International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

March 2018	Issue 34	Volume 10	Number 1	Pages 22-26

CAPACITOR BANK PLACEMENT AND CONTROL IN ELECTRICAL DISTRIBUTION SYSTEMS USING MULTIPLE OBJECTIVE FUZZY OPTIMIZATION METHOD

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Abstract- Optimal placement of static capacitor bank (SCB), power determination and control gains theoretical and practical significance for provision adjustable of voltages in the network, load buses and for reducing power loss. Reactive power compensation reduces a reactive current required in the distribution systems by means of application and control of structures and therefore, the significant decrease of active power loss is reached. Based on the current and up-to-date methods, a new approach is presented for the reactive power optimal distribution and automatic control depending on load conditions. The proposed method could be used for the optimal control of reactive power flows in the electrical distribution systems having numerous nodal points. The method was tested for the real power grid having 30 nodal standard IEEE schemes and 15 nodal points.

Keywords: Electrical Distribution System, Reactive Power, Static Capacitor Bank, Power Loss, Voltage Profile, Fuzzy Set, Objective Function, Multiple Objective Optimization, Membership Function.

I. INTRODUCTION

Power loss is one of the main characteristics typical for power energy transmission and distribution. In electrical distribution systems (EDS) the power losses are 70% of total losses in power grid [1, 2]. It is possible significantly to reduce the level of these losses by decreasing reactive power and respectively reactive current required by consumers by means of capacitor banks in EDS of distribution power generation system, at the same time to maintain the voltage profiles (U_i) on distribution substation busbars and displacement power factor of the network ($\tan\varphi$) within the required range.

From 60s of past century, different methods were used for the solution of problem of SCBs placement in electrical distribution systems. These methods include as follows: analytical methods [3,4], heuristic methods [5-7], numerous mathematical programming methods [8,9], fuzzy logical method [10-13], neural networks [14, 15], genetic algorithms [16-19], hybrid methods [20], etc.

Usually, the problems occurring during the determination of locations, number, capacity, type and control algorithm for SCBs installed in the EDSs are eliminated by means of complex solution of multiobjective optimization problems [21].

The subjection of load conditions to probable, uncertain changes may result in nonoptimality of solving problems of redundant labor and insufficient funds. All this in turn lead to the application of certain constraints when solving optimization problems.

In this paper is proposed the selection of sources for reactive power compensation in EDS and new approach based on the application of fuzzy logic theory for automatic power control.

II. OBJECTIVE FUNCTION GENERATION AND LIMITATIONS

As it was mentioned, the main problems required to be solved in the application of SCBs, taking into account limitations accepted for the regime parameters, consist of the determination of their optimal placement, number of SCB sections, capacities, types and control algorithm. Mathematically, these problems can be formed as a searching spatial complex optimization problem given in the $\nu\cdot(M+1)^N$ form; where, M is number of sections, ν is number of load conditions studied during reporting, and N is number of buses in the studied network.

The objective function is expressed as follows:

$$\min f(U,S)=f_C(U,S)+f_{\Delta P}(U,S) \tag{1}$$

where, $f(U,S)$ is objective function; $f_C(U,S)$ is component of the objective function concerned with SCB plant value and operation; $f_{\Delta P}(U,S)$ is components of expenses concerned with objective function power loss; U is nodal voltages vector (voltage profile); and S is vector indicating the numbers of network buses of the SCB in connected or open conditions.

The limitation conditions for the power flow is as follows:

$$\varphi(U^m,S^m)=0 \tag{2}$$

Limitation for voltage is as follows:

$$U_{\min} \le (U_j^m) \le U_{\max} \quad (3)$$

Limitation for displacement power factor is as follows:

$$\tan\varphi_{\min} \le (\tan\varphi_j^m) \le \tan\varphi_{\max} \quad (4)$$

where components of the objective function (1) are expressed as follows:

$$f_C(U,S) = \sum_{m=1}^{\nu}\sum_{j=1}^{N} K_C^{f,l} S_k^m C_k^m \quad (5)$$

$$f_{\Delta P}(U,S) = \sum_{m=1}^{\nu} K_{\Delta W}^m T^m P^m(U^m, S^m) \quad (6)$$

where, U_j^m is value of voltage in j bus for m load level; S_j^m differential logic capacity value in j bus for m load level; C_j^m is capacity of capacitor connected to j bus of m load level; U^m is voltage value for m load level; S^m is differential logic vector; C^m is vector showing capacitor's capacities for m load level; $\text{tg}\varphi_j^m$ is value of displacement power factor in j bus for m load level; ΔP^m is power losses for m load level; $K_{\Delta W}^m$ is amount of energy losses for m load level (man/MW-hour); $K_C^{f,l}$ is costs for parameters of each connected or open capacitor (man/kVAr); and T^m is duration of m load level.

