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Optimization of reactive power compensation in distribution networks

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Abstract. The optimal reactive-power compensation problem solving consists of finding the optimal combinations of the capacitors and their locations in a network in a way that technical requirements are satisfied and maximum economical effects are achieved.
An approach to the optimal reactive-power compensation in distribution networks based on simulated annealing method and deterministic initialization is presented. The objective function considers the savings due to the energy losses and reduction of the peak load. The costs are divided into two categories: constant and variable depending on the capacitors size. The power summation method is used for calculation of the power flows and voltages. The method is applied on a test distribution network.
By compensating the reactive power in distribution networks, several goals are achieved: voltages are increased to their nominal values, the network losses are decreased and power flows though interconnections are reduced.
Key words: optimization, capacitor, distribution network, reactive power

Optimizacija kompenzacije jalove moči v razdelilnih omrežjih

Povzetek. Problem optimizacije kompenzacije jalove moči pomeni določiti najprimernejše število kondenzatorjev in njihove lokacije v omrežju, da je zadoščeno tehničnim zahtevam in minimizaciji stroškov. Razvit je bil pristop za optimizacijo kompenzacije jalove moči za razdelilna omrežja. Pristop temelji na optimizacijski metodi simuliranega izžiganja in na deterministični inicializaciji. V ciljni funkciji so upoštevani prihranki zaradi manjših izgub energije in zaradi zmanjšanja vršne obremenitve. Stroški so razdeljeni na konstantne in variabilne in so odvisni od velikosti kondenzatorjev. Izračun pretokov moči in napetosti temelji na metodi vsot moči. Metoda je uporabljena na testnem razdelilnem sistemu. S kompenzacijo jalove moči v razdelilnih omrežjih je doseženih več učinkov: napetosti so povečane na njihove nazivne vrednosti, zmanjšane so izgube v omrežju in zmanjšani so pretoki moči.

Ključne besede: optimizacija, kondenzator, razdelilno omrežje, jalova moč

1 Introduction

Capacitors are widely used in distribution networks to allow reactive power compensation, reduction of power and energy losses, improvement of service quality through voltage regulation, and delaying construction via system capacity increase. The goal is to choose the optimum capacitor size and allocation in order to maximize the benefits against the cost of capacitors installation.

The early approaches are based on dynamic programming technique to consider the discrete nature of the capacitor size [1]. The analytical methods in conjunction with heuristics were applied [2], [3], [4].

The application of the simulated annealing (SA) and tabu search algorithm was developed [5], [6]. The genetic algorithm (GA) for searching the global optimal solution of capacitor placement problem was applied [7], [8], [9], [10], [11].

A heuristics SA method is developed and implemented for maximization of the optimized function, which is presented in the paper.

2 Problem definition

The optimized function is defined as a difference between the yearly savings due to the decreased losses of energy and the peak power in the network and the yearly expenses for installation and maintenance of the capacitors. Costs of capacitors are divided in two groups: costs independent from the size of the capacitors (protection, switching equipment) and the costs proportional to the size (procurement, installation, maintenance). These costs are included in the function through the rate of the actualization p_a that considers the yearly payment rate for capacitors installation, maintenance, amortization and insurance.
The optimized function is written as:

$$F = c_e \cdot (\Delta W_o - \Delta W) + c_p \cdot (P_{mo} - P_m) - p_a \cdot \left[\sum_{k=1}^{N_l} \left(c_{fk} + c_v \cdot Q_{ck} \right) \right] \quad (1)$$

Where:

c_e - price of electric energy €/kWh.

ΔW_o - annual loss of energy in the uncompensated network kWh.

ΔW - annual loss of energy in the compensated network kWh.

c_p - peak power price €/kW.

P_{mo} - peak power in the uncompensated network kW.

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P_m - peak power in the compensated network kW.

p_a - rate of actualization of costs in %.

c_{fk} - constant costs for installation of the capacitor in bus *k*.

c_v - price of the capacitor proportional to its size.

Q_{ck} - installed capacity of all capacitors in bus *k*.

N_l - number of buses with capacitors.

