CHAPTER 2

Optimal Power Flow with FACTS controller

2.1 Flexible AC Transmission System controller

At the present, the electrical power systems are large and very complex. They have many buses between a thousand or more. In additional, they have many generator more than a hundred devices, too. The installation of new power plants or transmission networks can help these requirements. However, there are some problems with these constructions, for examples, environment and pollution control, the cost of installation, and the land acquisition. The alternative solutions to respond these increasing demands are to improve the efficiency of power transfer capability in the power system using Flexible AC Transmission System (FACTS) controller [24]. The advantages of FACTS controller include less pollution, more acceptable of people who lived in the installed area, and less cost of installation. In addition, parameters of FACTS controllers can be adjusted to provide adaptability for the future planning of the transmission network.

The developments of FACTS controller are now favorite and popular [25]. These FACTS controller can increase the stability in electrical power system. These FACTS controller can increase the flexibility of power system, too. FACT controllers have been developed by Electric Power Research Institute (EPRI) and Westinghouse Electric Corporation. These can respond the demand of electricity and reach the maximum performance of electrical power system. Moreover, the modern FACTS controllers have the extend ability to control power flow in both steady state and dynamic state [26].

The standards of FACTS controller are regulated by IEEE (Institute of Electrical and Electronics Engineers) which define as AC power flow systems operating bases on power electronics device and control device. In additional, these devices can extend the control and enhance power flow capability.

According to the regulation, the objectives of these devices are

- enhance power flow in electrical power system

- increasing power flow from base case

There are many types of FACTS controller. For example, Static VAR Compensator (SVC), Static Synchronous Compensator (STATCOM), Thyristor-Controlled Series Capacitor (TCSC), Thyristor-controlled Phase Shifter (TCPS), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC). These FACTS controller are wellknown as connectable devices which can be used in series connection: SVC or STATCOM, shunt connection: TCSC and TCPS or both serial and shunt connection: UPFC.

This chapter presents the overview of FACTS controller which are used in this thesis. The basic structure and principles of FACT controllers, Static Var Compensator (SVC), Thyristor Controlled Phase Shifter (TCPS), Thyristor Controlled Series Capacitor (TCSC), and Unified Power Flow Controller (UPFC) are described in the following sections.

2.1.1 Static VAR Compensator: SVC

A static VAR compensator: SVC is one wellknown type of FACTS controller. SVC can provide fast-acting reactive power on high-voltage electricity transmission networks. Moreover, SVC can control regulating voltage, power factor, harmonics and stabilizing the system. Different from the synchronous condenser which is a rotating electrical machine, SVC has no significant moving parts. Prior to the invention of the SVC, power factor compensation are the preserves of large rotating machines such as synchronous condensers or switched capacitor banks. Basic structure of SVC is shown in Figure 2.1

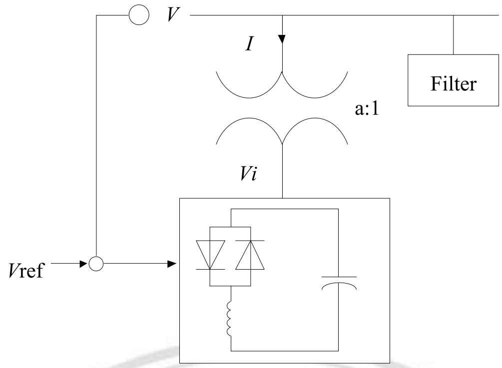

Figure 2.1 Basic structure of SVC.

Basic structure of SVC includes

- Fix Capacitor (FC) which provide permanent reactive power source

- Thyristor Controlled Reactor: TCR

- Thyristor Switch Capacitor: TSC

With FC type, it has main component less than TCR and TSC type. The disadvantage of this type is that it generates more loss than TCR and TSC type. TVR and TSC type use step switching to prevent switching losses. The choice of optimize decision is to take into account the price of equipment and investments. In additional, the return benefits like minimum losses, voltage stability, and etc.

2.1.2 Thyristor-controlled Phase Shifter: TCPS

Basic operating of Thyristor-controlled Phase Shifter: TCPS is to control power flow by inserting adaptive quadrature voltage into the transmission line. The effectiveness of this operating effect that power flow is one part of phase difference ratio between buses in transmission line. The adaptive quadrature voltage will be controlled and adopted by series connection of TCPS.

