Optimization of Shunt Capacitors in Electric Distribution Systems using Fuzzy Logic Technique

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Abstract

The impact of the power factor on the electric distribution networks has been investigated. The Fuzzy Logic Technique and the MATLAB Technique have been applied, to know the weak points and to determine the values of the capacitors, which will be connected in parallel to compensate the reactive power and to improve the voltage profile and the power factor, to reduce the power losses and to obtain the corresponding saving in the economical costs. The best economical costs saving will be determined.
The nine nodes power system is implemented. The on-line adding of the obtained shunt capacitors in different locations has been controlled to maintain the variables of the distribution network within the permissible range.

عنوان البحث : **مثالية مكثفات التوازي في نظم التوزيع الكهربائية باستخدام تقنية المنطق المبهم**

ملخص البحث :

تم دراسة تأثيرمعامل القدرة علي شبكات توزيع الطاقة الكهربائية وتم تطبيق تقنيه المنطق المبهم وتقنية الماتلاب لمعرفة نقاط الضعف علي الشبكه وتحسين معامل القدرة وتحسين الجهد وحساب قيم سعة المكثفات اللازم إضافتها علي التوازي لتعويض القدره المفاعله.

وقد تم دراسة نظام قوي كهربي يحتوي علي تسعة عقد وتم حساب قيم الجهد ومعاملات القدره قبل وبعد التحسين بتوصيل المكثفات التي تم ايجاد قيمتها وكذلك تقليل القدره المفقوده وتحقيق التوفير المناظر في التكلفه الإقتصاديه . كما تم التحكم في إضافة المكثفات مباشرة في مواقع مختلفه وتحديد اقصي قيمة في التوفير وكذلك الإحتفاظ بمتغيرات الشبكه خلال المدي المسموح به.

***Key Words**:* Power factor, Voltage Stability, Fuzzy Logic, Shunt Capacitors, Distribution Systems.

1. Introduction

Capacitors are widely used in distribution system for reactive power compensation to achieve power and energy loss reduction [1-3, 10]. The Artificial Intelligence-based techniques can solve the capacitor allocation problem in distribution system for power factor correction. Fuzzy logic techniques have various merits and are used to solve the capacitor allocation problem [4-7]. However their efficiency relies entirely on the goodness of the data used. Fuzzy logic has the advantage of including heuristics and representing engineering judgments into the capacitor allocation optimization process. The advantages of fuzzy logic technique are verified by the application to test feeders [8, 9]. Therefore, the capacitor placement problem in distribution feeders consists of determining the place (number and location), type, size, and control scheme of capacitors to be installed such that the benefits mention above is weighted against the fixed and running costs of the capacitors and their accessories. When the active power transmission in improved by means of reactive power injection the electric power system can operate too near its limits. [10]

The installation of shunt capacitors on radial distribution systems is essential for many reasons; some of these reasons are power flow control improving system stability, power factor correction, Voltage profile management and losses minimization, therefore, it is important to find the optimal size and location of shunt capacitor required to minimize feeder power losses and the suitable time to switch on and off the capacitor. Effects of low power factor increase of investment costs for generators, transformers, on the transmission lines and distribution lines [7]. In [8] the Fuzzy Theory is used and assigned three membership functions to describe power loss, bus voltage deviation, and harmonic distortion. A decision variable to determine nodes for capacitor placement is then calculated by taking the intersection of the three membership functions for each node in the distribution system. The node with the greatest decision values are selected for capacitor installation. Also, a mathematical optimization procedure is given and the method of calculating the capacitor size to be placed in the selected nodes by the fuzzy procedure is illustrated.

Reference [9] applied FST to the capacitor placement problem and used a fuzzy expert system containing a set of heuristic rules performs the inference to determine the capacitor placement suitability index of each node.