The power summation method [12] is used for calculation of voltages, power flows and losses of power and energy in the network.

The load diagram divided into two segments, with two types of load, is used for calculation of the energy losses. The time axis is divided into intervals in which the constant load is assumed. The annual energy loss is expressed as:

$$\Delta W = \sum_{i=1}^{N_s} \Delta P_i \cdot T_i \qquad (2)$$

Where:

ΔP_i - loss of the active power in the network in the interval i.

T_i - length of the time interval *i*.

N_s - number of time intervals.

3 The SA and deterministic initialization

The heuristic methods are effective in finding the optimal solution for large combinatorial problems. The number of possible solutions in the analyzed problem is $\left(n^N\right)^m$, where:

n- maximum number of capacitors of the same type in the bus.

N- number of the types of the capacitors.

m- number of the buses in the network.

The number of variables is equal to the number of buses *m*. The coding of the variables with real numbers is applied. Each variable X(n) is a real number in the interval 0<X(n)<1, corresponding to one bus in the network, containing the number of capacitors from each type in that bus.

For example:

X(z)=0.realcoding (3)

X(1)=0.1233210012 (4)

The variable given by Equation (4) corresponds to bus 1 and gives the number of capacitors from a specific type in that bus:

type 1 =1

type 2 =2 and so on for other buses.

The standard procedure for initialization of the heuristic algorithms is by random genesis of the initial population in a predefined interval of the allowed values:

$$X(i) = r_i \qquad (5)$$

Where:

r_i – evenly (normal) distributed random number in interval [0,1].

The initial population is calculated using the deterministic method. The deterministic initialization provides a good start to optimization algorithm, resulting in a faster and improved optimization [13], [14], [15].

The optimized function, after installation of capacitors and assuming change of flows only for the reactive power, can be written as:

$$F = c_e \cdot \left[\Delta W_o - \sum_{j=1}^{N_s} \sum_{i=1}^{m} R_i \cdot \frac{P_{ij}^2 + \left(Q_{ij} - q_i\right)^2}{U_{ij}^2} \cdot T_j \right] + \\ + c_p \cdot \left(P_{mo} - \sum_{i=1}^{m} R_i \cdot \frac{P_{iv}^2 + \left(Q_{iv} - q_i\right)^2}{U_{iv}^2} \right) - p_a \cdot \left[\sum_{k=1}^{N_l} \left(c_{fk} + c_v \cdot Q_{ck} \right) \right] \qquad (6)$$

Where:

P_{ij}, Q_{ij} - active and reactive power in branch *i* in time interval j.

U_{ij} -voltage of bus *i* in time interval j.

P_{iv}, Q_{iv} - active and reactive power in branch *i* in time interval j during the peak load.

U_{iv} - voltage of bus *i* during the peak load.

q_i - reactive power injection from capacitors in branch *i*.

For network with radial configuration:

$$q_i = \sum_{k=1}^{N_l} B_{ik} \cdot Q_{ck} \quad , \quad B_{ik} = \begin{cases} 1, \text{if } \mathrm{i} \in \mathrm{A_k} \\ 0, \text{if } \mathrm{i} \notin \mathrm{A_k} \end{cases} \qquad (7)$$

Where:

A_k - branches that constitute a path between bus *k* and the source bus.

The maximum of the function, given with equation (6), is obtained through differencing it:

$$\frac{\partial F}{\partial Q_{cl}} = 2 \cdot c_e \cdot \sum_{j=1}^{N_s} \sum_{i=1}^{m} R_i \cdot \frac{\left(Q_{ij} - \sum_{k=1}^{N_l} B_{ik} \cdot Q_{ck} \right) \cdot B_{il}}{U_{ij}^2} \cdot T_j + \\ + 2 \cdot c_p \cdot \sum_{i=1}^{m} R_i \cdot \frac{\left(Q_{iv} - \sum_{k=1}^{N_l} B_{ik} \cdot Q_{ck} \right) \cdot B_{il}}{U_{iv}^2} - p_a \cdot c_v \qquad (8)$$

l = 1, 2, ... N_l

The following system of linear equations is obtained with equalization of the first partial derivates of equations (8) to zero:

$$\sum_{k=1}^{N_l} C_{lk} \cdot Q_{ck} = D_l \text{ , } l = 1, 2, \ldots N_l \qquad (9)$$