Benefit of TCPS in the view of transients

- can control oscillation of system

- reduce transient or drop voltage which cause heavy load in transmission line

- reduce heavy power flows which are generated by abnormal state

Basic structure of TCPS is shown in Figure 2.2

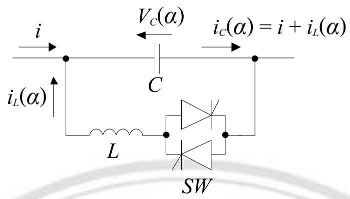

Figure 2.2 Basic structure of TCPS.

2.1.3 Thyristor Controlled Series Compensator: TCSC

In facts, the effective power flow between source and sink areas can be controlled by adapt series impedances. The conventional method is to install the series capacitors. These series capacitors can reduce series impedances which can increase the power flow. The limitations of this method are slow switching, discontinuous of mechanical switches. The thyristor controllers are developed. The advantages of this type device are fast switching and continuous operating. These effects to increase more control flexibility and this type device are developed to Thyristor Controlled Series Compensator: TCSC. TCSC uses parallel TCR with shunt capacitor. Basic structure of TCSC is shown in Figure 2.3

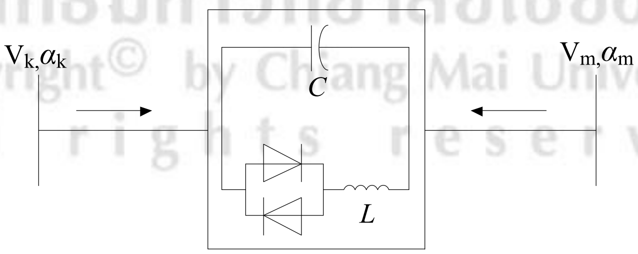

Figure 2.3 Basic structure of TCSC.

2.1.4 Unified power Flow Controller: UPFC

At the present day, it is already known that Unified Power Flow Controller: UPFC has capable and useful for power flow control. These capable are to adapt power flow. The response time is close to immediately response which is suitable to apply to any steady state power flow control or dynamic stability. UPFC includes two inverter sources. The first is the shunt connector and the second is series connector. The basic structure of UPFC is shown in Figure 2.4.

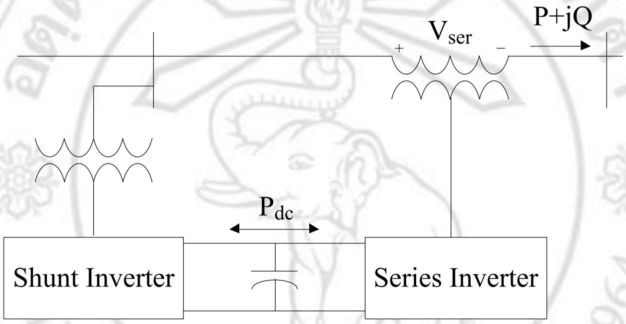

Figure 2.4 Basic structure of UPFC.

Both inverters work by using the same DC link which collect the DC current into capacitor. This enables UPFC to control real power and reactive power in line and bus voltage. The real power can flow freely between AC current connector of both inverters by DC link. The individual inverter can absorb or inject reactive power up to the minimum specific increase voltage and maximum line current which power can flow without any violating.

Each shunt inverter provides its voltage control at the specific bus when the joint operating appears. The shunt inverter has two functions,

- control bus voltage by increasing reactive power into system

- provide real power into series inverter DC link for series power flow control

Another aspect of series inverter is voltage controlling by increasing the AC voltage. This can control by magnitude and phase frequency at line pass through power transformer. The increase voltage effects as AC synchronous generator which can provide series compensation into line. Moreover, this can control regulate power angle through line current. This effect causes the exchange of active and reactive power between inverter and AC system. The AC active current is exchanged at AC series connector and change to DC current by inverter and appear at DC link connector. After that, the DC current is changed to reactive power which will absorb or inject up to the system demand and pass through the converter.

In fact, the operating of UPFC is highly important by its effect. This can effect to both line flow and voltage magnitude. In order to make UPFC works fully, the limitations of the implementation and control conditions must be considered.

2.2 Applications of FACTS controller

FACTS controllers are widely used in any electrical power system with different objectives. Examples of single-objective function are economics dispatch, enhancing power transfer capability, minimizing losses, and any power flow problem..

