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Reactive Power Planning for Loss Minimization Using Simulated Annealing

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Abstract: This paper addresses an optimal Reactive Power Planning (RPP) of power system. The Static Var Compensator (SVC) is introduced into power system in order to reactive power support and voltage control. The locations and the outputs of SVCs are determined using our proposed optimal reactive power planning model. The proposed method optimizes several objective functions at the same time within one general objective. The optimized objectives are minimization of total investment in reactive power support, average voltage deviation and minimization of total system loss. These objective functions are one of the most important objectives for every transmission and distribution systems. Simulated Annealing technique (SA) is used to solve the optimization problem. The validity of the proposed method is tested on a typical power system.

Key words: Reactive Power Planning; Static Var Compensator; Multi Objective Optimization; Simulated Annealing (SA).

INTRODUCTION

The losses are naturally occurring in electrical system components such as transmission lines, power transformers, measurement systems, etc. due to their internal electrical resistance. It is not possible to achieve zero losses in a power system, but it is possible to keep them at minimum. The losses are becoming higher when the system is heavily loaded and transmission lines are transmitting high amount of power. The transmitted power for this case consists of active and reactive power. Necessity of reactive power supply together with active power is one of the disadvantages of the power generation, transmission and distribution with alternating current (AC). Reactive power can be leading or lagging. It is either generated or consumed in almost every component of the power system. In AC system, Reactance can be either inductive or capacitive, which contribute to reactive power in the circuit. In general, most of the loads are inductive and they should be supplied with lagging reactive power. We need to release the power flow in transmission lines for partially solving of problem of supply the reactive power locally where it is highly consumed in a system. In this way the loading of lines would decrease. It would decrease the losses also and with this action the problem of voltage drops could be solved also. By means of reactive power compensation transmission system losses can be reduced as shown in many papers in the literature (Conejo, 2001; Abdel-Moamen, 2003; Mamandur, 1981; Iyer, 1984). It has also been widely known that the maximum power transfer of the transmission system can be increased by shunt reactive power compensation, typically by capacitors banks placed at the end of the transmission lines or a the load terminals (Wollenberg, 2002). Therefore, planning of reactive power supports would give benefits to the users of the transmission systems, in terms of loss reduction, among other technical benefits, such as improving steady-state and dynamic stability, improve system voltage profiles, etc. which are documented in (Timothy, 1982). The reactive power planning problem involves optimal allocation and sizing of reactive power sources at load centers to improve the system voltage profile and reduce losses. However, cost considerations generally limit the extent to which this can be applied.

This paper presents an optimal reactive power planning of power system using the Static Var Compensator (SVC). The proposed planning optimizes several objective functions at the same time within one general objective. The optimized objectives are minimization of average voltage deviation, minimization of total system loss and total system cost.

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Simulated Annealing (SA) is used to solve the optimization problem. Simulation results emphasis on the validity of the proposed method. Rest of the paper is structured as follows: In section 2, problem is formulated and required equations are introduced. In section 3, a brief description about SA technique is given. In section 4 a modified Graver system is considered as test system. In section 5, results and discussions are presented. And finally, the paper is concluded in section 6.

2. Problem Formulation:

As referred before, in this paper three different parameters are considered as objective function. These parameters are: total investment cost, average voltage deviation and total system loss. Also the power system constrains such as generation reactive limits, voltage limits and etc, should be incorporated in planning. Therefore, the objective functions are as follows:

$$J_1 = \sum_{i \in N_B} \left(c_{0i} + c_{1i} q_i \right) u_i \tag{1}$$

Where, c_0 and c_1 are fixed and variable costs of locally reactive sources. q is amount of locally reactive source in bus i and u_i is a binary vector that indicates whether or not to install reactive power sources at bus k.