Where:

$$C_{lk} = c_e \cdot \sum_{j=1}^{N_s} \sum_{i=1}^{m} \frac{R_i \cdot B_{il} \cdot B_{ik} \cdot T_j}{U_{ij}^2} + c_p \cdot \sum_{i=1}^{m} \frac{R_i \cdot B_{il} \cdot B_{ik}}{U_{iv}^2} \qquad (10)$$

$$D_l = c_e \cdot \sum_{j=1}^{N_s} \sum_{i=1}^{m} \frac{R_i \cdot B_{il} \cdot Q_{ij} \cdot T_j}{U_{ij}^2} + c_p \cdot \sum_{i=1}^{m} \frac{R_i \cdot B_{il} \cdot Q_{iv}}{U_{iv}^2} - \frac{1}{2} \cdot p_a \cdot c_v \qquad (11)$$

By solving the equations (9) for previously chosen $\mathrm{N_l}$ bus locations, the size of capacitors is determined.

The procedure for deterministic initialization has two steps: first buses, where capacitors will be installed, are randomly selected and then, by solving equations (9), the optimal capacitors size is determined.

From the available discrete capacitor sizes most adequate combination, the closest to the one calculated in step 2 of deterministic initialization, is selected and used as initial population.

The generated reactive power is limited to the value that prevents ‘return’ (overflow) in the high-voltage network. This constraint can be written as:

$$Q_o \geq 0 \tag{12}$$

Where:

Q_o - reactive power at the source bus.

The limitation given by Eq. (12) is included in the optimization with the application of the penalization function [14].

The SA optimization routine implements the continuous simulated annealing global optimization algorithm [16].

The SA starts with a random selection of a trial point within the step length VM (a vector of length N) of the user-selected starting point. The function is evaluated at this trial point and its value is compared to its value at the initial point. In a maximization problem, all the uphill moves are accepted and the algorithm continues from new trial point. The downhill moves may be accepted; the decision is made accounting to the Metropolis criteria. Temperature T and the size of the downhill move are applied in a probabilistic manner [17].

Parameter T is crucial for a successful use of SA. It influences VM, the step length over which the algorithm searches for optima. The relationship between the initial temperature and the resulting step length is function-dependent [17].

The starting temperature that is consistent with the optimized function is determined with trials in order to identify the T value that produces a large enough VM. For the specified optimization problem, the optimal value of T=5 is determined [17].

4 Results

Figure 1 shows the test distribution network with three voltage levels (35kV, 10 kV and 0.4 kV) and parameters given in Table 1. The input data include: interconnections parameters (transformer impedance is given for the higher voltage side), nominal voltage and peak load of the buses, type of the load diagram of the bus load, and constant expenses for installation of the capacitors in the bus. The bus data in Table 1 correspond to the second (last) bus of the given interconnection. The load diagram is approximated with two segments. The duration of the load diagram segments, load factor for peak loads and voltage of the source bus are given in Table 2. The values of the parameters, defined in Equation 1, are assumed to: c_e=0.05 €/kWh, c_p=150 €/kW, c_v=10 €/kVAr and p_a=12 %. Results for SA are obtained for the value of seed=3910, initial temperature T=5 and reduction of temperature ΔT=0.1. Four types of capacitors with sizes of 50, 100, 160 and 250 kVAr are taken in the analysis.

