Optimal Power Flow Enhancement In Deregulated Power Systems With Series Facts Devices

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***Abstract*— The Thyristor controlled series compensator (TCSC) and Thyristor controlled phase angle reactor(TCPAR) are most effective Flexible AC Transmission System(FACTS) devices. This paper investigates their effect on Optimal Power Flow (OPF) of a bulk power system. OPF of an IEEE – 30 bus system is carried out including TCSC and TCPAR individually by using MATPOWER simulation package. OPF solution with TCSC and TCPAR devices is carried out considering reactive power loss minimization and fuel cost minimization as objective. To examine the impact of TCSC and TCPAR, OPF solution is carried out in various operation environments, such as different TCSC locations and TCPAR locations. Finally, OPF solution is calculated assuming TCSC and TCPAR are always working and the results are compared with standard OPF solution of IEEE – 30 bus system.**

***Index Terms*—MATPOWER, FACTS devices, OPF, TCPAR, TCSC.**

I. Introduction

Deregulated electric power industries have changed the way of operation, structure, ownership and management of the utilities. In order to achieve better service, reliable operation, the power industry in many countries had undergone significant changes and was reforming into a free market, which is also known as deregulation. With the introduction of deregulation [1] to the electricity market, consumers have the option to choose whom to buy the electricity from. Factors such as prices and reliability of the power supply will become of increasing importance.

Restructuring of power industry presents several challenges and opportunities, some of which requires optimal use of the transmission system under various possible configurations.

As the system becomes deregulated, power companies becomes more and more conscious about the losses and the cost and they are driven to solutions where the system is operated more flexibly via the Flexible AC Transmission System (FACTS) devices[2,3].

Thyristor controlled switching compensator (TCSC) is one such device, which offers smooth and flexible control of line impedance with much faster response compared to traditional control devices.

The Thyristor controlled phase angle regulator (TCPAR) mainly controls the angle. In a thyristor-controlled phase angle regulator, the phase shifting is achieved by introducing a variable voltage component in perpendicular to the phase voltage of the line. This perpendicular voltage component is obtained from a transformer connected between the other two phases. A circuit concept that can handle voltage reversal can provide phase shift in either direction.

II. Opimal Power Flow

However, being critically loaded is not an ideal situation for the power system. Load curtailment is the collection of control strategies employed to reduce the electric power loading in the system and main aim is to push the disturbed system towards a new equilibrium state. Load curtailment may be required even when some lines reach their capacity limits but others still have not utilized their capacity completely, such a scenario can occur due to system topology. The power flows are rerouted in such a way so that the system transmission capability is completely utilized.

The objective function of OPF can take different forms other than minimizing the generation cost. It is common to express it as the minimum shift of generation and other controls from an optimum operating point. The adjustment of loads in order to determine the minimum load shedding schedule under emergency conditions is allowed. The following can be chosen as objective functions:

i. Transmission losses minimization
ii. Production cost minimization

The calculation of optimal power flow of a power system can be broken into three sections [4]. These are unconstrained parameter optimization, constrained with equality constraints and finally with inequality constraints. Firstly, look at the unconstrained case. The objective function is the cost function, denoted:

$$f(x_1,x_2,\dots,x_n) \qquad (1)$$

To minimize this function, the gradient must be set to zero, meaning

$$\frac{\partial f}{\partial x_i} = 0, i = 1, \dots, n \qquad (2)$$

This can be written as the gradient of function, $f\,\nabla$, producing the gradient vector. The matrix containing the second derivatives of the function is called the Hessian matrix.

Its elements are created using the following function:

$$H_{ij} = \partial^2 f \,/\, \partial x_i \partial x_j \qquad (3)$$

To ensure that a minima was found at the point corresponding to $0=\nabla f$, the Hessian matrix must evaluate to a positive value. If multiple points correspond to minima, then the minimum of this subset is chosen as the minima of the function.

Next, look at the same case including equality constraints. Given the cost function of above, include a group of equality constraints

$$g_i(x_1,x_2,\ldots,x_n) = 0, i = 1,2,\ldots,k \quad (4)$$

This vector of size k is then added to the function using the *Lagrange multiplier* method. This leads to the formula

$$L = f + \sum_{i=0}^{k} \lambda_i g_i \quad (5)$$

Where λ_i is a vector of size k containing the undetermined quantities of the system. For the case of a local minima, L must conform to the following condition:

$$\frac{\partial L}{\partial x_i} = \frac{\partial f}{\partial x_i} + \sum_{i=0}^{k} \lambda_i \frac{\partial g_i}{\partial x_i} = 0 \quad (6)$$

Along with the original equality constraint functions, $g_i = 0$.

