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Reactive Power Planning for Loss Minimization based on Harmony Search Algorithm

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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. Harmony Search Algorithm (HS) 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; Harmony Search Algorithm

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 [1-4]. 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 [5]. 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 [6]. 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. Harmony Search (HS) Algorithm is used to solve the optimization problem. Simulation results emphasis on the validity of the proposed method.

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:

$$J_1 = \sum_{k\in \grave{U}_1} \left(c_{0k} + c_{1k}\, q_k\right) u_k \tag{1}$$

Where, c_0 and c_1 are fixed and variable costs of locally reactive sources. q is amount of locally reactive source in bus K and u_k 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

$$P(V,\Theta,n)-P_G+P_D=0 \tag{5}$$

$$Q(V,\Theta,n)-Q_G+Q_D-q=0 \tag{6}$$

$$P_G^{min} \le P_G \le P_G^{max} \tag{7}$$

$$Q_G^{min} \le Q_G \le Q_G^{max} \tag{8}$$

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

$$(N+N0)S^{from} \le (N+N0)S^{max} \tag{10}$$

$$(N+N0)S^{to} \le (N+N0)S^{max} \tag{11}$$

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

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(V,Θ,n) and Q(V,Θ,n) in (5) , (6) are calculated as follows [7]:

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

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

The elements of bus admittance matrix (G and B) are calculated as follows [7]:

$$G=\left\{\begin{matrix} G_{ij}(n) = -\left(n_{ij}g_{ij} + n_{ij}^0 g_{ij}^0\right) \\ G_{ii}(n) = \sum_{j\in\Omega_1}\left(n_{ij}g_{ij} + n_{ij}^0 g_{ij}^0\right) \end{matrix}\right\} \tag{15}$$

$$B=\left\{\begin{matrix} B_{ij}(n) = -\left(n_{ij}b_{ij} + n_{ij}^0 b_{ij}^0\right) \\ B_{ii}(n) = b_i^{sh} + \sum_{j\in\Omega_1}\left[n_{ij}\left(b_{ij} + b_{ij}^{sh}\right) + n_{ij}^0\left(b_{ij}^0 + \left(b_{ij}^{sh}\right)^0\right)\right] \end{matrix}\right\} \tag{16}$$

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 Harmony Search Algorithm is used to solve the optimization problem. In the next section a brief introduction about HS is presented.

Harmony Search algorithm

Harmony search (HS) algorithm is based on natural musical performance processes that occur when a musician searches for a better state of harmony, such as during jazz improvisation. The engineers seek for a global solution as determined by an objective function, just like the musicians seek to find musically pleasing harmony as determined by an aesthetic [8]. In music improvisation, each player sounds any pitch within the possible range, together making one harmony vector. If all the pitches make a good solution, that experience is stored in each variable's memory, and the possibility to make a good solution is also increased next time. HS algorithm includes a number of optimization operators, such as the harmony memory (HM), the harmony memory size (HMS, number of solution vectors in harmony memory), the harmony memory considering rate (HMCR), and the pitch adjusting rate (PAR). In the HS algorithm, the harmony memory (HM) stores the feasible vectors, which are all in the feasible space. The harmony memory size determines how many vectors it stores. A new vector is generated by selecting the components of different vectors randomly in the harmony memory. For example, Consider a jazz trio composed of saxophone, double bass and guitar. There exist certain amount of preferable pitches in each musician's memory: saxophonist, {Do, Mi, Sol}; double bassist, {Si, Sol, Re}; and guitarist, {La, Fa, Do}. If saxophonist randomly plays {Sol} out of {Do, Mi, Sol}, double bassist {Si} out of {Si, Sol, Re}, and guitarist {Do} out of {La, Fa, Do}, that harmony (Sol, Si, Do) makes another harmony (musically C-7 chord). And if the new harmony is better than existing worst harmony in the HM, the new harmony is included in the HM and the worst harmony is excluded from the HM. This procedure is repeated until fantastic harmony is found. When a musician improvises one pitch, usually he (or she) follows any one of three rules: (1) playing any one pitch from his (or her) memory, (2) playing an adjacent pitch of one pitch from his (or her) memory, and (3) playing totally random pitch from the possible sound range [8]. Similarly, when each decision variable chooses one value in the HS algorithm, it follows any one of three rules: (1) choosing any one value from HS memory (defined as memory considerations), (2) choosing an adjacent value of one value from the HS memory (defined as pitch adjustments), and (3) choosing totally random value from the possible value range (defined as randomization). The three rules in HS algorithm are effectively directed using two parameters, i.e., harmony memory considering rate (HMCR) and pitch adjusting rate (PAR). The steps in the procedure of harmony search are as follows:

Step1. Initialize the problem and algorithm parameters.
Step2. Initialize the harmony memory (HM).
Step3. Improvise a new harmony from the HM.
Step4. Update the HM.
Step5. Repeat Steps 3 and 4 until the termination criterion is satisfied.

For better understanding, these steps are briefly described in the following subsections [9].

Initialize the problem and algorithm parameters

Specify the optimization problem as (23).

$$\text{minimise } f(x) \qquad (23)$$

$$\text{Subject to } x_i \in X_i \qquad i = 1,2,\ldots,N$$

Where $f(x)$ is an objective function, x is set of decision variables x_i, N is the number of decision variables and X_i represents the possible range of values for each decision variables.

The HS algorithm parameters to be initialized are as follows:

- Harmony memory size (HMS): this indicates the number of solution vectors in the harmony memory.
- HMCR.
- PAR.
- Number of improvisations (NI) or stopping criteria.

