CHAPTER 4

ELEGANT FACTS PLACEMENT STRATEGIES

4.1 GENERAL

Modern power systems are over expanded and getting complex due to ever-increasing power demand as a result of economic growth and industrial automation. They become very difficult to operate and insecure with unscheduled power flows, higher loss, which is about 5-13% of the total generated power (Asian Development Bank 1985) and poor voltage profile. In addition, they operate dangerously close to their voltage stability limits.

Voltage Stability is concerned with the ability of assessing the power system to maintain acceptable voltages at all system buses under normal conditions and after being subjected to disturbances. The lack of new transmission facilities, inadequate reactive power support, cutbacks in system maintenance, workforce downsizing, unpredicted power flow patterns, just to name a few, are some of the important factors that affect the stability of the system. Voltage collapse, a major threat for power system operation, can appear quite abruptly in systems or sub-systems due to the continuously-changing operating conditions and various unforeseen factors associated with large power systems. It is well known that unlike angle instability, voltage instability often starts in a local network and gradually extends to the whole system. This attribute slows down the process of system losing VS compared to that of losing angle stability, and allows time for a mechanism to predict static VS (Kundur 1993; Taylor 1994).

The process of voltage instability is generally triggered by some form of disturbance or change in the operating conditions that create an increased demand for reactive power, which is in excess of what the system is capable of supplying. Even if the reactive power support is physically far away, voltage collapse may occur in the system. The problem of voltage instability propounds to assume great significance to the utilities necessitating its prediction, prevention and necessary corrections to accomplish stable operation. The other problems are increased losses, poor voltage profile, unwanted loop flows and line overloads. The control of voltage level is accomplished by controlling the production, absorption and flow of reactive power at all levels in the system. Optimal real and reactive power dispatch and the installation of reactive power sources at appropriate buses can minimize the losses, improve the voltage profile and enhance the voltage stability (Kumar et al 2013). The other strategies involve control over line parameters through the use of FACTS devices, which allow the operation of the power systems more flexible, secure and economical through controlling various electrical parameters of transmission circuits. However, the decision on the size, the locations and their parameters is of great significance in obtaining the benefits of the FACTS devices (Hingorani, and Gyugyi 2000; Zhang et al 2006).

The placement of FACTS devices can be described as an optimization problem with an objective of minimizing a cost function while satisfying system constraints. Owing to rigorous constraints, the FACTS placement problem may be a non-convex and nonlinear problem, and becomes the most challenging optimization problem in power systems. This chapter is thus oriented towards developing a new methodology for solving FACTS placement problem with a view of reducing network loss, improve voltage profile and enhance voltage stability.

4.2 PROPOSED METHOD

The aim of this chapter is to develop methodologies for placing appropriate FACTS devices at the best possible locations with optimal parameter settings with a view of enhancing the performances of the power system. Three different FACTS devices one from each type with specific characteristics are selected to place them at suitable locations in order to control active power flows and reactive power injections in the PM. They are SVC, TCSC and UPFC. Only one type of FACTS device may be allowed at each line. The proposed method uses BBO (Pl refer appendix 1) besides exploiting a repair algorithm that avoids placing two or more FACTS devices on a line.

4.2.1 Mathematical Modelling

The active and reactive power flow from bus i to j through transmission line-m may be approximated by the following equations

$$P_{ij} = \frac{V_i V_j}{x_{ij}} \sin \delta_{ij} \tag{4.1}$$

$$Q_{ij} = \frac{1}{x_{ij}} (V_i^2 - V_i V_j \cos \delta_{ij}) \tag{4.2}$$

Under normal operating conditions for high voltage transmission systems, the voltage at any two buses are approximately equal and the voltage angle difference between any two buses are very small, which decouples the active and reactive power flow through any line. Active and reactive power flows depend only on the voltage angle difference and voltage magnitude difference respectively. However, both of them can be controlled by varying the line reactance.

