Reactive Power Expansion Planning under a Deregulated Market Power System

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Abstract: In deregulated electric power systems, one of the most important topics is to augment the total system social welfare. Many different methods have been carried out for this problem. One of the most viable methods to increasing system social welfare is to supply the reactive demands as locally. In this way, the reactive demands are supplied via locally reactive sources and the capacity of transmission lines is not used to transfer reactive power of demands. Thus, the congestion of lines is not reached and the system social welfare which is related to the congestion of lines is increased. In this scope, this study addresses an optimal Reactive Power Planning (RPP) in a deregulated power system. The proposed method optimizes two objective functions at the same time within one general objective. The optimized objectives are minimization of total investment in reactive power support and maximizing of total system social welfare. Genetic Algorithm (GA) is used to solve the optimization problem. The validity of the proposed method is verified on a typical power system.

Keywords: Genetic algorithm, local marginal prices, reactive power planning, social welfare

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 (Mamandur and Chenoweth, 1981; Iyer et al., 1984; Conejo et al., 2001; Abdel-Moamen and Padhy, 2003). 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 by Miller (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.

As referred in last sections, RPP is performed in order to power system utilization in a better way. The proposed RPP can also be performed to improve power system social welfare. In this scope, this paper presents an optimal reactive power planning of power system using the Static Var Compensator (SVC) in a deregulated electricity market. The proposed planning optimizes two objective functions at the same time within one general objective. The optimized objectives are minimization of total system cost and maximizing of social welfare. GA 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 two different parameters are considered as objective function. These parameters are: total investment cost and social welfare.
Also the power system constraints such as generation reactive limits, voltage limits and etc, should be incorporated in the planning. Therefore, the objective functions are as follows:

\[ J_1 = \sum_{k \in \Omega} (c_{0k} + c_{1k} q_k) u_k \]  

(1)

\[ J_2 = \min \left( \sum_{k \in \Omega} \Pi_{Dk} x_{Pk}, \sum_{k \in \Omega} \Pi_{Gk} x_{Gk} \right) \]  

(2)

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 \( k \). \( \Pi_{Dk} \) and \( \Pi_{Gk} \) are demand and supply bids, respectively. \( P_D \) and \( P_G \) are demand and supply powers respectively. \( J_1 \) shows the investment cost due to locally reactive sources. \( J_2 \) shows the system social welfare.

Eventually, reactive power planning formulation can be represented as follows:

\[ \text{Min} \, \omega_1 J_1 + \omega_2 J_2 \]  

(3)

Subject to:

\[ P(V, \Theta, n) - P_D + P_G = 0 \]  

(4)

\[ Q(V, \Theta, n) - Q_G + Q_D - q = 0 \]  

(5)

\[ P_{\text{min}} \leq P_G \leq P_{\text{max}} \]  

(6)

\[ Q_{\text{min}} \leq Q_G \leq Q_{\text{max}} \]  

(7)

\[ V_{\text{min}} \leq V \leq V_{\text{max}} \]  

(8)

\[ (N+N_0)S_{\text{from}} \leq (N+N_0)S_{\text{max}} \]  

(9)

\[ (N+N_0)S_{\text{to}} \leq (N+N_0)S_{\text{max}} \]  

(10)

\[ q_{\text{min}} \leq q \leq q_{\text{max}} \]  

(11)

where, the coefficients \( \omega \) is a weighting factor. Equation (4) and (5) introduce the conventional equations of AC power flow and (6) and (7) show the limits for real and reactive power for generators. Equation (8) presents the limits for voltage magnitude. Capacity limits of the line flows are presented by (9) and (10). Equation (11) presents the limit for locally reactive sources.