Initialize the harmony memory (HM)

The harmony memory is initialized with as many randomly generated vectors as the HMS as (24).

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \qquad (24)$$

Improvise a new harmony from the HM

A new harmony vector $x^t = (x_1^t, x_2^t, \ldots, x_i^t)$ is generated based on three rules as following:

memory consideration pitch adjustment random selection as (25)

$$x_i^t \leftarrow \begin{cases} x_i^t \in \{x_i^1, x_i^2, \ldots, x_i^{HMS}\} \text{ with probability HMCR} \\ x_i \in X_i \text{ with probability } (1 - \text{HMCR}) \end{cases} \qquad (25)$$

A HMCR of 0.90 indicates that the HS algorithm will choose the decision variable from the stored values in the HM with 90% probability and from the entire range with (100–90%) probability [9]. Every component chosen by harmony consideration is examined for pitch adjustment based on the following rule:

Pitch adjusting decision for x_i^t is given as (26).

$$x_i^t \leftarrow \begin{cases} \text{Yes with probability PAR} \\ \text{No with probability } (1 - \text{PAR}) \end{cases} \qquad (26)$$

The value of $(1 - PAR)$ sets the rate of doing nothing. If pitch adjustment decision for x_i^t is yes, x_i is modified as (27).

$$x_i^t = x_i^t + \text{rand}() * \text{bw} \qquad (27)$$

Where bw is an arbitrary distance bandwidth and rand() is a random number between 0 and 1.

The PAR and bw are adjusted as (28).

$$\text{PAR}(gn) = \text{PAR}_{min} + \frac{\text{PAR}_{max} - \text{PAR}_{min}}{\text{NI}} \times gn \qquad (28)$$

Where $gn = 1,2,\ldots,NI$, PAR(gn) is the pitch adjusting rate for generation or improvisation of gn . PAR_{min} is the minimum pitch adjusting rate and PAR_{max} is the maximum pitch adjusting rate [9].

To explore the search space, the control parameter bandwidth ‘bw’ is adjusted depending upon the variance of the population in each improvisation, and is given by (29).

$$\text{bw}(gn) = \sqrt{\text{var}(X)} \qquad (29)$$

Update the HM

The new memory is judged in terms of the objective function (fitness function) value and if the new memory is better than the previous memory in the HM, then new harmony memory is included in the HM and the existing worst harmony is excluded from the HM.

Check for stopping criteria

If maximum number of improvisations is reached, then stop, otherwise steps 3 and 4 are repeated.

Illustrative system

Figure 1 shows a typical electric power system. Graver modified system is considered as illustrative system. The system data are presented appendix [7]. The fixed and variable costs of locally reactive sources are as c_0 = 100$ and c1 = 0.3$/kvar, respectively. To implement HS, number of decision variables (N), Harmony memory size (HMS), number of improvisations (NI) and HMCR are chosen as 4, 60, 100 and 0.9 respectively. Also 110% and 90% of the nominal value are used for the maximum and minimum voltage magnitude limits.

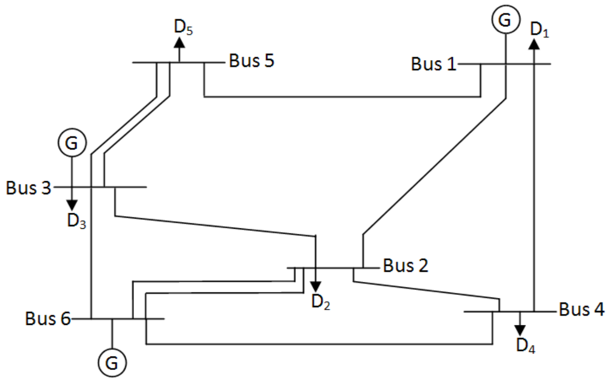

Fig. 1. Graver modified system

RESULTS and DISCUSSIONS

In this section the SVC placement based on the Harmony Search Algorithm is presented. The SVC places are accuracy calculated using HS 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.

CONCLUSION

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

Appendix

Table 4 shows the Modified Graver system data.

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	0.28564	0.28564	1.0
Bus1	Bus2	0.18139	0.18139	1.2
Bus5	Bus1	0.40865	0.40865	1.2
Bus2	Bus4	0.25747	0.25747	1.2
Bus3	Bus2	1.0426	1.0426	1.2
Bus3	Bus6	0.17303	0.17303	1.2
Bus5	Bus3	1.0842	1.0842	1.2
Bus5	Bus3	1.0842	1.0842	1.2
Bus2	Bus6	0.79619	0.79619	1.2
Bus2	Bus6	0.79619	0.79619	1.2
Bus4	Bus6	1.1324	1.1324	1.2

Table 3. Power flow results

Bus	(P_G-P_L) [MW]	(Q_G-Q_L) [MVAR]	V [p.u.]
Bus1	80	32	0.992
Bus2	-240	-48	0.956
Bus3	298.657	93	1.0214
Bus4	-160	2.5636	0.956
Bus5	-240	-41.5	0.95
Bus6	277.1496	120.0024	1.05

Table 4. Modified Graver system data

Bus Data							
Bus	Type	P_D [MW]	Q_D[MVar]	P_G^{max} [MW]	P_G^{min} [MW]	Q_G^{max} [MW]	Q_G^{min} [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

Branch Data

Bus From	Bus To	r_{ij}[p.u.]	x_{ij}[p.u.]	b_{ij}^{sh} [p.u.]	s_{ij}^{max} [MVA]	$c_{ij}[\text{US}\$]$	n_{ij}^{0}	n_{ij}^{max}
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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