TCSC acts either as a capacitive or inductive compensator by modifying the reactance of the transmission line, thereby changes line flow. The net reactance x_{ij}' of the transmission line-m, connected between buses i and j, after inclusion of TCSC can be written as

$$x_{ij}' = x_{ij} + x_F \tag{4.3}$$

where

$x_F = \eta_k \, x_{ij}$ the reactance of the FACTS device

η_k line compensation factor in the range of (-0.8, 0.2) to avoid overcompensation

The SVC is shunt connected static VAR generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of electrical power system, typically a bus voltage. The change in reactive power at bus-i with SVC can be represented as

$$\Delta Q_i = Q_F \tag{4.4}$$

UPFC consists of two converters. The series converter injects a voltage that alters the line reactance, thereby controls active power flow and the shunt converter independently supplies or absorbs the reactive power. In the existing UPFC model, converters are replaced by voltage or current sources, which in turn change the corresponding Jacobian elements in accordance with the changes in the real and reactive bus power injections. It is modelled as a combination of SVC and TCSC through Equations. (4.3) and (4.4) in order to avoid alteration of the Jacobian and power flow structure in this thesis.

4.2.2 Problem Formulation

The objective of this problem may be to reduce the power loss, minimize the voltage magnitude deviation and maximize the voltage stability margin. The constraints may include limits on FACTS device parameters, power flow, limits on reactive power generation at PV buses and voltage constraints.

The FACTS placement problem is formulated as an optimization problem of minimizing one or more objectives, while satisfying several equality and inequality constraints as

$$\text{Minimize} \quad \Phi(x,u) \tag{4.5}$$

Subject to

$$g(x,u) = 0 \tag{4.6}$$

$$h(x,u) \leq 0 \tag{4.7}$$

where x is the vector of dependent variables comprising of real and reactive power generations at slack bus, reactive power generation at PV buses and network loss. u is the vector of control or independent variables consisting of the type of FACTS devices, location for FACTS installation , FACTS parameters, generator bus voltage magnitudes, transformer tap settings, real and reactive power loads and real power generation at PV buses.

The equality constraints g(x, u) are the set of non linear power flow equations that govern the power system

$$P(V,\delta) - P^{sp} = 0 \qquad \text{for PV and PQ buses} \tag{4.8}$$

$$Q(V,\delta) - Q^{sp} = 0 \qquad \text{for PQ buses} \tag{4.9}$$

The inequality constraints $h(x,u)$ represent the limits on FACTS device parameters, limits on reactive power generation at PV buses and boundaries on voltage magnitudes

FACTS device constraints

$$-0.8 \le \eta_k \le 0.2 \qquad \text{for TCSC} \tag{4.10}$$

$$-100\,MVAR \le Q_{Fi} \le +100\,MVAR \quad \text{for SVC} \tag{4.11}$$

Equations (4.10) and (4.11) for UPFC (4.12)

Reactive power generation constraints

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \qquad \text{at PV buses} \tag{4.13}$$

Voltage constraints

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad \text{at PQ buses} \tag{4.14}$$

The objective function $\Phi(x,u)$ can take different forms. Four different cases involving real power loss, voltage deviations and voltage stability are considered in forming the objective functions.

Case-1: Minimization of Real power loss

$$\text{Minimize} \quad \Phi(x,u) = \sum_{k=1}^{nl} g_k (V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij}) \tag{4.15}$$

Case-2: Minimization of Voltage deviations

The solutions of case-1 will attempt to minimize the network loss while bringing the load bus voltage within the lower and upper voltage limits of Equation (4.14). The load bus voltage can be brought to the normal value of 1.0 per unit through tailoring the objective function for minimizing the sum of deviations of all load bus voltages from the nominal voltage of 1.0 per unit. The objective function is formulated as

$$\text{Minimize}\,\Phi(x,u)=\sum_{i=1}^{nload}(\exp\{\psi(|1-V_i|)\}-1) \tag{4.16}$$

Case-3: Minimization of Real power loss and voltage deviations

The FACTS placement problem with an objective of minimizing voltage deviations Equation (4.16), offers a solution that enhances the voltage profile through placing FACTS devices at appropriate transmission lines. This is achieved by altering the network parameters and injecting or absorbing reactive power at appropriate lines, which may increase the transmission losses. It necessitates reducing the network loss in addition to enhancing the voltage profile. The increase in power loss can however be controlled by blending both the net voltage deviations and the network loss as a bi-objective function of Equation (4.17).