The elements of vectors \( P(V, \Theta, n) \) and \( Q(V, \Theta, n) \) in (4), (5) are calculated as follows (Rider et al., 2007):

\[ P_j(V, \Theta, n) = V_i \sum_{j \in N_j} \left[ G_{ij}(n) \sin \theta_j + B_{ij}(n) \cos \theta_j \right] \]  

(12)

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

\[ G_{ij}(n) = \begin{cases} g_{ij} + g_{ij}^0 & \text{if } j \in \Omega, i \notin \Omega \\ g_{ij} + g_{ij}^0 & \text{if } j \notin \Omega, i \in \Omega \\ g_{ij} + g_{ij}^0 & \text{if } j \notin \Omega, i \notin \Omega \end{cases} \]  

(13)

\[ B_{ij}(n) = \begin{cases} b_{ij} + b_{ij}^0 & \text{if } j \in \Omega, i \notin \Omega \\ b_{ij} + b_{ij}^0 & \text{if } j \notin \Omega, i \in \Omega \\ b_{ij} + b_{ij}^0 & \text{if } j \notin \Omega, i \notin \Omega \end{cases} \]  

(14)

Elements (ij) of vectors \( S_{\text{from}} \) and \( S_{\text{to}} \) of (9) and (10) are given by the following relationship:

\[ S_{ij}^{\text{form}} = \sqrt{\left( P_{ij}^{\text{form}} \right)^2 + \left( Q_{ij}^{\text{form}} \right)^2} \]  

(16)

\[ S_{ij}^{\text{to}} = \sqrt{\left( P_{ij}^{\text{to}} \right)^2 + \left( Q_{ij}^{\text{to}} \right)^2} \]  

(17)

where,

\[ P_{ij}^{\text{form}} = V_i^2 g_{ij} - V_i V_j \left( g_{ij} \cos \theta_j + b_{ij} \sin \theta_j \right) \]  

(18)

\[ Q_{ij}^{\text{form}} = -V_i^2 \left( b_{ij} + b_j \right) - V_i V_j \left( g_{ij} \sin \theta_j - b_j \cos \theta_j \right) \]  

(19)

\[ P_{ij}^{\text{to}} = V_i^2 g_{ij} - V_i V_j \left( g_{ij} \cos \theta_j - b_j \sin \theta_j \right) \]  

(20)

\[ Q_{ij}^{\text{to}} = -V_i^2 \left( b_{ij} + b_j \right) - V_i V_j \left( g_{ij} \sin \theta_j + b_j \cos \theta_j \right) \]  

(21)

The proposed formulation in used to find the best place of SVCs. In this study GA is used to solve this optimization problem. In the next section a brief introduction about GA is presented.

**GENETIC ALGORITHMS**

Genetic Algorithms (GA) are global search techniques, based on the operations observed in natural selection and genetic (Randy and Sue, 2004). They
operate on a population of current approximations—the individuals—initially drawn at random, from which improvement is sought. Individuals are encoded as strings (Chromosomes) constructed over some particular alphabet, e.g., the binary alphabet \{0,1\}, so that chromosomes values are uniquely mapped onto the decision variable domain. Once the decision variable domain representation of the current population is calculated, individual performance is assumed according to the objective function which characterizes the problem to be solved. It is also possible to use the variable parameters directly to represent the chromosomes in the GA solution. At the reproduction stage, a fitness value is derived from the raw individual performance measure given by the objective function and used to bias the selection process. Highly fit individuals will have increasing opportunities to pass on genetically important material to successive generations. In this way, the genetic algorithms search from many points in the search space at once and yet continually narrow the focus of the search to the areas of the observed best performance. The selected individuals are then modified through the application of genetic operators. In order to obtain the next generation Genetic operators manipulate the characters (genes) that constitute the chromosomes directly, following the assumption that certain genes code, on average, for fitter individuals than other genes. Genetic operators can be divided into three main categories: Reproduction, crossover and mutation (Randy and Sue, 2004).

**Illustrative system**: Figure 1 shows a typical electric power system. IEEE 6-bus power system is considered as illustrative system. The system data are presented in Appendix. The fixed and variable costs of locally reactive sources are as \(c_0 = 100\) and \(c_1 = 0.3\$/kvar, respectively. Also 110 and 90\% of the nominal value are used for the maximum and minimum voltage magnitude limits.