$$J_2 = P_{loss} \tag{2}$$

$$J_3 = \sum_{i=1}^{n} (V_{ref} - V_i)^2 \tag{3}$$

Where, J_1 shows the investment cost due to locally reactive sources. J_2 shows the system losses and J_3 presents the voltage deviation. These objective functions should be converted to a unique unit. The coefficients ω convert the proposed functions to a unique unit. Eventually, reactive power planning formulation can be represented as follows:

$$\text{Min } \omega_1 J_1 + \omega_2 J_2 + \omega_3 J_3 \tag{4}$$

Subject to

$$P_i(V,\Theta,n) - P_{Gi} + P_{Di} = 0 \tag{5}$$

$$Q_i(V,\Theta,n) - Q_{Gi} + Q_{Di} - q_i = 0 \tag{6}$$

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max} \tag{7}$$

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max} \tag{8}$$

$$V_i^{min} \le V_i \le V_i^{max} \tag{9}$$

$S^{from} \le S^{max}$ (10)
$S^{to} \le S^{max}$(11)

$$q_i^{min} \le q_i \le q_i^{max} \tag{12}$$

Equations (5) and (6) introduce the conventional equations of AC power flow and (7) and (8) show the limits for real and reactive power for generators. Equation (9) presents the limits for voltage magnitude. Capacity limits of the line flows are presented by (10) and (11). Equation (12) presents the limit for locally reactive sources.

The elements of vectors $P_i(V,\Theta,n)$ and $Q_i(V,\Theta,n)$ (5), (6) are calculated as follows (Rider, 2007):

$$P_i(V,\Theta,n) = V_i \sum_{j\in N_B} V_j \left[G_{ij}(n)\cos\theta_{ij} + B_{ij}(n)\sin\theta_{ij} \right] \tag{13}$$

$$Q_i(V,\Theta,n) = V_i \sum_{j\in N_B} V_j \left[G_{ij}(n)\sin\theta_{ij} + B_{ij}(n)\cos\theta_{ij} \right] \tag{14}$$

The elements of bus admittance matrix (G and B) are calculated as follows (Rider, 2007):

$$G = \begin{cases} G_{ij}(n) = -(g_{ij}) \\ G_{ii}(n) = \sum_{j\in\Omega_1} (g_{ij}) \end{cases} \tag{15}$$

$$B = \begin{cases} B_{ij}(n) = -(b_{ij}) \\ B_{ii}(n) = b_i^{sh} + \sum_{j\in\Omega_1} \left[(b_{ij} + b_{ij}^{sh}) \right] \end{cases} \tag{16}$$

Where, g_{ij} and b_{ij} show conductance and susceptance of the transmission line or transformer *ij*. b_{ij}^{sh} shows shunt susceptance of the transmission line or transformer *ij* (if *ij* is a transformer $b_{ij}^{sh} = 0$) and b_i^{sh} shows shunt susceptance at bus *i*. Ω_1 indicates Set of all load buses.
Elements (ij) of vectors S^{from} and S^{to} of (10) and (11) are given by the following relationship:

$$S_{ij}^{from} = \sqrt{\left(P_{ij}^{from}\right)^2 + \left(Q_{ij}^{from}\right)^2} \tag{17}$$

$$S_{ij}^{to} = \sqrt{\left(P_{ij}^{to}\right)^2 + \left(Q_{ij}^{to}\right)^2} \tag{18}$$

Where:

$$P_{ij}^{from} = V_i^2 g_{ij} - V_i V_j \left(g_{ij}\cos\theta_{ij} + b_{ij}\sin\theta_{ij} \right) \tag{19}$$

$$Q_{ij}^{from} = -V_i^2 \left(b_{ij}^{sh} + b_{ij} \right) - V_i V_j \left(g_{ij}\sin\theta_{ij} - b_{ij}\cos\theta_{ij} \right) \tag{20}$$

$$P_{ij}^{to} = V_j^2 g_{ij} - V_i V_j \left(g_{ij}\cos\theta_{ij} + b_{ij}\sin\theta_{ij} \right) \tag{21}$$

$$Q_{ij}^{to} = -V_j^2 \left(b_{ij}^{sh} + b_{ij} \right) - V_i V_j \left(g_{ij}\sin\theta_{ij} - b_{ij}\cos\theta_{ij} \right) \tag{22}$$

The proposed formulation in used to find the best place of SVCs. In this paper Simulated Annealing (SA) is used to solve the optimization problem. In the next section a brief introduction about SA is presented.