Examples of compound objective are minimizing cost of FACTS controller and minimizing pollution, and minimizing cost of FACTS controller and maximizing power transfer capability, and other combination objective functions.

Examples of three compound objective functions are minimize cost of FACTS controller, maximizing power transfer capability and minimizing pollution of power generators, minimizing cost of FACTS controller, maximizing power transfer capability and minimizing losses, and other combination objective functions.

The main concept of applications of FACTS controller is not only setting the objective function but also placing FACTS controller in the power system. The optimal allocations such as type of FACTS controller, sizing of FACTS controller and location of FACTS controller are extremely important. Moreover, the suitable operating points of used FACTS controllers are important, too. These parameters of FACTS controller can be limited by equality and inequality constraint.

There is the wellknown conventional methods named linear programming (LP) which is used to determine allocation of FACTS controller. Moreover, any conventional method and the modern heuristic method such as genetic algorithm (GA), evolutionary programming (EP), simulated annealing (SA), and particle swarm optimization (PSO) are used, too. In this thesis, the optimal allocation of FACTS controller will be determined by hybrid particle swarm optimization which is explained in chapter 3.

2.3 Optimal Power Flow

An important point for solving the power flow is appropriate to analyze the flow of power in a steady state [27-29]. The main point is to consider the objective function including the boundary conditions. These boundary conditions are used with control variables and state variables to limit the value of variables. The limit means minimum and maximum value of all variables. This concept is generally used to control the power flow under optimal feasible operating. The general concept which is used to conduct the power flow problem is to maximize or minimize objective function. This can describe as follows.

$$\text{Min/Max } f(x,u) \tag{2.1}$$

subject to

$$g(x,u)=0, \tag{2.2}$$

$$h(x,u)\le 0. \tag{2.3}$$

where

$f(x,u)$	objective function,
$g(x,u)$	equality constraint,
$h(x,u)$	inequality constraint,
x	state variables, and
u	control variables, respectively

2.3.1 Objective function

The objective function is defined by mathematic equation for determining the best operating state of the system. In the case of multi-objective functions, these can be defined as a function of the total or combined objective function or function of multipurpose or multi-objective function. The examples which are wellknown to be used to analyze the power system can largely be classified as power transfer.

The main concept of this objective function is to reach objective power transfer value in the system. Power transfer capability is defined as total transfer capability (TTC) value, which is the power that can be transferred from the set of generators in a source area to loads in a sink area subjected to real and reactive power generation limits, voltage limits, and line flow limits. This objective function is shown as (2.8)

$$f = \sum_{i=1}^{ND\_SNK} (P_{Di} - P_{Di}^{base}) - \sum_{i=1}^{NL} (P_{Li} - P_{Li}^{base}) \tag{2.8}$$

subject to

$$P_{Gi} - P_{Di} + \sum_{j=1}^{N} V_i V_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j) = 0 \tag{2.9}$$

$$Q_{Gi} - Q_{Di} + \sum_{j=1}^{N} V_i V_j Y_{ij} \sin(\theta_{ij} - \delta_i + \delta_j) = 0 \tag{2.10}$$

where

P_{Di}	real power loads in the sink area,
P_{Di}^{base}	base case real power loads in the sink area,
P_{Li}	the losses in line flows,
P_{Li}^{base}	the base case losses in line flows,
ND_SNK	number of load buses in sink area,
NL	number of branches,

V_i	voltage magnitude at bus i,
V_j	voltage magnitude at bus j,
Y_{ij}	magnitude of the ij th element in the bus admittance matrix,
θ_{ij}	angle of the ij th element in the bus admittance matrix,
δ_i	voltage angles of bus i,
δ_j	voltage angles of bus j,
Q_{Gi}	reactive power generation at bus i,
Q_{Di}	reactive power load at bus i, and
N	total number of buses

2.3.2 State variable and control variable

1) State variable

State variable refer to the variable which cannot be defined and its value changed by the electrical analysis.

