CHAPTER 3

OPTIMAL REACTIVE POWER DISPATCH

3.1 INTRODUCTION

The Optimal Reactive Power Dispatch (ORPD) problem is a non-linear optimization problem with many uncertainties. The reactive power is required for magnetizing purposes at no load conditions. The change of load causes variation in the reactive power requirement. The reactive power will depend on the voltage, so that the variation of the load causes the variation of the voltage. Hence the important operating task is to maintain the voltage within the allowable range for high quality consumer service. The objective of the ORPD to minimize the transmission line losses and improve the voltage profiles. The objective can be achieved by employing the various reactive compensation devices such as automatic voltage regulators (continuous variable), tap changing transformers, and shunt capacitors/reactors (discrete variables) (Mamundur and Chenoweth 1981). This is a complex combinatorial optimization problem involving non-linear functions having multiple local minima and non-linear and discontinuous constraints.

3.2 PROBLEM FORMULATION

3.2.1 Loss Minimization

In this research work, three cases are considered in ORPD problem.

Case-1: Loss minimization

Case-2: Improvement of voltage profile

Case-3: Voltage stability enhancement
Among them, the first one, loss minimization is dealt in this subsection.

### 3.2.1.1 Objective Function

The objective of the reactive power dispatch is to minimize the transmission line losses of the system. It can be described as follows:

\[
\min P_{loss} = \sum_{k \in N_E, k \neq (i,j)} g_k (V_i^2 + V_j^2 - 2V_i V_j \cos \theta_{ij})
\]  

The power loss is a non-linear function of bus voltages which are implicit functions of control variables (Abdul-Rahman et al 1995). The minimization problem is subject to operating constraints. The operating constraints are limits on the control variables and power flow.

### 3.2.1.2 Equality Constraints

The equality constraints are power flow equations and these constraints seek to find the set of voltages that satisfy the system conditions.

\[
0 = P_i - V_i \sum_{j \in N_i} V_j (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \quad i \in N_{B} \quad \text{(3.2)}
\]

\[
0 = Q_i - V_i \sum_{j \in N_i} V_j (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \quad i \in N_{PQ} \quad \text{(3.3)}
\]

### 3.2.1.3 Inequality Constraints

#### Bus voltage limits

The purpose of defining bus voltage limits are to keep the buses operating between desired per unit voltage limits and determine the reactive power production related to the voltage profile. Bus voltages are state
variables derived from the solution of the power flow problem. These constraints with respect to the bus voltage limits are defined as:

\[ V_{i_{\min}} \leq V_i \leq V_{i_{\max}} \quad i \in N_B \]  \hspace{1cm} (3.4)

**Transformer taps limits**

There are transformers that are capable of providing small adjustments to the output voltage by changing their turns ratio or taps. Transformers that can perform this operation while energized are called on-load-tap-changing (OLTC) transformers. These taps can be changed within a range usually of \( \pm 10\% \). These bounds can be defined as:

\[ T_{k_{\min}} \leq T_k \leq T_{k_{\max}} \quad k \in N_T \]  \hspace{1cm} (3.5)

**Capacitor bank limits**

Capacitor banks can adjust their capacity by connecting/disconnecting some of the capacitors. These have a region of operation with lower and upper limits and defined as:

\[ Q_{ci_{\min}} \leq Q_c \leq Q_{ci_{\max}} \quad i = 1, \ldots, N_c \]  \hspace{1cm} (3.6)

**3.2.1.4 Fitness Function**

Fitness function is directly obtained from the objective function. Transformer tap-setting \( T \) and generator bus voltages \( V_g \) are control variables that are self-restricted. Load bus voltages \( V_{load} \) and reactive power generations \( Q_g \) are state variables, which are restricted by adding them as the quadratic penalty terms to the objective function to form a generalized objective function as:
min \( f = P_{\text{loss}} + \sum_{i=1}^{N} \lambda_{V_i} (V_i - V_i^{\text{lim}})^2 + \sum_{i=1}^{N} \lambda_{Q_{gi}} (Q_{gi} - Q_{gi}^{\text{lim}})^2 \) \hspace{1cm} (3.7)

\( V_i^{\text{lim}} \) and \( Q_{gi}^{\text{lim}} \) are defined as:

\[
V_i^{\text{lim}} = \begin{cases} 
V_i^{\text{min}} & \text{if } V_i < V_i^{\text{min}} \\
V_i^{\text{max}} & \text{if } V_i > V_i^{\text{max}}
\end{cases}
\] \hspace{1cm} (3.8)

\[
Q_{gi}^{\text{lim}} = \begin{cases} 
Q_{gi}^{\text{min}} & \text{if } Q_{gi} < Q_{gi}^{\text{min}} \\
Q_{gi}^{\text{max}} & \text{if } Q_{gi} > Q_{gi}^{\text{max}}
\end{cases}
\] \hspace{1cm} (3.9)

The above generalized objective function in equation (3.7) is used as fitness function. The objective function of the target power system is calculated using load flow calculation with the above-mentioned equality and inequality constraints.