2. Problem formulation and application of Fuzzy logic for power factor correction in radial distribution feeders

In a three phase radial distribution feeder with (n) number of nodes [1], we can write

$$S_j = P_j + j\,Q_j \ , \qquad j = 1, \ldots\ldots, n \qquad (1)$$

$$P_{(j+1)} = P_j - R_{(j+1)}(P_j^2 + Q_j^2)/V_j^2 - P_{L(j+1)} \qquad (2)$$

$$Q_{(j+1)} = Q_j - X_{(j+1)}(P_j^2 + Q_j^2)/V_j^2 - Q_{L(j+1)} \qquad (3)$$

$$Pf_j = \frac{P_j}{\sqrt{P_j^2 + Q_j^2}} \qquad (4)$$

$$\begin{aligned} V_{(j+1)} &= V_j - 2(R_{(j+1)}P_j + X_{(j+1)}Q_j) \\ &+ (R_{(j+1)}{}^2 + X_{(j+1)}{}^2) \times (P_j{}^2 + Q_j{}^2)/V_j{}^2 \end{aligned} \qquad (5)$$

$$P_{loss\,(j+1)} = R_{j+1}(P_j^2 + Q_j^2)/V_j^2 \qquad (6)$$

$$Q_{LOSS(j+1)} = X_{j+1}(p_j^2 + Q_j^2)/V_j^2 \qquad (7)$$

$$P = \sum_{j=0}^{n-1}(P_{loss\,(j+1)}) \qquad (8)$$

$$Q_{\max} = L \times Q_c \qquad (9)$$

Where : L is an integer. Then at each selected location there are L sizes to choose from.

K_{1c} , K_{2c}, …. K_{Lc} be the corresponding capital invested per KVAR assuming that only capacitor banks are used voltage excursions.

R_{j+1}, X_{j+1} are the resistance and the reactance at the bus j+1, respectively, The cost function (Cost) can be selected as, [8],

$$Cost = Kp \times P_{lossnew} + \sum_{j-1}^{k} Kc_j Qc_J \qquad (10)$$

$$\mathrm{Q_{cj}} = P_j(\tan\varnothing_j - \tan\varnothing_{jnew}) \qquad (11)$$

$$\varnothing_{\mathrm{jnew}} = \tan^{-1}\left(\frac{P_j\ \tan\varnothing_j - Q_{cj}}{P_j}\right) \qquad (12)$$

$$Pf_{new} = \cos\varnothing_{jnew} \qquad (13)$$

Where: Kp : is cost per power losses ($ / kW / year) , assume Kp = 200$/KW/Year [8] .

j = 1, 2, …….. k represents the selected buses.

The objective function is to be minimized as $V_{min} \le V_j \le V_{max}$, j = 1, 2,3, …………., n

Pf_{new} : is power factor after compensation

Q_{cj} : KVAR compensation

Kcj :Cost of KVAR ($/KVAR)

Fuzzification is to make a crisp quantity fuzzy. This process recognizes the quantity that carries considerable uncertainty. So the variable is fuzzy and can be presented by membership function. The main difference between crisp sets and fuzzy sets is that the first one deals with binary logic (0, 1) providing two membership functions either "true" or "false", mathematically for a set A

MA (X) = 1 if $A \in X$ - MA (X) = 0 if $A \notin X$

But in fuzzy set the variables are allowed to have a degree of truth in the interval (0, 1). The most popular shapes and membership functions used in fuzzy applications are triangle shapes.

Table (1) The rule base of Fuzzy system operation for two membership function inputs, power losses and power factor

		Power factor				
And		***Low***	***low/medium***	***medium***	***high/medium***	***high***
Power losses	***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

The rule base of Fuzzy system operation for two membership function inputs, power losses and power factor is shown in Table (1).

3. Case study

The IEEE, nine-bus radial distribution feeder of rated voltage 23 KV is show in Fig (1) and the input data is given in Table (2) .