3. Simulated Annealing:

In the early 1980s the method of simulated annealing (SA) was introduced in 1983 based on ideas formulated in the early 1950s. This method simulates the annealing process in which a substance is heated above its melting temperature and then gradually cooled to produce the crystalline lattice, which minimizes its energy probability distribution.

This crystalline lattice, composed of millions of atoms perfectly aligned, is a beautiful example of nature finding an optimal structure. However, quickly cooling or quenching the liquid retards the crystal formation, and the substance becomes an amorphous mass with a higher than optimum energy state. The key to crystal formation is carefully controlling the rate of change of temperature.

The algorithmic analog to this process begins with a random guess of the cost function variable values. Heating means randomly modifying the variable values. Higher heat implies greater random fluctuations. The cost function returns the output, *f*, associated with a set of variables. If the output decreases, then the new variable set replaces the old variable set. If the output increases, then the output is accepted provided that:

(23)

Where, *r* is a uniform random number and *T* is a variable analogous to temperature. Otherwise, the new variable set is rejected. Thus, even if a variable set leads to a worse cost, it can be accepted with a certain probability. The new variable set is found by taking a random step from the old variable Set as (24).

$$P^{new} = dP^{old} \tag{24}$$

The variable *d* is either uniformly or normally distributed about p^{old}. This control variable sets the step size so that, at the beginning of the process, the algorithm is forced to make large changes in variable values. At times the changes move the algorithm away from the optimum, which forces the algorithm to explore new regions of variable space. After a certain number of iterations, the new variable sets no longer lead to lower costs. At this point the value of T and d decrease by a certain percent and the algorithm repeats. The algorithm stops when $T \approx 0$.The decrease in *T* is known as the cooling schedule. Many different cooling schedules are possible. If the initial temperature is T_0 and the ending temperature is T_N, then the temperature at step *n* is given by (25).

$$T_n=f(T_0,\ T_N,\ N,\ n) \tag{25}$$

Where, *f* decreases with time. Some potential cooling schedules are as follows:

a. Linearly decreasing: $T_n=T_0-n(T_0-T_n)/N$
b. Geometrically decreasing: $T_n=0.99\ T_{n-1}$
c. Hayjek optimal: $T_n=c/\log(1+n)$, where *c* is the smallest variation required to get out of any local minimum.

Many other variations are possible. The temperature is usually lowered slowly so that the algorithm has a chance to find the correct valley before trying to get to the lowest point in the valley. This algorithm has been applied successfully to a wide variety of problems (Randy, 2004).

4. Illustrative System:

Figure 1 shows a typical electric power system. Modified Graver system is considered as illustrative system. The system data are presented in appendix (Rider, 2007). The fixed and variable costs of locally reactive sources are as c_0 = 100$ and c1 = 0.3$/kvar, respectively.

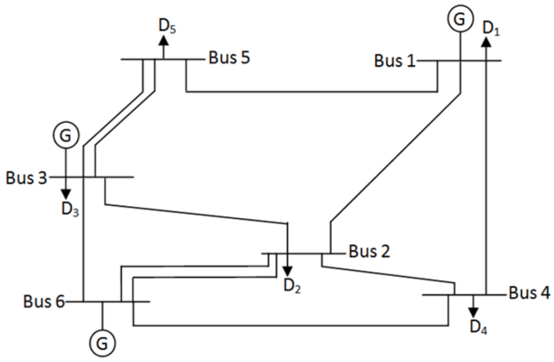

Fig. 1: Schematic of modified Graver system.

It should be noted that SA algorithm is run several times and then optimal parameters is selected respectively. Also 110% and 90% of the nominal value are used for the maximum and minimum voltage magnitude limits.