According to voltage reduction, taking into account the χ penalty factor and $\varphi(U^m, S^m) = 0$, the objective function is expressed as follows:

$$f(U,S) = f_C(U,S) + f_{\Delta P}(U,S) + \chi \cdot \sum_{j,m}^{N,\theta} F_{U_j^m} \quad (7)$$

where,

$$F_{U_j^m} = \begin{cases} 0.01 & , U_{\min} \le U_j^m \le U_{\max} \\ 0.5\left|1-(U_j^m)^2\right| & , U_j^m < U_{\min} \ , U_j^m > U_{\max} \end{cases} \quad (8)$$

III. APPLICATION OF THEORY FUZZY LOGIC AND PROBLEM SOLUTION ALGORITHM

Due to fuzzy nature of the objective function, it is more advisable to use Bellman-Zadeh maximization method in the rational solving and decision making procedure for the problem. The essence of the maximization method is that the objectives in view are minimized and then maximums that allow for the finding of the rational solution are selected within the minimal criteria. In this case, during the decision making the initial data non-smoothness for each objective function will be taken into account.

It is possible to express quantitatively the fuzzy objectives by means of appropriate membership functions. These functions show the extent of belonging of the parameter value to certain fuzzy subset (term) using figures from [0;1] interval. Membership function value equal to 0 shows that it is not the fuzzy sets element, and its value equal to 1, forming the core of set, demonstrates the inclusion of all characteristics: $\mu_A(x): X \to [0,1]$ [9-12], where X is universal set; A is fuzzy set determined in X universal set; x is elements of this set. Then, for the fuzzy set we write the following:

$$A = \frac{\mu_A(x_1)}{x_1} + \frac{\mu_A(x_2)}{x_2} + \cdots + \frac{\mu_A(x_k)}{x_k} = \sum_{i=\overline{1,k}} \frac{\mu_A(x_i)}{x_i} \quad (9)$$

where sign "+" indicates the elements include into A set.

It should be noted that the choice of form of $\mu(f_i)$ membership function for the case under consideration, depending on the objective is selected subjectively by expert.

In the present work for each i criterion the $\mu(f_i)$ membership function is considered as monotonic decreasing and continuous one. This function is expressed as below:

$$\mu(f_i) = \begin{cases} 1 & , \ f_i \le f_i^{\min} \\ \dfrac{f_i^{\max} - f_i}{f_i^{\max} - f_i^{\min}} & , \ f_i^{\min} \le f_i \le f_i^{\max} \\ 0 & , \ f_i \ge f_i^{\max} \end{cases} \quad (10)$$

where, $f_i^{\min}$ and $f_i^{\max}$ are minimum and maximum values of the objective function and the optimal solution beyond the interval, restricted by these values, is not expected. The objective function value (by [0;1] scale) shows how this solution meets the objective.

For fuzzy objectives in number of Z taking into account functions (7), (10), the optimal solution searching is performed based on the below algorithm.

1. $i = \overline{2,Z}$ hypercube is defined around w_i^c, and the combinations set is created in the below form in number 2^{Z-1} for the hyper cube's lateral edges:

$$w_i^p = w_i^c + \tilde{D}_i^p \ ; \ i = \overline{2,Z} \ ; \ p = \overline{1,\ 2^{Z-1}} \quad (11)$$

$$w_1^p = 1 - \sum_{i=2}^{L} w_i^p \ ; \ p = \overline{1,\ 2^{Z-1}} \quad (12)$$

where, $\tilde{D}_i^p$ indicates a distance from the end points starting the hypercube formation.

2. For each objective the intersection of membership functions $\mu(f_i)^j \big|_{i=\overline{1,Z}}$ and $\mu_j^{\min} = \min\left(\mu(f_i)^{j,k} \big|_{i=\overline{1,Z}}\right)$ is determined and then the degree of weighting for each combination is calculated.

3. Finally, the best solution is determined by the choice of the membership function in the below form using the minimax composition songs [10,11]:

$$\mu^0 = \max\left\{\mu_j^{\min} \ ; \ k = \overline{1,\ 2^{Z-1}+1}\right\} \quad (13)$$

Number of end points $(Z-1)$ of multidimensional hypercube shows a sequence of objectives in number of Z.