$$\begin{aligned} &\textit{Minimize} \quad \Phi(x,u) = w_1\{\sum_{k=1}^{nl} g_k(V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij})\} \\ &+ w_2[\sum_{i=1}^{nload}(\exp\{\psi(|1-V_i|)\}-1)] \end{aligned} \tag{4.17}$$

Case-4: Minimization of Real power loss, voltage deviation and enhancement of voltage stability

Though the problem comprising the objective of Equation (4.17) reduces the network loss and improves the voltage profile, it may not indicate the enhancement of voltage stability, which can be accessed through the RVI indicator (L_i) of Equation (2.14). The maximum value of this indicator, close to one, is indicative of the proximity to power flow divergence, which is prone to voltage collapse. The minimum value, close to zero, is indicative of the most stable state. The objective of Equation (4.17) is modified to include a term that represents VS of the power system as

$$\begin{aligned} Minimize \quad \Phi(x,u) &= w_1\{\sum_{k=1}^{nl} g_k(V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij})\} \\ &+ w_2[\sum_{i=1}^{nload}(\exp\{\psi(|1-V_i|)\} - 1)] + w_3\sum_{i=1}^{nload} L_i \end{aligned} \tag{4.18}$$

where

L_i = RVI indicator at i-th load bus

w_1, w_2 and w_3 are the weight constants

The FACTS placement problem can be solved using proposed strategy BBO with any one of the objective functions, defined through four different cases along with constraints of Equations (4.8)- (4.14). The solution process involves identification of control variables, formation of a *HSI* function and execution of the algorithm through migration and mutation operations till convergence, which are explained in the following sections.

4.2.3 Representation of BBO Variables

Each island in the PM is defined to denote the type of the devices, their locations and parameters in matrix form as shown in Figure. 4.1.

T_1	T_2	T_3	$\cdots$	T_{nf}
L_1	L_2	L_3	$\cdots$	L_{nf}
η_1	η_2	η_3	$\cdots$	η_{nf}
$Q_F^{\ 1}$	$Q_F^{\ 2}$	$Q_F^{\ 3}$	$\cdots$	$Q_F^{\ nf}$

Figure 4.1 Representation of decision variables

The first row contains integer numbers in the range of (1-3) and represents the type T_k of the FACTS devices. In this formulation, 1 represents SVC, 2 denotes TCSC and 3 indicates UPFC. The second row corresponds to the location of the devices. It represents the numbers of the line L_k where the devices are to be located. The shunt devices are connected at the starting bus of the chosen line. The third and fourth rows correspond to line compensation factor η_k and injected reactive power $Q_F^{\ k}$ respectively. The parameter that is not required for a particular type of device is ignored. The problem variables contain both integer value for representing T_k and L_k and real values to denote η_k and $Q_F^{\ k}$ but the BBO algorithm deals with real numbers. Therefore, the values in the first two rows are rounded off to the nearest integer values.

4.2.4 Repair Algorithm

It is undesirable to fix two or more FACTS devices at a line. During the iterative process, there is a possibility that a solution point may contain same line numbers in the second row of Figure 4.1. If this happens, it may be corrected by the following repair mechanism.

- Alter any one line number by generating a random number to represent another line.

- Repeat the above step till no two numbers in the second row is same.