**3.2.2 Improvement of Voltage Profile**

The objective of ORPD is not only to minimize the real power loss but also to improve the voltage profile of the system. Bus voltage is one of the most important security and service quality indices. Considering only loss-based objectives in ORPD problem may result in a feasible solution that has unattractive voltage profile. So, in this case a two-fold objective function (Abido 2002) will be considered in order to minimize the loss and improve the voltage profile by minimizing the load bus voltage deviations from 1.0 per unit. To achieve this, the objective function in equation (3.1) is modified as:

\[
J = P_{\text{loss}} + \eta \sum_{i=1}^{N_{PQ}} |V_i - 1.0|
\] \hspace{1cm} (3.10)

With this penalty, the objective function will attempt to minimize the real power loss while trying to maintain the load voltages close to 1.0 p.u.
3.2.3 Voltage Stability Enhancement

Voltage stability is concerned with the ability of a power system to maintain acceptable voltages in the system under normal operating conditions and after being subjected to a disturbance. A system enters a state of voltage instability when a disturbance causes a progressive and uncontrollable decline in voltage. Hence it is important to optimize power system operation, while maintaining system security and quality of supply to consumers. Ideally, all load nodes have a voltage of 1.0 p.u. It is very important characteristic to maintain constantly acceptable bus voltage at each bus under normal operating conditions, after load increase, following system configuration changes, or when the system is being subjected to a disturbance. The non-optimized control variables may lead to progressive and uncontrollable drop in voltage resulting in an eventual wide-spread voltage collapse. Enhancing voltage stability profile, through out the whole power network, can be achieved through minimizing the voltage stability indicator \( L \)-index values at every bus of the system and consequently the global power system \( L \)-index. In order to improve the voltage stability and move the system operating far from the voltage collapse point, the objective function in equation (3.1) is modified as two-fold objective function (Abido 2002) and defined as:

\[
J = P_{\text{loss}} + \frac{\gamma}{2} L_{\text{max}} \tag{3.11}
\]

Using the load flow results, \( L \)-index for any load bus is computed as:

\[
L_j = \left| 1 - \sum_{i=1}^{N_{\text{pq}}} F_{ji} \frac{V_i}{V_j} \angle (\theta_q + \delta_i - \delta_j) \right| \quad \text{and} \quad F_{ji} = - \left[ Y_{ji} \right]^{-1} \left[ Y_{ji} \right] \tag{3.12}
\]

\[
F_{ji} = - \left[ Y_{ji} \right]^{-1} \left[ Y_{ji} \right] \tag{3.13}
\]
3.3 DESCRIPTION OF TEST SYSTEMS

In order to evaluate the performance of the existing and proposed algorithms, three standard test systems having non-linear characteristics are chosen. The first test system is IEEE 14 bus system. It consists of five generator buses (bus 1 is slack bus, buses 2, 3, 6 and 8 are with continuous operating values), 9 load buses and 20 lines in which 3 lines (4–7, 4–9 and 5–6) are tap changing transformers with discrete operating values. In addition, buses 9 and 14 are selected as shunt VAR compensation buses with discrete operating values. In the IEEE 14 bus system, totally 10 control variables are taken for optimal reactive power dispatch. The line parameters and the loads are taken from (Yoshida et al 2000). The total loads are $P_{\text{load}} = 259$ MW and $Q_{\text{load}} = 73.5$ MVAR. The initial generations are $P_{\text{Generation}} = 272.49$ MW and $Q_{\text{Generation}} = 78.5$ MVAR. The initial transmission line loss is 13.49 MW for the base case. The initial voltage deviations are 0.0345 p.u and the initial max. $L$-index value is 0.1430. The values of network parameters are given in Appendix 1.

The second test system is IEEE 30 bus system. It consists of six generator buses (bus 1 is slack bus, buses 2, 5, 8, 11 and 13 are with continuous operating values), 24 load buses and 41 lines in which 4 lines are tap changing transformers with discrete operating values. In addition, buses 10, 12, 15, 17, 20, 21, 23, 24 and 29 have been selected as shunt VAR compensation buses. In IEEE 30 bus system, totally 19 control variables are taken for optimal reactive power dispatch. The line parameters and loads were taken from (Lee et al 1985). The total loads are $P_{\text{load}} = 283.4$ MW and $Q_{\text{load}} = 126.2$ MVAR. The initial generations are $P_{\text{Generation}} = 289.211$ MW and $Q_{\text{Generation}} = 156.397$ MVAR. The initial transmission line loss is 5.817 MW. The initial voltage deviations are 1.1554 p.u and the initial max. $L$-index value is 0.1681. The values of network parameters are given in Appendix 2.
To test the potential of proposed algorithms in solving bigger systems, a standard IEEE 118 bus test system is considered. The system has 54 generator buses, 64 load buses and 186 transmission lines of which nine lines are tap changing transformers with discrete operating values. In addition, 12 buses have been selected as shunt VAR compensation buses. In IEEE 118 bus system, totally 75 control variables are taken for optimal reactive power dispatch. The line parameters and loads were taken from (Vlachogiannis and Lee 2006). The total loads are $P_{\text{load}} = 4242$ MW and $Q_{\text{load}} = 1438$ MVAR. The initial generations are $P_{\text{Generation}} = 4374.45$ MW and $Q_{\text{Generation}} = 881.92$ MVAR. The initial transmission line loss is 132.45 MW. The initial voltage deviations are 3.5612 p.u and the initial max. $L$-index value is 0.3122. The values of network parameters are given in Appendix 3. The control variables setting for the test systems are given in Appendix 4.

The proposed approaches were implemented to solve ORPD problem using software package, MATLAB 6.5 on a Pentium dual core, 1.86 GHz, processor.

3.4 CONCLUSION

The ORPD problem formulation is presented in this chapter. The equality and inequality constraints, objective function, and fitness function are described. The need for improvement of voltage profiles and voltage stability enhancement are discussed. Three standard test systems which are used for evaluating the performance of the proposed methods are also given.