4. After that for the iteration process continuation, another hypercube is formed around the w_i^{c0}, which at most meets the μ^0 membership function in comparison with the previous year, and the process continues until the best solution is obtained.

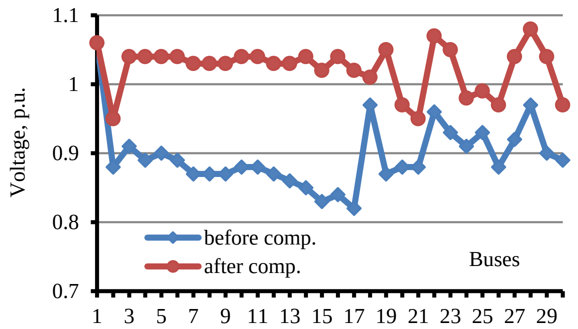
It should be noted that cost limitations stipulate the minimization of number of capacitor banks, connected to busbars, as far as possible. Power transmission lines (cables and overhead lines) and distribution substations are not connected directly with objective function. At the same time, these limitations are very important for the more favorable placement of SCB.

IV. RESULTS OF COMPUTER REALIZATION OF ALGORITHM

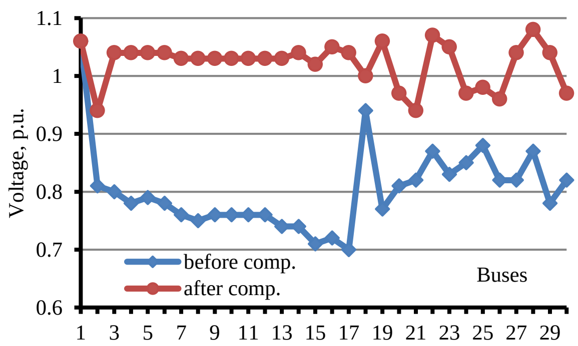
The algorithm's computer realization developed using fuzzy sets for the optimal placement and control of reactive power sources in the conditions of indefinite changes of the above-mentioned scheme and mode was implemented for 30-bus standard IEEE scheme and real electric network.

Figure 1 shows the voltage profiles constructed on the basis of calculations performed for normal and maximum modes on 30-bus scheme without compensation sources and with optimal placement. As is seen from the Figure 1(a), under normal mode without compensation the lowest limit of the voltage in bus 17 was 0.82 and in maximum mode in the same mode - 0.7. As a result of the algorithm's computer realization, after the reactive power compensation in this bus the voltage under normal and maximum load modes is 1.02 and 1.04, respectively.

After compensation the lower limits of the voltage in normal conditions were 2 (0.95), 21 (0.95), 26 (0.97), 30 (0.97), and in maximum conditions again in the same buses 0.94, 0.94, 0.96 and 0.97, respectively. Thus, in other buses the voltage passes 0.95. In other words, after compensation the voltage profile improved significantly.



(a)



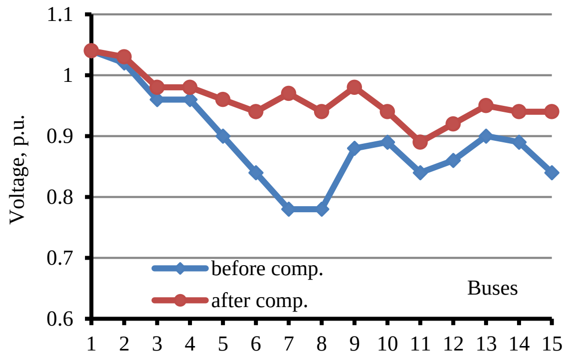
(b)

Figure 1. Voltage profiles for 30-bus standard scheme (a) at normal load conditions of the network; (b) at maximum load conditions of the network

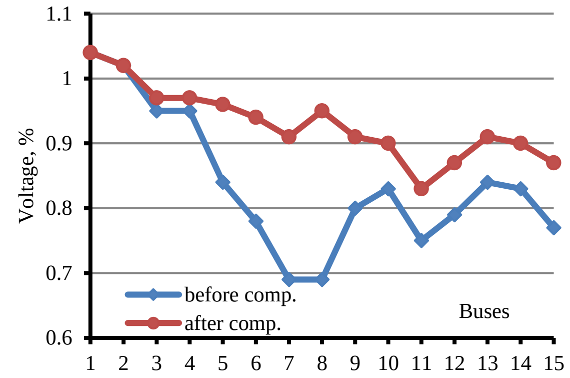
Capacitor banks consisting of 67 sections and with 67 MVAr capacity were located under normal load conditions in bus 18. Calculations of power flows showed that at that the power loss reduced from 45.3 MW to 38.3 MW, that is to 15.4%.