2) Control variable

The control variable means the variable that can be defined or controller

a) Slack bus

- State variables contain (P_G) and reactive power (Q_G).
- Control variables contain voltage magnitude $(|V|)$ and voltage angle (δ).

b) Load bus

- State variables contain voltage magnitude $(|V|)$ and voltage angle (δ).
- Control variables contain real power (P_D) and reactive power (Q_D).

c) Voltage bus

- State variables contain angle of voltage (δ) and reactive power (Q_G).
- Control variables contain real power (P_G) and voltage magnitude $(|V|)$.

2.3.3 General power flow calculating

Power flow calculating is aim to determine the unknown variable such as voltage magnitude $(|V|)$ and voltage angle (δ). The unknown variables in section 2.3.2 can be determined by using Newton-Raphson power flow solution. The equation is expressed as follow.

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_j| \qquad (2.11)$$

This can express in polar equation in (2.12)

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_j| \angle \theta_{ij} + \delta_j \qquad (2.12)$$

Thus, the complex power at bus i is in (2.13)

$$P_i - jQ_i = V_i^* I_i \qquad (2.13)$$

Substituting the equation (2.12) into equation (2.13) resulting in (2.14)

$$P_i - jQ_i = \left(\left|V_i\right|\angle-\delta_i\right)\sum_{j=1}^{n}\left|Y_{ij}\right|\left|V_j\right|\angle\theta_{ij}+\delta_j \tag{2.14}$$

According equation 2.14, the real part and imagine part can express as (2.15) and (2.16)

$$P_i = \sum_{j=1}^{n}\left|V_i\right|\left|V_j\right|\left|Y_{ij}\right|\cos\left(\theta_{ij}-\delta_i+\delta_j\right) \tag{2.15}$$

$$Q_i = -\sum_{j=1}^{n}\left|V_i\right|\left|V_j\right|\left|Y_{ij}\right|\sin\left(\theta_{ij}-\delta_i+\delta_j\right) \tag{2.16}$$

The equation of Newton-Raphson form can be expressed in matrix from as (2.17)

$$\begin{bmatrix}\Delta P_i\\ \Delta Q_i\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\cdot\begin{bmatrix}\Delta\delta_i\\ \Delta\left|V_i\right|\end{bmatrix} \tag{2.17}$$

where

J the jacobian matrix

2.3.4 Equality constraint

The problem of optimal solution is the equations which define power flow problem. The equation defines the relationship between real power and reactive power. By relationships of real power are true for all buses except slack bus. The equations of reactive power are condition of all load buses which can be expressed as (2.18) and (2.19)

$$P_{Gi} - P_{Di} - \sum_{j=1}^{N}\left|V_i\right|\left|V_j\right|\left|Y_{ij}\right|\cos\left(\theta_{ij}-\delta_i+\delta_j\right) = 0, \tag{2.18}$$

$$Q_{Gi} - Q_{Di} + \sum_{j=1}^{N}\left|V_i\right|\left|V_j\right|\left|Y_{ij}\right|\sin\left(\theta_{ij}-\delta_i+\delta_j\right) = 0, \tag{2.19}$$

where

P_{Di} real power loads in the sink area,

P_{Li} the losses in line flows,

P_{Li}^{base} the base case losses in line flows,

$|V_i|$ voltage magnitude at bus i,

$|V_j|$ voltage magnitude at bus j,

$|Y_{ij}|$ magnitude of the ij th element in bus admittance matrix,

θ_{ij} angle of the ij th element in bus admittance matrix,

δ_i voltage angles of bus i,

δ_j voltage angles of bus j,

Q_{Gi} reactive power generation at bus i,

Q_{Di} reactive power load at bus i, and

N total number of buses

The unknown variable: x of equality constraint is voltage magnitude and voltage angle at load buses and voltage buses. The other variables is u such as real power, voltage at voltage control bus, voltage angle and voltage magnitude at slack bus, and transformer tapping can be defined from system operating point. These variables can be defined in vector equation as $g(x,u)=0$.

2.3.5 Inequality constraint

The inequality constraints show the limitation of devices in electrical power system. These limitations are set to aim for feasible operating and safety of the system. The widely inequality constraint which are used can be shown as follow.

