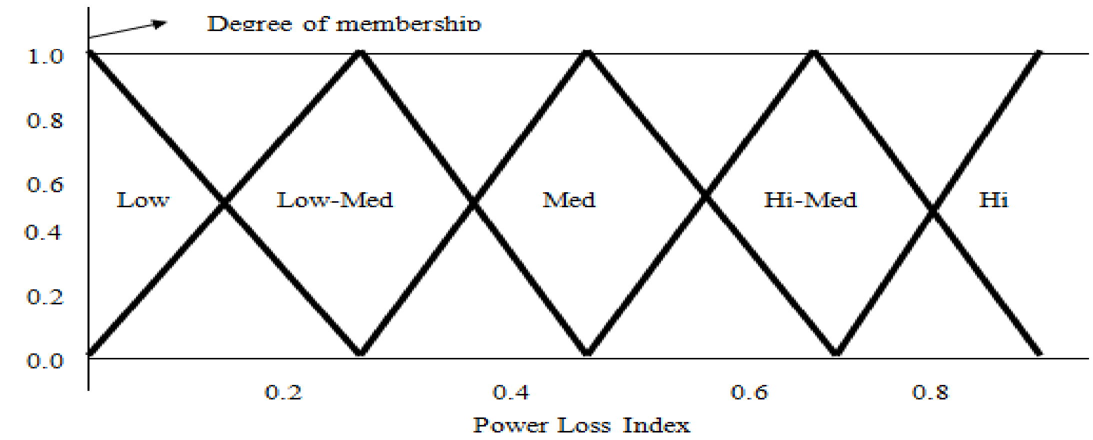

Fig.2 Membership function of Power loss index

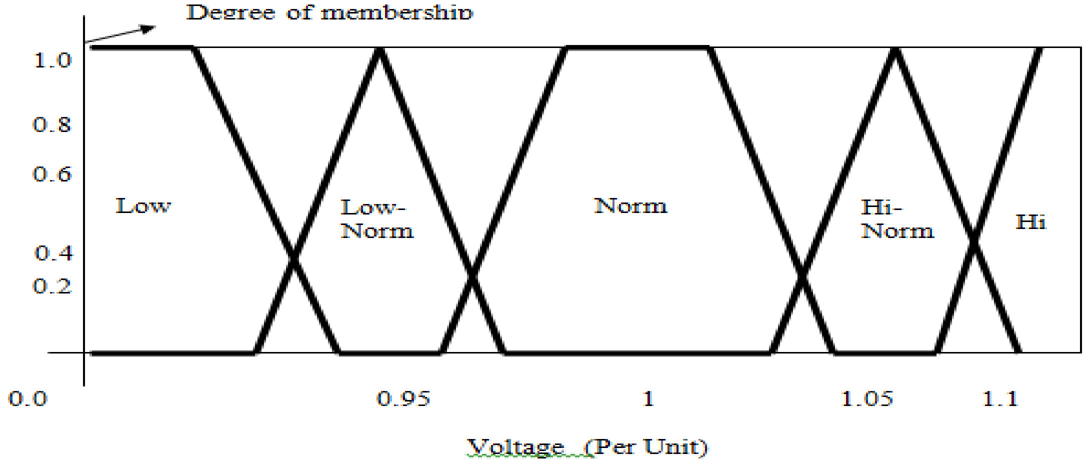

Fig.3 Membership function of Bus Voltage

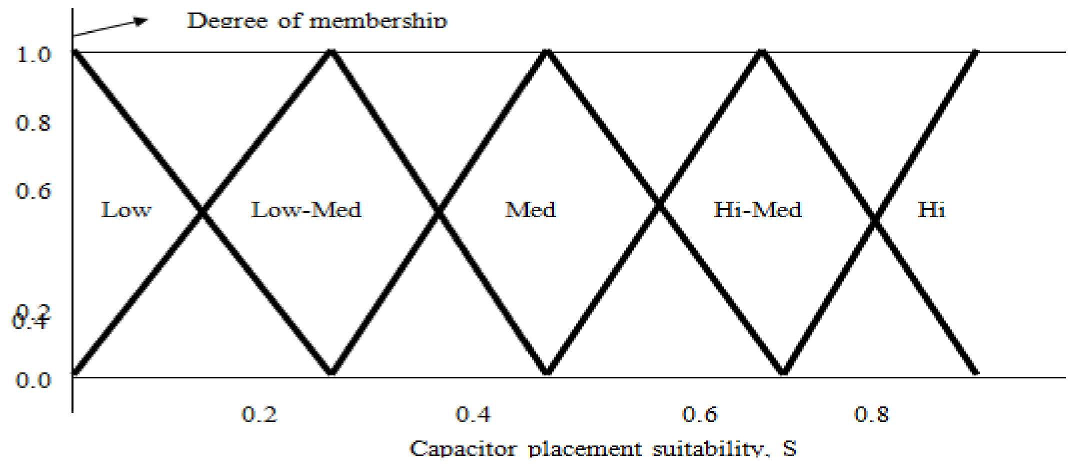

Fig.4 Membership function of Capacitor placement suitability

IV. RESULTS AND DISCUSSIONS

The fuzzy rules and membership functions of power loss index and per unit voltages at each bus are implemented using Fuzzy logic toolbox in Matlab based Simulink. Fuzzy inference system determines the most suitable nodes by finding a compromise between the possible power loss reduction from capacitor installation and voltage levels at each node. Table-4 shows the inputs and outputs of the fuzzy inference system.

TABLE IV: input and output of fuzzy system

Bus No	**Inputs to Fuzzy**		**Output**
	Voltage per Unit	**Power loss index linearly normalized**	**Capacitor placement suitability**
1	1	0	0.080
2	0.9956	0.2313	0.249
3	0.9918	0.3806	0.250
4	0.98627	0.5447	0.306
5	0.9777	0.6865	0.424
6	0.9754	0.7985	0.50
7	0.9675	0.4328	0.250
8	0.96527	0.3657	0.250
9	0.9630	0.3209	0.250
10	0.9615	0.2388	0.244
11	0.9607	0.2164	0.244
12	0.96836	0.0522	0.194
13	0.98972	0.0447	0.150
14	0.98936	0.0298	0.124
15	0.98927	0.01492	0.108
16	0.98918	0.000	0.08
17	0.96827	0.7015	0.420
18	0.9651	0.7015	0.386
19	0.9609	1.00	0.50
20	0.9576	0.9776	0.750
21	0.95436	0.9104	0.750
22	0.95109	0.8507	0.750
23	0.95236	0.7388	0.726
24	0.94672	0.5895	0.590
25	0.9430	0.4851	0.475
26	0.94136	0.2910	0.299
27	0.94045	0.1492	0.250
28	0.9658	0.0970	0.228
29	0.9655	0.0672	0.233
30	0.96527	0.0298	0.187
31	0.96063	0.1119	0.244
32	0.96018	0.0746	0.250
33	0.96009	0.0746	0.250
34.	0.95982	0.0373	0.250

The savings function is given by

$S = K_E \Delta L_E + K_P \Delta L_P - K_C C$

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.

The savings are calculated by assuming