**RESULTS AND DISCUSSION**

The proposed method is carried out on the test system given in section 4. The optimal places of reactive sources are accuracy obtained based on the proposed method by using GA. The results are listed in Table 1. The locally reactive sources are places near to load buses and it is due
Table 1: Locally reactive sources places

<table>
<thead>
<tr>
<th>Bus</th>
<th>Locally reactive source (Mvar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>-20.144</td>
</tr>
<tr>
<td>5</td>
<td>53.4674</td>
</tr>
<tr>
<td>6</td>
<td>-61.2244</td>
</tr>
</tbody>
</table>

Table 2: Power flow results

<table>
<thead>
<tr>
<th>Bus</th>
<th>(P_{ij}(\text{MW}))</th>
<th>(Q_{ij}(\text{MVAR}))</th>
<th>(V) [p.u.]</th>
<th>(\text{LMP} ) [$/Mwh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus1</td>
<td>90</td>
<td>38.690</td>
<td>1.1</td>
<td>6.8165</td>
</tr>
<tr>
<td>Bus2</td>
<td>137.402</td>
<td>97.700</td>
<td>1.1</td>
<td>6.8635</td>
</tr>
<tr>
<td>Bus3</td>
<td>63.81</td>
<td>108.88</td>
<td>1.1</td>
<td>6.8635</td>
</tr>
<tr>
<td>Bus4</td>
<td>-90</td>
<td>-80.140</td>
<td>1.027</td>
<td>7.1802</td>
</tr>
<tr>
<td>Bus5</td>
<td>-100</td>
<td>-66.530</td>
<td>1.016</td>
<td>7.3082</td>
</tr>
<tr>
<td>Bus6</td>
<td>-90</td>
<td>-121.22</td>
<td>1.009</td>
<td>7.2028</td>
</tr>
</tbody>
</table>

Total lost: 11.274 [MW]
Social welfare: 21.6138 [$/h]

Table 3: Flows in transmission lines

<table>
<thead>
<tr>
<th>From bus</th>
<th>To bus</th>
<th>(I_{ij}) [p.u.]</th>
<th>(I_{ji}) [p.u.]</th>
<th>(I_{ij\text{ max}}) [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus2</td>
<td>Bus3</td>
<td>0.13001</td>
<td>0.11748</td>
<td>0.3082</td>
</tr>
<tr>
<td>Bus3</td>
<td>Bus6</td>
<td>0.92341</td>
<td>0.95066</td>
<td>1.3973</td>
</tr>
<tr>
<td>Bus4</td>
<td>Bus5</td>
<td>0.08943</td>
<td>0.07907</td>
<td>0.1796</td>
</tr>
<tr>
<td>Bus5</td>
<td>Bus6</td>
<td>0.30182</td>
<td>0.33648</td>
<td>0.6585</td>
</tr>
<tr>
<td>Bus1</td>
<td>Bus2</td>
<td>0.01103</td>
<td>0.05973</td>
<td>0.2000</td>
</tr>
<tr>
<td>Bus3</td>
<td>Bus4</td>
<td>0.71413</td>
<td>0.72730</td>
<td>1.3740</td>
</tr>
<tr>
<td>Bus1</td>
<td>Bus4</td>
<td>0.13098</td>
<td>0.11153</td>
<td>0.2591</td>
</tr>
<tr>
<td>Bus1</td>
<td>Bus6</td>
<td>0.44553</td>
<td>0.47078</td>
<td>0.9193</td>
</tr>
<tr>
<td>Bus1</td>
<td>Bus5</td>
<td>0.38621</td>
<td>0.41505</td>
<td>0.8478</td>
</tr>
<tr>
<td>Bus2</td>
<td>Bus6</td>
<td>0.49788</td>
<td>0.52973</td>
<td>0.9147</td>
</tr>
<tr>
<td>Bus2</td>
<td>Bus5</td>
<td>0.32611</td>
<td>0.34906</td>
<td>0.7114</td>
</tr>
</tbody>
</table>

CONCLUSION

In this study a reactive power planning in a deregulated power system has been successfully carried out. In the proposed planning, the locally reactive sources have been replaced with considering cost and also local marginal prices. This planning results in increasing social welfare of network. The proposed method has been carried out on IEEE 6-bus test system. The GA approach has been used to solve the problem. By the proposed approach, more savings on the energy and installment costs achieved and breaking of the constraints (i.e., voltage and reactive power limits) eliminated.

Appendix: Table 4 shows the IEEE 6-bus system data. Also the data for electricity market are presented in Table 5.

ACKNOWLEDGMENT

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Table 5: IEEE 6-bus system data for market analysis

<table>
<thead>
<tr>
<th>Bus</th>
<th>MW offer</th>
<th>Price ($/Mwh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>9.7</td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>8.8</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

REFERENCES