1) Real power of generator at bus i

$$P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \tag{2.20}$$

where

P_{Gi} real power of generator at bus *i*,

$P_{Gi}^{\min}$ minimum real power of generator at bus *i*, and

$P_{Gi}^{\max}$ maximum real power of generator at bus *i*

2) Reactive power of generator at bus i

$$Q_{G,i}^{\min} \le Q_{G,i} \le Q_{G,i}^{\max}, \tag{2.21}$$

where

Q_{Gi} reactive power of generator at bus *i*,

$Q_{G,i}^{\min}$ minimum reactive power of generator at bus *i*, and

$Q_{G,i}^{\max}$ maximum reactive power of generator at bus *i*

3) voltage bus at bus i

$$V_i^{\min} \le |V_i| \le V_i^{\max} \tag{2.22}$$

where

$|V_i|$ voltage magnitude at bus *i*,

$V_i^{\min}$ minimum voltage at bus *i*, and

$V_i^{\max}$ maximum voltage at bus *i*

4) System power flow

System power flow must not over system line limit.

$$\left|S_{Li}\right| \le S_{Li}^{\max} \tag{2.23}$$

where

$\left|S_{Li}\right|$ apparent power flow at *i*th *line* and

$S_{Li}^{\max}$ maximum power flow at *i*th line

5) Transformer tapping at bus i

$$t_i^{\min} \le t_i \le t_i^{\max} \tag{2.24}$$

where

t_i transfer tapping at bus *i*,

$t_i^{\min}$ minimum transformer tapping at bus *i*,and

$t_i^{\max}$ minimum transformer tapping at bus *i*

6) Maximum system current

$$\left|I_i\right| \le I_i^{\max} \tag{2.25}$$

where

$\left|I_i\right|$ current flow at *i*th line and

$I_i^{\max}$ maximum current flow at *i*th line

2.3.6 Penalty function

The penalty function is applied with inequality constraint of the system. The initial function adjustments are varied up to the system. By choosing the proper adjustment function can make the objective function value in reasonable range. The example of penalty function is shown as Figure 2.5

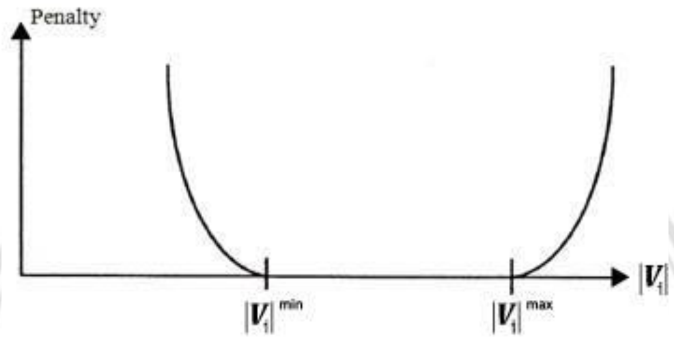

Figure 2.5 Penalty function of limitation of voltage magnitude.

The variables of inequality constraints except control variables use multiplier function. The mathematic equation of equality constraint is shown as (2.26)

$$PF = w\left(h^2\right) \tag{2.26}$$

Subject to

$$w > 0 \tag{2.27}$$

where

PF penalty function value, and

w weight value.

The weight value is included in the objective function if the inequality constraint is over limit. For example, the using weight value for adjusting voltage magnitude at each bus is shown in (2.28)

$$
h(|V_i|) = \begin{cases} K\left(|V_i| - |V_i|^{\min}\right)^2 & for \quad |V_i| < |V_i|^{\min} \\ 0 & for \quad V \text{ within limits} \\ K\left(|V_i|^{\max} - |V_i|\right)^2 & for \quad |V_i|^{\max} > |V_i| \end{cases} \tag{2.28}
$$

The penalty function in Figure 2.5 can be adjusted by multiplying weight value into the objective function. This penalty function value will over limit if the voltage magnitude is over or under limit. Thus, the procedure of the optimal power flow attempts to force the calculation under voltage limit by reducing the objective function value.

The conventional optimal power flow attempts to consider the system scale, objective function including equality constraints and inequality constraints. Due to the general problems are complex non linear. The algebra cannot determine the answer of these problems. Thus, the numerical methods or artificial methods are used to solve these problems and describe in next section.

2.4 Optimal power flow solving

This section presents the optimal power flow solving method which contains 2 main concepts. The first is conventional methods such as nonlinear programming method, quadratic programming method, Newton method, and linear programming method. The second is artificial intelligence methods such as heuristic methods, evolutionary programming, and swarm intelligence [30].