i) 6 peak hours per day at a cost of Rs. 9 per unit

ii) Cost of Energy Rs. 4.5 per unit.

iii) Cost of Capacitor of Rs. 300 per kVAR

Life of a capacitor for 10 years and 10% interest and depreciation costs. The defuzzified suitability index from fuzzy inference system indicated that nodes 20,21,22,23 have highest capacitor placement suitability. The capacitor placement suitability values at each bus are shown in Table-4. Compensating at Bus-19 is the most suitable candidate bus, since it needs a maximum compensation of 1100 KVAR to attain a maximum power loss reduction of 13.4 KVA and for its maximum savings of Rs 5109.789 per day. Instead of compensating at a single bus, compensations at two buses and combinations of the above sensitive nodes were studied. The combination of buses 21 and 22 need a total reactive power compensation of 1600 KVAR to attain a maximum power loss reduction of 56.1 KVA and the greatest economic savings of Rs 6482.441 per day.

V. CONCLUSION

A novel method to determine suitable candidate nodes in distribution systems for capacitor installation is presented. Fuzzy inference system determines the most suitable buses for capacitor placement by finding a compromise between the possible power loss reductions from capacitor installation and voltage levels at each bus. A compromise of results from compensation at a single bus with compensation at two buses shows that the combination achieves better savings. In addition, the Fuzzy expert system can easily be adapted for capacitor allocation in distribution system planning, expansion or operation.

ACKNOWLEDGEMENT

The Author gratefully acknowledge the encouragement of Principal, EEE HOD and Management of BMS Institute of Technology, Bangalore in carrying out this work.

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