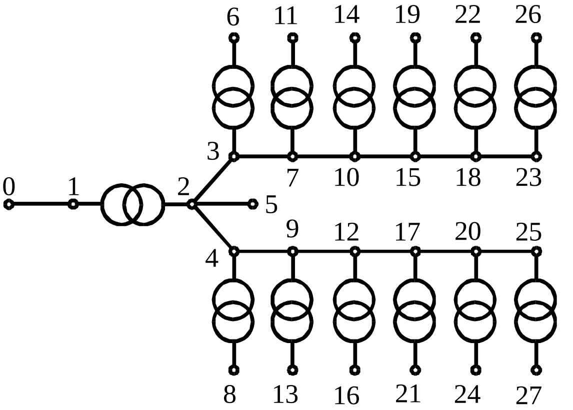

Figure 1. Test network

Table 1 Input data for the test network

Line	U_n (kV)	R (Ω)	X (Ω)	B (μS)	Type	P (kW)	Q (kVAr)	c_{fk} (€)
0-1	35	3.19	3.67	31.3	2	0	0	20.000
1-2	10	0.77	10.00	0.0	2	0	0	15.000
2-3	10	1.12	0.75	6.1	2	0	0	15.000
2-4	10	1.12	0.75	6.1	2	0	0	15.000
2-5	10	1.12	0.75	6.1	1	1040	416	15.000
3-6	0.4	1.35	5.85	0.0	2	800	150	1.000
3-7	10	1.12	0.75	6.1	2	0	0	15.000
4-8	0.4	2.88	9.38	0.0	2	504	94.5	1.000
4-9	10	1.12	0.75	6.1	2	0	0	15.000
7-10	10	1.12	0.75	6.1	2	0	0	15.000
7-11	0.4	2.88	9.58	0.0	2	320	60	1.000
9-12	10	1.12	0.75	6.1	2	0	0	15.000
9-13	0.4	2.88	9.58	0.0	2	320	60	1.000
10-14	0.4	2.88	9.38	0.0	2	504	94.5	1.000
10-15	10	1.12	0.75	6.1	2	0	0	15.000
12-16	0.4	1.35	5.85	0.0	2	800	150	1.000
12-17	10	1.12	0.75	6.1	2	0	0	15.000
15-18	10	1.12	0.75	6.1	2	0	0	15.000
15-19	0.4	2.88	9.38	0.0	2	504	94.5	1.000
17-20	10	1.12	0.75	6.1	2	0	0	15.000
17-21	0.4	2.88	9.38	0.0	2	504	94.5	1.000
18-22	0.4	1.35	5.85	0.0	2	800	150	1.000
18-23	10	1.12	0.75	6.1	2	0	0	15.000
20-24	0.4	2.88	9.38	0.0	2	504	94.5	1.000
20-25	10	1.12	0.75	6.1	2	0	0	15.000
23-26	0.4	1.35	5.85	0.0	2	800	150	1.000
25-27	0.4	1.35	5.85	0.0	2	800	150	1.000

Table 2 Load diagram parameters

	Segment 1	Segment 2
Duration (h)	4344	4416
Factor for type 1	1	1
Factor for type 2	0.76075 + j0.05736	0.64453 + j0.10415
U_o (pu)	1.03	1.00

The analysis is done with (case A) and without (case B) deterministic initialization. The obtained results in Table 3 include the yearly loss of energy, peak load in the network and reactive-power flow from the high-voltage network to the distribution network.

Table 3 Obtained results

	SA case A	SA case B
ΔW (kWh)	5755967	6458532
P_{max} (kW)	9649	9956
Q_o (kVAr)	-2.113739	2.552657
F (€)	**200355.6**	**121967.4**

Table 3 shows that deterministic initialization results in a considerable increase in the yearly savings. The value of the reactive power returned in the network Q_0 is negative for case A, implying a backflow of the reactive energy from the network to the power system. The small value of Q_0 can be neglected and the imposed limitation is assumed to be satisfied. The necessity for deterministic generation of the initial population is confirmed.

Allocation and sizes of the capacitors for the SA case A are given in Table 4.

Table 4 Optimal allocation and sizes of capacitors

SA case A					
	(kVAr)				
	50	100	160	250	
Bus	Number of capacitors				Q_c (kVAr)
2	6	7	5	7	3690
3	7	2	0	0	510
8	0	1	0	0	150
11	2	0	0	0	50
13	0	0	1	0	150
14	0	0	1	0	150
16	5	0	0	0	250
19	2	0	0	0	200
21	0	0	1	0	150
22	5	1	0	0	160
24	2	0	0	0	160
26	0	0	1	0	200
27	1	2	0	0	150
Total					5990

The voltages in uncompensated U_u and compensated network U_c, and the increase in voltages ΔU in a compensated network are given in Table 5.