Finally, the optimization is performed including inequality constraints. To express this, again consider the system equations (1) and (4) with the inequality constraints

$$u_j(x_1,x_2,\ldots,x_n) \le 0, i = 1,2,\ldots,k \quad (7)$$

The cost function becomes:

$$L = f + \sum_{i=1}^{k} \lambda_i g_i + \sum_{j=1}^{k} \mu_j u_j \quad (8)$$

The resulting necessary conditions for constrained local minima of L are the following:

$$\frac{\partial L}{\partial x_i} = 0,\ i = 1,2,\ldots,n. \quad (9)$$

$$\frac{\partial L}{\partial \lambda_i} = g_i = 0,\ i = 1,\ldots,k. \quad (10)$$

$$\frac{\partial L}{\partial \mu_i} = \mu_j \le 0, i = 1,2,\ldots,m. \quad (11)$$

$$\mu_j u_j = 0 \ \&\ \mu_j > 0, j = 1,\ldots, m. \quad (12)$$

GOALS OF THE OPF

Before beginning the creation of an OPF, it is useful to consider the goals that the OPF will need to accomplish. The primary goal of a generic OPF is to minimize the costs of meeting the load demand for a power system while maintaining the security of the system. The costs associated with the power system may depend on the situation, but in general they can be attributed to the cost of generating power (megawatts) at each generator. From the viewpoint of an OPF, the maintenance of system security requires keeping each device in the power system within its desired operation range at steady state. This will include maximum and minimum outputs for generators, maximum MVA flows on transmission lines and transformers, as well as keeping system bus voltages within specified ranges. It should be noted that the OPF only addresses steady-state operation of the power system.

To achieve these goals, the OPF will perform all the steady-state control functions of the power system. These functions may include generator control and transmission system control. For generators, the OPF will control generator MW outputs as well as generator voltage. For the transmission system, the OPF may control the tap ratio or phase shift angle for variable transformers, switched shunt control, and all other flexible ac transmission system (FACTS) devices.

The secondary goal of an OPF is the determination of system marginal cost data. This marginal cost data can aid in the pricing of MW transactions as well as the pricing ancillary services such as voltage support through MVAR support. In solving the OPF using Newton's method, the marginal cost data are determined as a by-product of the solution technique.

III. STATIC MODELING OF FACTS DEVICES

a. STATIC MODELING OF THYRISTOR CONTROLLED SERIES COMPENSATOR(TCSC)

Figure-1 shows the basic Thyristor-controlled series compensators (TCSC) scheme [5,6]. TCSC are connected in series with the lines. The effect of a TCSC on the network can be seen as a controllable reactance inserted in the related transmission line that compensates for the inductive reactance of the line. This reduces the transfer reactance between the buses to which the line is connected. This leads to an increase in the maximum power that can be transferred on that line in addition to a reduction in the effective reactive power losses. The series capacitors also contribute to an improvement in the voltage profiles.

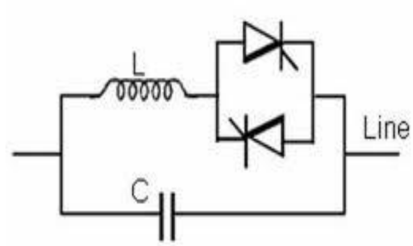

Figure-1. Basic TCSC Scheme

Figure-2 shows a model of a transmission line with a TCSC connected between buses i and j. The transmission line is represented by its lumped π-equivalent parameters connected between the two buses. During the steady state, the TCSC can be considered as a static reactance $-jx_c$. This controllable reactance, x_c, is directly used as the control variable to be implemented in the power flow equation.

Let the complex voltages at bus *i* and bus *j* be denoted as $V_i\angle\delta_i$ and $V_j\angle\delta_j$, respectively. The complex power flowing from bus *i* to bus *j* can be expressed as

$$S_{ij}^* = P_{ij} - jQ_{ij} = V_i^* I_{ij}$$
$$= V_i^*[(V_i - V_j)Y_{ij} + V_i\,(jB_c)]$$
$$= V_i^2[G_{ij} + j\,(B_{ij} + B_c)] - V_i^* V_j(G_{ij} + jB_{ij}) \qquad (13)$$

Where $G_{ij} + jB_{ij} = 1/(R_L + jX_L - jX_C)$ (14)

Equating the real and imaginary parts of the above equations, the expressions for real and reactive power flows can be written as

$$P_{ij} = V_i^2 G_{ij} - V_iV_jG_{ij}\cos(\delta_i - \delta_j) - V_iV_jB_{ij}\sin(\delta_i - \delta_j) \qquad (15)$$
$$Q_{ij} = -V_i^2(B_{ij} + B_c) - V_iV_jG_{ij}\sin(\delta_i - \delta_j) + V_iV_jB_{ij}\cos(\delta_i - \delta_j) \qquad (16)$$