4.2.5 Fitness Function

Case-1

The solution of the island can be limited to satisfy the constraints of Equation (4.10)-(4.12) and the constraints of Equations (4.8), (4.9) and (4.13) are taken care of by the load flow algorithm during the search process. The constraint on bus voltages at load buses of Equation (4.14) can only be controlled through penalizing the problem objective, if they violate. The augmented objective function that blends both the problem objective and the load voltage, is formulated as

$$\Psi_1 = W_1[\sum_{k=1}^{nl} g_k (V_i + V_J - 2V_i V_j \cos\delta_{ij})] + W_2 \sum_{i=1}^{nload} V_{di} \tag{4.19}$$

where

$$V_{di} = \begin{cases} 0 & if\ V_i \in \left[V_i^{\min}, V_i^{\max}\right] \\ \exp\{\Psi_v\ (|1 - V_i| - 0.05)\} - 1 & if\ V_i \notin \left[V_i^{\min}, V_i^{\max}\right] \end{cases} \tag{4.20}$$

The value of V_{di} equals to zero if the voltage magnitude falls between the lower and upper voltage limits. Outside the range, it increases exponentially with the voltage deviations. The coefficient Ψ_v is used to adjust the slope of the exponential function.

The proposed strategy BBO searches for optimal solution by maximizing a fitness function, denoted by HSI, which measures the quality of the solution of an island. The HSI is problem dependant and obtained by suitably converting the objective function into a maximization function as

$$\text{Maximize} \qquad HSI = \frac{1}{1+\Psi_1} \tag{4.21}$$

The penalty term reduces the HSI of the island depending on the magnitude of the violation. This penalty approach does not disregard infeasible solutions; instead it uses these solutions in such a way as to aid the search process. Sometimes these infeasible solutions may provide much more useful information about the optimum than the feasible solutions.

Case-2

The objective of Equation (4.17) and the constraints of Equations (4.10)-(4.13) represent the FACTS placement problem that attempts to bring the voltage magnitude of all load buses to the nominal value of 1.0 per unit. In this case, the constraints are controlled by variable limit adjustment in BBO and through load flow algorithm. There is no constraint to be included in the objective function as penalty terms. The HSI function can therefore be written using Equation (4.17) as

$$\text{Maximize} \qquad HSI = \frac{1}{1+\Psi_2} \tag{4.22}$$

where

$$\Psi_2 = [\sum_{i=1}^{nload}(\exp\{\psi(|1-V_i|)\}-1)]$$

Case -3

The objective of Equation (4.17) and the constraints of Equations (4.10)-(4.13) represent the FACTS placement problem that attempts to bring the voltage magnitude of all load buses to the nominal value of 1.0 per unit and simultaneously reduce the network loss. In this case, the HSI function can be developed as

$$\text{Maximize} \qquad HSI = \frac{1}{1+\Psi_3} \tag{4.23}$$

where

$$\Psi_3 = w_1\{\sum_{k=1}^{nl} g_k(V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij})\}$$
$$+ w_2[\sum_{i=1}^{nload}(\exp\{\psi(|1-V_i|)\}-1)]$$

Case-4

The objective of Equation (4.18) and the constraints of Equations (4.10)-(4.13) represent the FACTS placement problem that attempts to bring the voltage magnitude of all load buses to the nominal value of 1.0 per unit and simultaneously reduce the network loss and enhance VS. In this case, the HSI function can be built as

$$\text{Maximize} \qquad HSI = \frac{1}{1+\Psi_4} \tag{4.24}$$

where

$$\Psi_4 = w_1\{\sum_{k=1}^{nl} g_k (V_i^2 + V_j^2 - 2V_iV_j \cos \delta_{ij})\}$$
$$+ w_2[\sum_{i=1}^{nload} (\exp\{ \psi(|1 - V_i|)\} - 1)] + w_3 \sum_{i=1}^{nload} L_i$$

4.2.6 Stopping Criterion

The process of generating new population can be terminated either after a fixed number of iterations or if there is no further significant improvement in the global best solution.

4.2.7 Solution Process

An initial population of habitats is obtained by generating random values within their respective limits to every individual in the population. The *HSI* is calculated by considering *SIVs* of each habitat and the migration and mutation operations are performed for non-elite habitats with a view of maximizing the *HSI*. The iterative process is continued till convergence. The flow of the proposed strategy is shown in Figure 4.2.