Table 5 Voltages in an uncompensated and compensated network

Bus	Uu(pu)	Uu(kV)	Uc(pu)	Uc(kV)	ΔU(V)
0	1.03	36.05	1.03	36.05	0
1	0.98979	34.643	0.99853	34.948	305
2	0.94972	9.497	0.97924	9.792	295
3	0.88169	8.817	0.92267	9.227	410
4	0.88857	8.886	0.92891	9.289	403
5	0.93391	9.339	0.96392	9.639	300
6	0.85731	0.343	0.89956	0.36	17
7	0.82602	8.26	0.87615	8.762	502
8	0.85987	0.344	0.90167	0.361	17
9	0.83527	8.353	0.88437	8.844	491
10	0.7757	7.757	0.83489	8.349	592
11	0.80669	0.323	0.85806	0.343	20
12	0.78727	7.873	0.84504	8.45	577
13	0.81619	0.326	0.86647	0.347	21
14	0.74186	0.297	0.80397	0.322	25
15	0.73444	7.344	0.79776	7.978	634
16	0.75928	0.304	0.81938	0.328	24
17	0.75314	7.531	0.81875	8.188	657
18	0.70274	7.027	0.76931	7.693	666
19	0.69817	0.279	0.76508	0.306	27
20	0.72824	7.282	0.79637	7.964	682
21	0.71802	0.287	0.78709	0.315	28
22	0.67035	0.268	0.74049	0.296	28
23	0.6867	6.867	0.75495	7.55	683
24	0.69158	0.277	0.76362	0.305	28
25	0.7129	7.129	0.7826	7.826	697
26	0.65331	0.261	0.72544	0.29	29
27	0.68113	0.272	0.7544	0.302	30

Table 5 shows that the bus voltages in the compensated network, compared to the uncompensated one, are improved to nominal values. The voltages (pu) increase as the bus nominal voltage decreases.

The power flows through interconnections, for the uncompensated network, are shown in Table 6. The losses in the uncompensated network, as shown in Table 6, are ΔP=2195.4 kW and ΔQ=3114.4 kVAr.

Table 7 shows the power flows in the compensated network, with annual losses ΔP=1746.4 kW and ΔQ=2496.3 kVAr. Decrease of the losses in compensated network, compared to the uncompensated are ΔP_d=448.9 kW and ΔQ_d=618.1 kVAr.

Table 3 shows that yearly savings, resulting from the decrease in energy losses and peak load, are in the range of 200000 €.

Table 6 Power flows (kVA) in uncompensated network

Line	P_{lineS} [kW]	Q_{lineS} [kVAr]	P_{lineE} [kW]	Q_{lineE} [kVAr]	ΔP_{line} [kW]	ΔQ_{line} [kVAr]
0-1	10395.4	4845.8	10072.5	4474.3	322.9	371.5
1-2	10072.5	4493.5	9994.5	3479.9	78.1	1013.6
2-3	4695.7	1626.2	4389.1	1420.9	306.6	205.3
2-4	4242.7	1428.1	3993.8	1261.5	248.8	166.6
2-5	1056.1	426.5	1040.0	415.7	16.1	10.8
3-6	812.2	202.7	800.0	150.0	12.2	52.7
3-7	3576.9	1218.7	3371.2	1081.0	205.7	137.8
4-8	514.2	127.9	504.0	94.5	10.2	33.4
4-9	3479.6	1134.2	3289.6	1007.0	190.0	127.2
7-10	3046.5	1006.0	2877.5	892.8	169.0	113.1
7-11	324.7	75.6	320.0	60.0	4.7	15.6
9-12	2965.0	932.4	2809.9	828.5	155.1	103.9
9-13	324.6	75.2	320.0	60.0	4.6	15.2
10-14	517.8	139.3	504.0	94.5	13.8	44.8
10-15	2359.8	754.1	2245.5	677.6	114.2	76.5
12-16	815.5	217.2	800.0	150.0	15.5	67.2
12-17	1994.4	611.9	1915.8	559.2	78.6	52.7
15-18	1726.0	533.1	1658.2	487.8	67.8	45.4
15-19	519.5	145.1	504.0	94.5	15.5	50.6
17-20	1397.1	417.5	1355.1	389.4	42.0	28.1
17-21	518.7	142.3	504.0	94.5	14.7	47.8
18-22	819.9	236.2	800.0	150.0	19.9	86.2
18-23	838.3	252.1	821.0	240.5	17.4	11.6
20-24	519.8	146.1	504.0	94.5	15.8	51.6
20-25	835.3	243.9	819.3	233.2	16.0	10.7
23-26	821.0	240.8	800.0	150.0	21.0	90.8
25-27	819.3	233.5	800.0	150.0	19.3	83.5