As is seen from Figure 1(b), the compensation was done by placing a capacitor bank consisting of 102 sections with total capacity of 102 MVAr under maximum load mode in bus 17 and at that the active power loss reduced from 59.5 MW to 41.9 MW, that is by 29.5%. The comparative analysis of engineering-and-economic performance (installation, maintenance costs and annual profit due to the loss reduction) has shown that in both cases the reactive power compensation measures are self-repaying in the first year.

Similar calculations were performed for the 15-bus real electric network scheme. Figure 2 describes the voltage profiles constructed on the basis of results of calculation performed in two modes for the same network.



(a)



(b)

Figure 2. Voltage profiles for 15-bus real electric network scheme (a) at normal load conditions of the network; (b) at maximum load conditions of the network

As is seen from Figure 2, under normal load conditions, the hardest case for the voltage profile is in buses 7 and 8, respectively the voltages in these buses are 0.78. And after compensation the voltage in these buses is 0.97 and 0,94 respectively. For these purpose capacitor banks, consisting of 81 sections, with total capacity of 48,6 MVAr were connected to bus 7. At the same time, as is seen from Figure 2(b), under maximum load mode of this network, the voltage in these buses before the compensation increased up to 0.69, and after compensation up to 0.91 and 0.95, respectively. In maximum mode the SCB, consisting of 106 sections, with the capacity of 63.6 was connected to bus 7 for the compensation purpose. In this mode, in the buses 9-15, the voltage level was below normal, so there was the need to take other additional measures. This measure can consist of the change of transformer branching.

Table 1. Calculation results of steady regimes in normal and maximum load cases of 30-bus and 15-bus networks

Quantities		30-bus standard IEEE scheme				
		P_G MW	Q_G MVAr	P_y MW	Q_y MVAr	$\cos\varphi$
Normal mode	before *k*	442	303	396.7	158	0.82
	after *k*	435	192.9	396.7	78,6	0.91
Maximum mode	before *k*	470	389.1	410.9	183	0.77
	after *k*	453	200	411	71.6	0.92

Quantities		15-bus standard IEEE scheme				
		P_G MW	Q_G MVAr	P_y MW	Q_y MVAr	$\cos\varphi$
Normal mode	before *k*	148.2	106.1	131.4	75.5	0.81
	after *k*	144.9	53.6	132.8	31.5	0.94
Maximum mode	before *k*	194.9	145.6	161.7	91.9	0.8
	after *k*	187.2	74.9	164.5	37.2	0.93

Active power loss at normal load conditions decreased from 16.7 MW to 11.9 MW (28.7%), and at maximum load conditions from 33.1-22.7 MW (31.4%). The self-repayment period for the measures taken with respect to reactive power compensation is 1 year.

Results of total calculation of power moment for standard and real electrical networks in both regimes are given in Table 1. As is seen from the table, as a result of compensation the power factor value on standard scheme in normal regime increased from 0.82 to 0.91, and in maximum regime from 0.77 to 0.92. This parameter for the real electric network improved from 0.81 to 0.94 and from 0.8 to 0.93, respectively.

The above results of the analysis of the algorithm's computer realization prove the effectiveness of the proposed method for the estimation of voltage profiles, active power losses and power factor. This method can be applied for the optimal placement and efficient control of reactive power sources in electrical distribution systems of power system with complex topology and the impact of uncertain factors, the probability of which is either lacking or it is small.

V. CONCLUSION

1. Under the impact of uncertain factors in electrical distribution systems with complex topology, with the goal of optimal placement and control of reactive power sources, the effective method and algorithm were developed based on fuzzy sets theory.

2. Algorithm's computer realization was performed on the example of 30-bus standard network and 15-bus real electrical network. Comparative analysis of the voltage profiles, active power loss, power factor value and self-repayment period of reactive power compensation measures justify the advantage of the proposed algorithm.

3. As a result of implementation of reactive power compensation based on the suggested algorithm, the voltages on the network buses become steady within the permissible limits, the active power loss reduces significantly and power factor increases. The self-repayment period for the measures taken with respect to reactive power compensation is 1 year.

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