RESULTS AND DISCUSSIONS

In this section the result of the SVC placement based on the SA is presented. The SVC places are accuracy calculated using SA and the results are listed in Table 1. The locally reactive sources are places near to load buses and it is due to compensation of reactive demands. In this way, the current in transmission lines are reduced and the total loss is reduced. Also, because of locally supply of reactive demands, the congestion of lines is reduced. The flows in transmission lines are listed in Table 2. It is clearly seen that the maximum admissible flows are not violated. The power flow results are also presented in Table 3. The voltages are in allowable limits.

Table 1: Optimal SVC places.

Bus	Locally Reactive Source (MVAR)
4	34.5636
5	6.5

Table 2: Flows in transmission lines.

From bus	To bus	S_ij (p.u.)	S_ji (p.u.)	S_ij max (p.u.)
Bus1	Bus4	0.28346	0.27333	1.0
Bus1	Bus2	0.18	0.17341	1.2
Bus5	Bus1	0.38822	0.40553	1.2
Bus2	Bus4	0.24616	0.24638	1.2
Bus3	Bus2	1.0649	0.99677	1.2
Bus3	Bus6	0.17673	0.18168	1.2
Bus5	Bus3	1.03	1.1074	1.2
Bus5	Bus3	1.03	1.1074	1.2
Bus2	Bus6	0.76119	0.836	1.2
Bus2	Bus6	0.76119	0.836	1.2
Bus4	Bus6	1.0836	1.189	1.2

Table 3: Power flow results.

Bus	(P_G-P_L) [MW]	(Q_G-Q_L)[MVAR]	V [p.u.]
Bus1	80	32	0.99237
Bus2	-240	-48	0.95604
Bus3	315.17	93	1.0214
Bus4	-160	2.5636	0.95693
Bus5	-240	-41.5	0.95
Bus6	260.6903	120.0024	1.05

Conclusion:

The SA approach has been developed for solving the Reactive Power Planning (RPP) problem in large-scale power systems. The application studies on the modified Graver system show that SA gives suitable results and always leads to the global optimum points of the multi-objective RPP problem. By the SA approach, more savings on the energy and installment costs are achieved and the violations of the voltage and reactive power limits are eliminated.

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Appendix:

Table 4 shows the Modified Graver system data.

Table 4: Modified Graver system data.

Bus Data							
Bus	Type	P_D [MW]	Q_D [MVar]	P^{max}_G [MW]	P^{min}_G [MW]	Q^{max}_G [MW]	Q^{min}_G [MW]
1	VΘ	80	16	150	0	48	-10
2	PQ	240	48	-	-	-	-
3	PV	40	8	360	0	101	-10
4	PQ	160	32	-	-	-	-
5	PQ	240	48	-	-	-	-
6	PV	0	0	600	0	183	-10

Table 4: Continue.

Branch Data								
Bus From	Bus To	rij[p.u.]	xij[p.u.]	b^{sh}_{ij} [p.u.]	S^{mzx}_{ij} [MVA]	c_{ij} [US$]	n^{o}_{ij}	n^{max}_{ij}
1	2	0.040	0.400	0.00	120	40	1	5
1	3	0.038	0.380	0.00	120	38	0	5
1	4	0.060	0.600	0.00	100	60	1	5
1	5	0.020	0.200	0.00	120	20	1	5
1	6	0.068	0.680	0.00	90	68	0	5
2	3	0.020	0.200	0.00	120	20	1	5
2	4	0.040	0.400	0.00	120	40	1	5
2	5	0.031	0.310	0.00	120	31	0	5
2	6	0.030	0.300	0.00	120	30	0	5
3	4	0.059	0.590	0.00	120	59	0	5
3	5	0.020	0.200	0.00	120	20	1	5
3	6	0.048	0.480	0.00	120	48	0	5
4	5	0.063	0.630	0.00	95	63	0	5
4	6	0.030	0.300	0.00	120	30	0	5
5	6	0.061	0.610	0.00	98	61	0	5

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