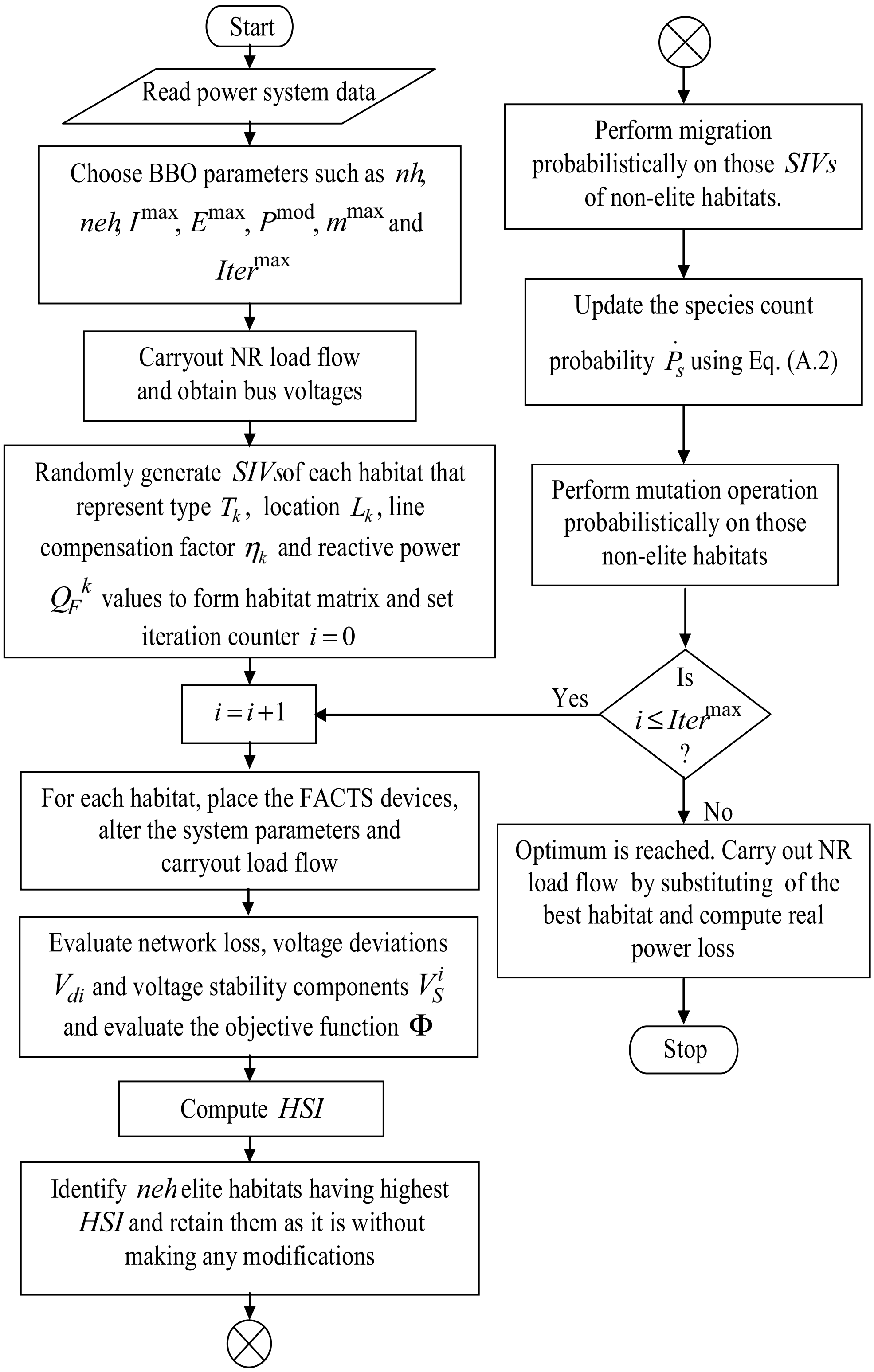

Figure 4.2 Flow chart of the proposed strategy

4.3 SUMMARY

An elegant BBO based method for FACTS placement with different objectives of reducing the network loss, improving voltage profile and enhancing the voltage stability has been proposed. This approach has been developed to identify the best locations, appropriate FACTS devices and their optimal parameters to obtain the desired performances.