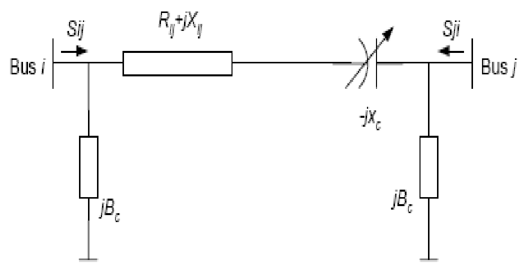

Figure-2. Model of aTCSC

Similarly, the real and reactive power flows from bus *j* to bus *i* can be expressed as

$$P_{ij} = V_i^2 G_{ij} - V_iV_jG_{ij}\cos(\delta_i - \delta_j) + V_iV_jB_{ij}\sin(\delta_i - \delta_j) \qquad (17)$$
$$Q_{ij} = -V_i^2(B_{ij} + B_c) + V_iV_jG_{ij}\sin(\delta_i - \delta_j) + V_iV_jB_{ij}\cos(\delta_i - \delta_j) \qquad (18)$$

The active and reactive power loss in the line can be calculated as

$$P_L = P_{ij} + P_{ji}$$
$$= V_i^2 G_{ij} + V_j^2 G_{ij} - 2V_iV_jG_{ij}\cos(\delta_i - \delta_j) \qquad (19)$$
$$Q_L = Q_{ij} + Q_{ji}$$
$$= -V_i^2(B_{ij} + B_c) - V_j^2(B_{ij} + B_c) + 2V_iV_jB_{ij}\cos(\delta_i - \delta_j) \qquad (20)$$

These equations are used to model the TCSC in the OPF formulations.

Criterion for optimal location of TCSC

The following criteria have been used for optimal placement of TCSC.

- The branches having transformers have not been considered for the TCSC placement.
- The branches having generators at both the end buses have not been considered for the TCSC placement, in this work.

Mathematical calculation for X_{TCSC}

To evaluate the value of X_{TCSC} in p.u system, following method is used.
The base impedance value of a system can be given as

$$Z_{base} = V_{base}^2 / S_{base} \qquad (21)$$

Then consider the values of X_{TCSC} as 4 Ω,6 Ω and 12 Ω. Now convert the X_{TCSC} into p.u system by dividing with Z_{base}.

$$X_{TCSC\ p.u} = X_{TCSC}\ in\ \Omega / Z_{base}\ in\ \Omega \qquad (22)$$

The value of X_{TCSC} is should be between the -70% of line reactance to 20% of line reactance.

$$-0.7X_L \le X_{TCSC} \le 0.2X_L \qquad (23)$$

Sample calculation of X_{TCSC} for 30 – bus system

Base voltage of the IEEE 30-bus system, V_{base} = 135kv. Base apparent power of the IEEE 30-bus system , S_{base} = 100MVA.
From equation (4.9), the base impedance of IEEE 30-bus system is

$$Z_{base} = 135^2/100$$
$$= 182.25\ \Omega$$

Let the value of X_{TCSC} is 4 Ω.
From the equation (22), the value of $X_{TCSC\ p.u}$ is

$$X_{TCSC\ p.u} = 4/182.25$$
$$= 0.0219$$

Similarly consider the X_{TCSC} values as 8 Ω and 12 Ω. Then the respective values of $X_{TCSC\ p.u}$ are 0.0438 and 0.0657.

If the TCSC is placed in the line 2 of IEEE 30-bus system, then the value of $X_{TCSC\ p.u}$ must be in between -0.1296 and 0.03704. The value of $X_{TCSC\ p.u}$ may be positive or negative depending on the value of X_{TCSC}. Randomly placing the TCSC at different locations with satisfying the Criterion for Optimal Location of TCSC and equation (4.11), find the OPF of the system.

b. STATIC MODELING OF THYRISTOR CONTROLLED PHASE ANGLE REGULATOR(TCPAR)

The basic structure of a TCPAR is given in Figure-3. The shunt connected transformer draw power from the network then provide it to the series connected transformer in order to introduce a injection voltage at the series branch [3,7]. Compare to conventional phase shifting transformer, the mechanical tap changer is replaced by the thyristor controlled unit.