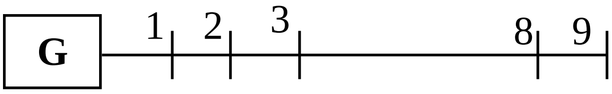

Fig 1 Case study of nine bus system

Table (2) Input data of first case study nine-bus system

Section Feeder No.		**R (Ohm)**	**X (Ohm)**	**P(kW)**	**Q(KVAR)**
0	1	0.1233	0.4127	1840	460
1	2	0.0140	0.6051	980	340
2	3	0.7463	1.2050	1790	446
3	4	0.6984	0.6084	1598	1840
4	5	1.9831	1.7276	1610	600
5	6	0.9053	0.7886	780	110
6	7	2.0552	1.1640	1150	60
7	8	4.7953	2.7160	980	130
8	9	5.3434	3.0264	164	200

4. The Proposed Solution

The fuzzy logic technique operation finds suitability index at each node of distribution system. The maximum value of suitability index represents sensitive node depending on the value of reactive power and power losses in this node. The high value of Q_{old} and power losses have a high suitability index.The program chooses the value of shunt capacitor that must be added in this node This test is carried out when the power factor at each sensitive node is less than 0.94 The proposed algorithm can be summarized as follows:

1. Input system data shown in table (2).
2. Perform the load flow program using equation (1 to 13) calculate bus voltages, power losses and power factor using numerical method .
3. Find the membership functions of power losses and power factor and decision for the fuzzy sets of power losses and power factor decision.
4. Identify the candidate node at the bus with the lowest membership function Ms (bus k).
5. Install a capacitor at bus (k) with size varying in integer steps select Qc that has the lowest cost without violating the constraints from table (6).
6. Add this Qc at bus (k) and perform the load flow again If power factor is corrected and power losses reduced go to steps 3, otherwise end the program.
7. Assuming that (n) busses have been chosen for placing new capacitors, adjust the first capacitor (i = 1) in integer steps while keeping others fixed. Select Qc for the first one that has the lowest cost without violation Repeat for (i =2 ... n).
8. Repeat step 7 if the cost function still decreases.

The size and location of the shunt capacitors is given in Table (3) and the Power factor, power losses and cost with and without compensation of 9-bus system are tabulated in Table (4). The Voltage profile, voltage drop, and VPu with and without compensation of 9-bus system are given in Table (5).

Table (3) Size and location of shunt capacitor

sensitive nodes selected =	4	5	9
Q_c std (KVAR) =	1200	600	150

Table (4) The Power factor, power losses and cost with and without compensation of 9-bus system

Section feeder No.		**PF old**	**PF new**	**P_{loss} old (kW)**	**P_{loss} new (kW)**	**Cost-old ($)**	**Cost-new ($)**
0	1	0.9700	0.9701	34.2400	22.9110	6848	4582.300
1	2	0.9440	0.9443	2.7663	1.7014	553.260	340.280
2	3	0.9700	0.9708	119.0560	68.7400	23811.200	13748.000
3	4	0.6550	0.9288	71.1615	34.8200	14232.300	7168
4	5	0.9370	0.9999	90.1799	79.1827	18035.980	15968.540
5	6	0.9902	0.9902	17.376	16.3598	3475.340	3271.960
6	7	0.9986	0.9987	22.3555	20.6262	4471.100	4125.240
7	8	0.9913	0.9914	14.1010	12.0422	2820.200	2408.440
8	9	0.6340	0.9560	0.6757	0.2717	135.14	129.340

Table (5) The Voltage profile, voltage drop, and VPu with and without compensation of 9-bus system