2.4.1 Conventional method

The applied of methods which aim to solve power flow problem considering system limit and system physical constraints. These conventional methods aim to reduce the operating cost by considering the balance of real power and reactive power. The conventional method can be classified in 4 types as follows.

1) Nonlinear method

   a) The objective function is formulated as non linear objective function.

b) The set of constraint is defined as equality constraint and inequality constraint.

2) Quadratic programming method

a) The objective function of Quadratic programming method is formulated as quadratic function.

b) The set of constraint is defined as linear both equality constraint and inequality constraint.

3) Newton method

a) This method gives fast convergence to final answer.

4) Linear programming method

a) The objective of Linear programming method is formulated as linear objective function.

b) The equality and inequality constraints are set to linear.

The conventional methods can be used to solve linear and non liner objective functions, resulting in fast convergence. However, these conventional methods cannot be used to solve complex problem. However these methods are unable to solve complex problems and give absolute global answer. The local maximum and local minimum get chances to determine by conventional methods. Examples of optimum points are shown in Figure 2.6.

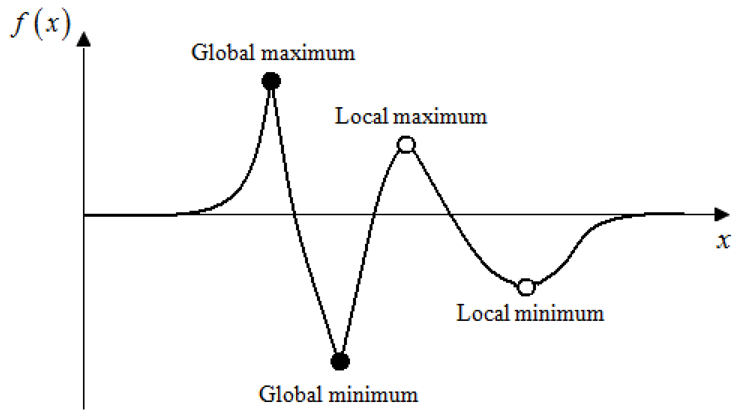

Figure 2.6 Partial global points and local points of objective function

The new concept which named artificial intelligence is created to solve this limitation of conventional methods. The artificial intelligence methods are proposed to determine the global optimum of objective function.

2.4.2 Artificial intelligence

1) Heuristic approach

Heuristic approach is one type of artificial intelligence which can determine the answer of any problem. The concept of heuristic approach is to learn to solve not directly solving. There are many ways to find out the answer.

The wellknow heuristic approaches are Tabu search:TS and Simulated Annealing: SA.

2) Evolutionary computation

This method mimics the natural process of evolution to determine the optimal answer. Living things in nature have to adapt in order to survive in an changeable environment. This is a concept of evolutionary computation that simulates the process of evolution to adapt and survive in nature. The components of evolutionary computation are competition, selection, reproduction, mutation etc.

3) Swarm intelligence

This concept derived from the model organism in nature such as ants or birds. Each individual particle will exchange its information between the particles in group in order to achieve the trajectory to get answers to the most appropriate. The examples of this concept are particle swarm intelligence: PSO, ant colony, and bee algorithm.

2.5 Optimal Power Flow with FACTS controller

There have been proved that FACTS controllers can be used to enhance the flexibility of power flow [31]. The flexibility of power flow then provides the direct control power flow, which resulted in improving of efficiency of transmission system in various objective functions. Four types of FACTS controller, including TCSC, TCPS, SVC, and UPFC are used in this thesis.

TCSC is able to adjust the line reactance. TCPS can help to adjust the voltage phase angle. SVC is used as static var generator or absorber while UPFC can also be used to adjust both the voltage phase angle and the voltage level. Abilities of these FACTS controllers are wellknown and widely used worldwide with many objective functions. Two types of these objective functions are for examples, traditional and emerged functions. First traditional functions include fuel cost function, power losses minimization, enhanced power transfer capability and emission of generating units. Second, emerged functions are maximizing of the social welfare, wheeling rate, and bidding strategy [30].

The electrical power systems installed FACTS controllers can enhance their performances by adjusting parameter of FACTS controllers [32, 33]. Better performances are resulted from suitable parameters. The suitable parameters of FACTS controllers and parameter of OPF are determined by the proposed method which is described in chapter 3. The objective functions and the equation of OPF with FACTS controller are described in chapter 5.