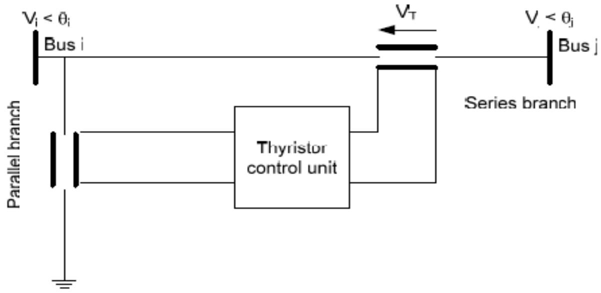

Figure-3. Basic structure of TCPAR

The thyristor controlled phase angle regulator mainly controls the angle. In a thyristor-controlled phase angle regulator, the phase shifting is achieved by introducing a variable voltage component in perpendicular to the phase voltage of the line. This perpendicular voltage component is obtained from a transformer connected between the other two phases. A circuit concept that can handle voltage reversal can provide phase shift in either direction.

Mathematical calculations of TCPAR:

TCPAR can be modeled by phase shifting transformer with control parameter a α .Figure-4 shows the model of TCPAR. The static model of a TCPAR having a complex tap ratio of 1:a∠α and a transmission line between bus i and bus j is shown in Figure-4.

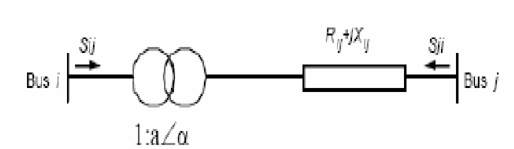

Figure-4 Model of TCPAR

The real and reactive power flows from bus *i* to bus *j* can be expressed as

$$P_{ij}=\mathrm{Re}\{V_i^*[(a^2V_i-a^*V_j)Y_{ij}]\}$$

$$=a^2V_i^2G_{ij}-aV_iV_jG_{ij}\cos(\delta_i-\delta_j+\alpha)-aV_iV_jB_{ij}\sin(\delta_i-\delta_j+\alpha) \quad (24)$$

and

$$Q_{ij}=-\mathrm{Im}\{V_i^*[(a^2V_i-a^*V_j)Y_{ij}]\}$$

$$=-a^2V_i^2G_{ij}-aV_iV_jB_{ij}\cos(\delta_i-\delta_j+\alpha)-aV_iV_jG_{ij}\sin(\delta_i-\delta_j+\alpha) \quad (25)$$

Similarly, real and reactive power flows from bus *j* to bus *i* can be written as

$$P_{ji}=\mathrm{Re}\{V_j^*[(V_j-aV_i)Y_{ij}]\}$$

$$=V_j^2G_{ij}-aV_iV_jG_{ij}\cos(\delta_i-\delta_j+\alpha)+aV_iV_jB_{ij}\sin(\delta_i-\delta_j+\alpha) \quad (26)$$

and

$$Q_{ji}=-\mathrm{Im}\{V^*_j[(V_j-aV_i)Y_{ij}]\}$$

$$=-V^2_jB_{ij}+aV_iV_jB_{ij}\cos(\delta_i-\delta_j+\alpha)+aV_iV_jG_{ij}\sin(\delta_i-\delta_j+\alpha) \quad (27)$$

The real and reactive power loss in the line having a TCPAR can be expressed as:

$$P_l=P_{ij}+P_{ji}$$

$$=a^2V_i^2G_{ij}+V_j^2G_{ij}-2V_iV_jG_{ij}\cos(\delta_i-\delta_j+\alpha) \quad (28)$$

$$Q_l=Q_{ij}+Q_{ji}$$

$$=-a^2V_i^2G_{ij}-V_j^2B_{ij}+2aV_iV_jB_{ij}\cos(\delta_i-\delta_j+\alpha) \quad (29)$$

These equations will be used to model the TCPAR in the power flow formulation. The injection model of the TCPAR is shown in Figure-5.

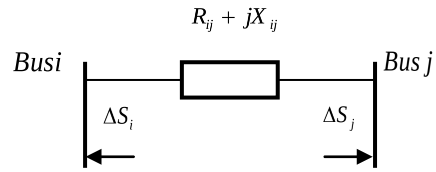

Figure-5 Injection model of TCPAR

The TCPAR grants an efficient ability to reduce losses, control steady-state power flow, and efficiently and flexibly maximize line utilization and consequently can increase system capability and improve reliability. The TCPAR can change the relative phase angle between the system voltages. Therefore, can control the real power flow in transmission lines in order to remove congestion, mitigate the frequency oscillations and enhance power system stability. The steady-state injection model of a TCPAR having complex tap ratio located in a transmission line between buses i and j is shown in Figure- 5

FACTS DEVICES LOCATION

The objective for the device placement may be one of the following

i. reduction in the real power loss of a particular line
ii. reduction in the total system real power loss
iii. reduction in the total system reactive power loss
iv. Maximum relief of congestion in the system

IV. MATPOWER

Matpower is a simulation tool within Matlab that was easy to use and modify. Matpower consists of a multitude of m-files, each designed for a different purpose [8]. Matpower has a number of options which can be changed by modifying the m-file mpoption.m. These options vary the performance and characteristics of Matpower to suit the needs of the user.