Section feeder No.		**VP old (V)**	**VD old (V)**	**VPu-old**	**VP-new (V)**	**VD-new (V)**	**VPu-new**
0	1	22773	226.98	0.9900	22814	185.67	0.9919
1	2	22500	269.00	0.9784	22603	210.99	0.9828
2	3	21938	566.12	0.9538	22173	430.184	0.9640
3	4	21642	295.65	0.9410	21966	206.828	0.9551
4	5	21081	560.85	0.9166	21441	525.546	0.9322
5	6	20915	166.33	0.9090	21274	161.396	0.924
6	7	20669	246.33	0.8986	21028	236.619	0.9138
7	8	20370	298.84	0.8856	20729	276.173	0.9018
8	9	20301	69.00	0.8826	20660	43.787	0.8999

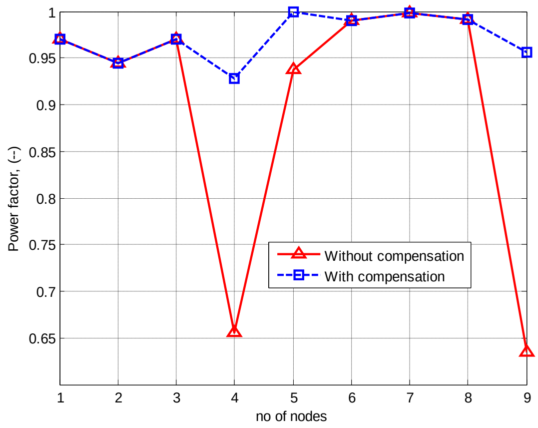

Fig 2 Power factor with and without compensation of 9-bus system

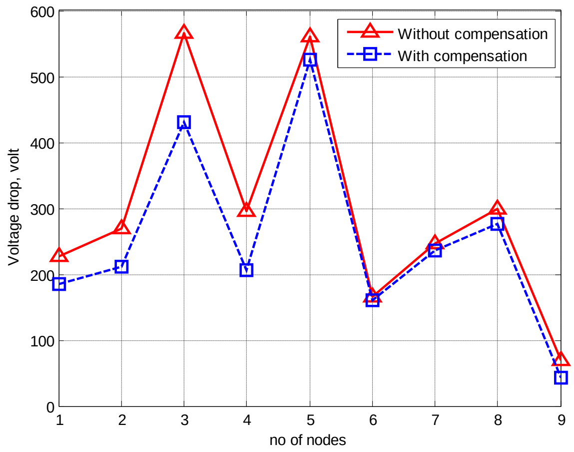

Fig 3 Voltage drop with and without compensation of 9-bus system

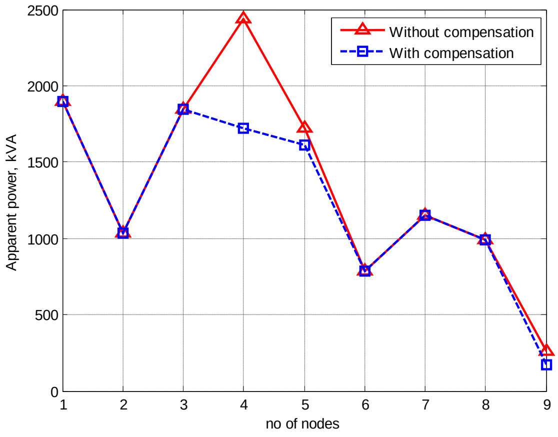

Fig 4 Apparent power with and without compensation of 9-bus system

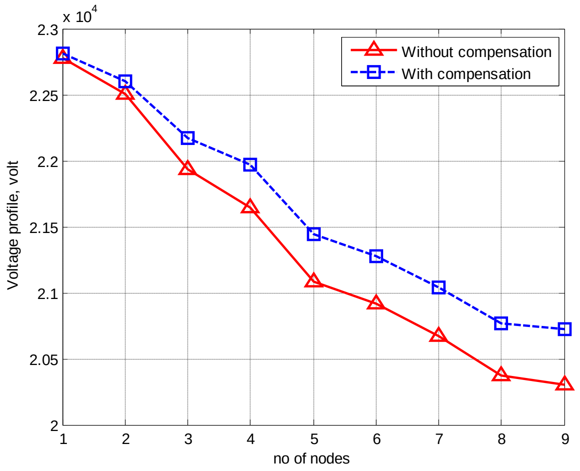

Fig 5 Voltage profile with and with out compensation of 9-bus system

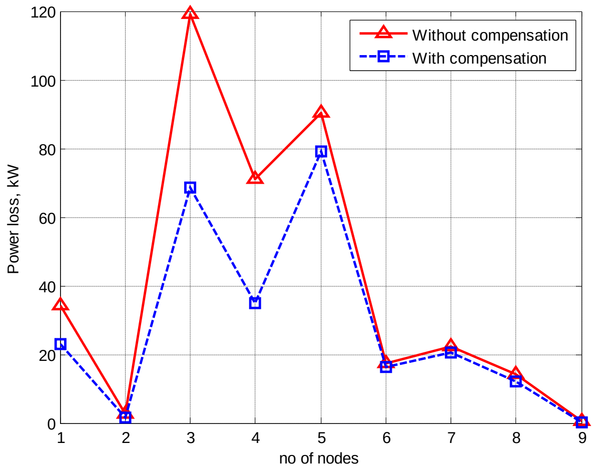

Fig 6 Power loss with and without compensation of 9-bus system

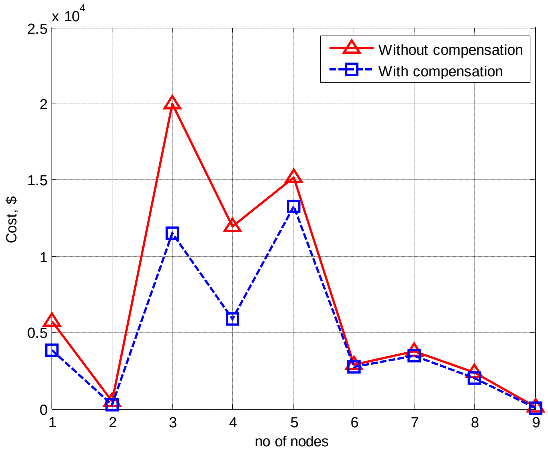

Fig 7 Cost with and without compensation of 9-bus system

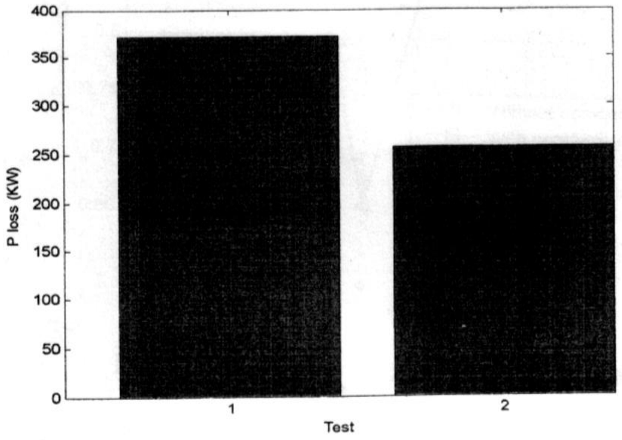

Fig 8 Total power losses with and without compensation

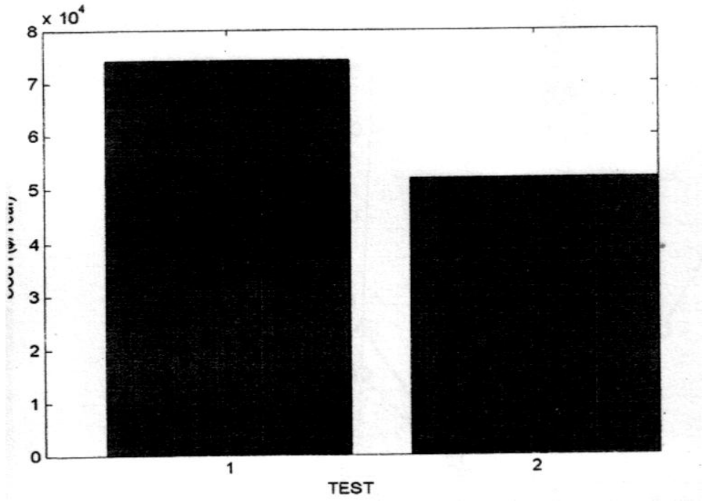

Fig 9 Total cost with and without compensation

Figures from (2) to (7) show the comparison between the performance of network before (without compensation) and after (with compensation) correction power factor. Figures from (8) to (10) show the comparison between total power losses, total cost and total apparent power with (new) and without (old) compensation.

The numerical method had been used to calculate the load flow and to find the values of the network by improving the power factor and the voltage as shown in Tables (4) and (5).