Table 7 Power flows (kVA) in compensated network

Line	P_{lineS} [kW]	Q_{lineS} [kVAr]	P_{lineE} [kW]	Q_{lineE} [kVAr]	ΔP_{line} [kW]	ΔQ_{line} [kVAr]
0-1	9946.5	2267.7	9691.0	1973.8	255.5	293.9
1-2	9691.0	1993.0	9629.3	1191.5	61.7	801.4
2-3	4497.8	718.5	4255.5	556.2	242.3	162.3
2-4	4076.4	528.2	3879.1	396.0	197.3	132.1
2-5	1055.1	425.8	1040.0	415.7	15.1	10.1
3-6	811.1	197.9	800.0	150.0	11.1	47.9
3-7	3444.4	608.9	3283.5	501.1	161.0	107.8
4-8	513.3	124.8	504.0	94.5	9.3	30.3
4-9	3365.7	521.8	3215.2	421.0	150.6	100.8
7-10	2959.3	427.9	2828.9	340.6	130.4	87.4
7-11	324.1	73.8	320.0	60.0	4.1	13.8
9-12	2891.1	348.0	2769.7	266.7	121.4	81.3
9-13	324.1	73.5	320.0	60.0	4.1	13.5
10-14	515.7	132.7	504.0	94.5	11.7	38.2
10-15	2313.2	688.5	2219.6	625.9	93.6	62.7
12-16	813.3	207.7	800.0	150.0	13.3	57.7
12-17	1956.3	59.6	1896.3	19.4	60.1	40.2
15-18	1702.6	489.8	1647.4	452.8	55.2	37.0
15-19	516.9	136.6	504.0	94.5	12.9	42.1
17-20	1380.0	385.7	1345.7	362.7	34.3	23.0
17-21	516.2	134.3	504.0	94.5	12.2	39.8
18-22	816.3	220.7	800.0	150.0	16.3	70.7
18-23	831.1	232.8	817.0	223.3	14.1	9.4
20-24	517.0	136.8	504.0	94.5	13.0	42.3
20-25	828.8	226.5	815.7	217.8	13.0	8.7
23-26	817.0	223.6	800.0	150.0	17.0	73.6
25-27	815.7	218.1	800.0	150.0	15.7	68.1

5 Conclusions

A new approach for optimal compensation of the reactive power in the distribution networks is presented. The optimized function is defined as a difference between the yearly savings resulting from the decreased losses and peak power, and the yearly costs for installation and maintenance of the capacitors. The combination and allocation of the capacitors resulting in maximum yearly savings are integrated into the optimization.

The simulated annealing algorithm is applied for function maximization. A procedure for deterministic initialization of the algorithm is developed. The method is tested on an example distribution networks. The obtained results demonstrate an improvement due to application of the deterministic initialization.

The results confirm the need for application and optimization of the reactive power compensation in the distribution networks. The bus voltages are improved, losses are decreased and the available transfer capacities of the interconnections are increased. The decrease in energy losses and peak load in the distribution network results in substantial yearly savings.

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