The standard method used is Newton's method with a full Jacobian matrix which is updated at each iteration. As well as this, the fast decoupled method is also implemented.

V. RESULTS AND DISCUSSIONS

Test has been done with help of MATPOWER simulation package. Figure-6 shows the standard IEEE 30-bus system.

OPF solution of IEEE 30-bus system without any FACTS devices is given in Table-1.

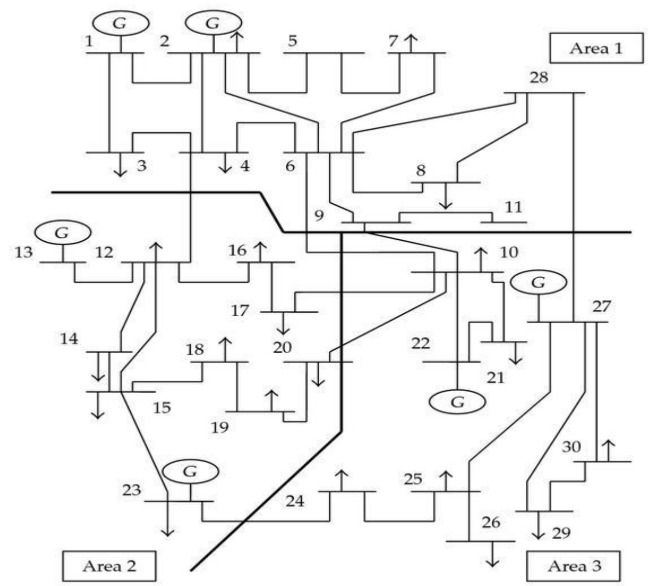

Figure-6. IEEE 30 – bus system

TABLE-1. OPF solution for standard IEEE 30-bus system

Reactive Power loss (MVAR)	Active Power loss (MW)	Generation Cost ($/hr)
13.33	2.86	576.89

Placing a TCSC in the lines 2,7,10,30,33,35,40 and 41 of IEEE 30-bus system, OPF solution is given in Table-2.

TABLE-2. OPF solution for IEEE 30-bus system with TCSC

Reactive Power loss (MVAR)	Active Power loss (MW)	Generation Cost ($/hr)
9.05	2.31	574.08

Placing a TCPAR in the lines 33,35,40 and 41 of IEEE 30-bus system, OPF solution is given in Table-3.

TABLE-3. OPF solution for IEEE 30-bus system with TCPAR

Reactive Power loss (MVAR)	Active Power loss (MW)	Generation Cost ($/hr)
9.16	2.376	574.34

VI. CONCLUSION

The OPF of IEEE 30–bus system has been carried out by using MATPOWER. From these results following conclusions are made.

The IEEE 30-bus system is converged in 4.41 seconds , Objective function value is 576.89$/hr, actual active power generation is 192.1MW, actual reactive power generation is 105.1MVAr, total active and reactive power losses in the system are 2.86MW and 13.33MVAr respectively. At bus no. 29 Vmax limit is violated and power flow constraint is violated in the branch 10 and 35.

Placing a TCSC in the lines 2,7,10,30,33,35,40 and 41 of IEEE 30-bus system, time taken to converge the system is 0.33 seconds, actual reactive power generation is 98.8MVAr i.e., reduced by 6% over the base case. Total active and reactive power losses in the system are 2.31MW and 9.05MVAr respectively i.e., reduced by 19.23% and 32.1% respectively over the base case. Objective function value is 574.08$hr reduced slightly over the base case. Violation of voltage constraint at bus29 eliminated but the same problem is occurred at bus1, bus12 and bus25.

In this paper, when TCPAR is added into the IEEE-30 bus system. The generation cost of the best solution is reduced from 576.89 $/hr in the case without FACTS device to 574.34 $/hr in the case with TCPAR at lines 33, 35, 40, 41. As a result, the near optimal placement of TCPAR can lead to generation cost saving of 2.55 $/hr or 0.0044%. The real and reactive power losses are 2.860 MW and 13.33 MVAr respectively in the base case, which are reduced to 2.376 MW and 9.16 MVAr in the case with incorporating of FACTS device TCPAR.

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