The MATLAB program is used to find the optimal value of the shunt capacitors as shown Table (3).The results finds the sensitive node and the value of shunt capacitors.

The power factor equals (0.655) at node (4) and after the addition of 1200 KVAR shunt capacitor; the power factor will be improved to (0.928). At node (5) the power factor equals (0.937), after addition of 600 KVAR shunt capacitor; the power factor will be improved to (0.999). At node (9) the power factor equals (0.634), after addition 150 KVAR shunt capacitor; the power factor will be improved to (0.956).

Table (6) Standard KVAR and COST/KVAR

No.	Qc (KVAR)	Kc ($)
1	5	0.8
2	15	0.75
3	30	0.7
4	50	0.65
5	100	0.6
6	150	0.5
7	300	0.35
8	450	0.253
9	600	0.22
10	750	0.276
11	900	0.183
12	1050	0.228
13	1200	0.17
14	1350	0.207
15	1500	0.201
16	1650	0.193
17	1800	0.187
18	1950	0.211
19	2100	0.176
20	2250	0.197
21	2400	0.17
22	2550	0.189
23	2700	0.187
24	2850	0.183
25	3000	0.18
26	3150	0.195
27	3300	0.174
28	3450	0.188
29	3600	0.17
30	3750	0.183
31	3900	0.182
32	4050	0.179

5. *Conclusions*

The study shows that the location and size of shunt capacitors have very important impact on the power factor correction problem. It is clear from the tests that the accuracy of the appropriate sizes of the capacitors will affect the values of reactive power compensation added to reduce the power losses in electric power system, the possible value added to mitigate the loss of energy or increase it according to the added value of reactive power compensation. This value must be carefully chosen because it also affects the value of the voltage in the network so that it should not exceed the allowable value in the network.

The location and size of shunt capacitors must be selected on the basis of the point known variables and the reasons of the correction because the location has the possibility to be changed and the appropriate location provides us with different benefits and increases the saving power after power factor correction. The best investment cost could be obtained by finding the best size and location of shunt capacitors.

By the proposed program the optimal location and size of the shunt capacitor and the economic saving will be determined, as shown in Table (6).

3.

6. DISCUSSION

1. Fuzzy logic technique depends of IF -THEN rule base, as shown in Table (1).
2. The Fuzzy Logic Technique operation depends on tile number of membership function and rule base that selected by the user. The number of rule base is selected according to the relation between membership function and the number of the input data.

Number of member ship function= (1, 3, 5, 7.. ..... n) .

Number of rule base = (number of membership function) power to the number of input data.

The input data is the power factor and the power losses. The output data is the capacitor placement suitability.

3. The improvement of the power factor provides us with several benefits, as follows:
   1. Reduce the power losses and increase the active power,
   2. Saving in the investment costs of the power plant,
   3. Reduction in the drawn reactive power from the network, which provides an additional capacity to the network.
   4. Improve the voltage profile and reducing the current passing through the network, which leads to improve the performance of the network.

7. References

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