Minimization of Reactive Power Losses in Power Systems Through Facts Controller

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Abstract—In this paper, a sensitivity-based method has been proposed for optimal placement of various types of FACTS controllers. An Optimal Reactive Power Dispatch problem has been formulated and solved using computer programming to determine the optimal placement of FACTS controller on IEEE-30 bus system. FACTS – Flexible AC transmission systems, SVC – static VAR compensator, TCPAR – thyristor controlled phase angle regulator, TCSC – thyristor controlled series capacitor.

Index Terms — FACTS, SVC, TCPAR & TCSC

1. INTRODUCTION

With ever-increasing interconnections and stressed operating conditions, the secure and stable operation of power systems has become a challenging task. Due to economical and environmental reasons, the expansion of generation and transmission facilities has not been in proportion with the growth in the load. This has resulted in increased real and reactive power losses in the transmission network and voltage variation problems at the load bus occurs in most of the power systems.

Voltage at the load bus should be constant for smooth operation of loads. Voltage variation is associated with reactive power limitations of the power system. Hence it is very necessary to control the reactive power of the system. Achievable generator reactive capability (GRC) is generally much less than indicated by the manufacturer’s reactive capability curves, due to constraints imposed by plant auxiliaries and the power system itself. Over-heating of rotor takes place due to over-excitation and armature heating takes place due to large reactive power generation [1-3]. Hence the need is to minimize the reactive power losses in the power system. Reactive power losses in power systems can be minimized with the help of optimal scheduling of reactive power outputs of sources, transformer tap settings and other compensating devices.

The Flexible AC Transmission Systems (FACTS) controllers are being popularly utilized in power system networks [4-5]. Mainly FACTS controllers include Thyristor Controlled Series Capacitor (TCSC), Thyristor Controlled Phase Angle Regulator (TCPAR) and Static VAR Compensator (SVC). These controllers enable fast and efficient control of active and reactive power flows in the transmission networks. High cost of these FACTS controllers requires their optimal placement in the system. The optimal placement of these controllers minimizes the reactive power losses.

2. OPTIMAL PLACEMENT OF FACTS CONTROLLERS

In this study, the placement of FACTS controllers have been considered from the static point of view to reduce the total system reactive power loss. A method based on the sensitivity approach, as described below, has been suggested for the placement of FACTS controllers.

2.1 Loss sensitivity indices

The proposed method utilizes the sensitivity of total reactive power loss with respect to the control parameters of FACTS controllers for their optimal placement. The control parameters for the three FACTS controllers include line net series reactance ($X_k$) for the TCSC placed in line-k, phase shift($\phi_k$) for the TCPAR placed in line-k and reactive power injection ($Q_i$) for the SVC placed at bus-i. The loss sensitivity factors with respect to the parameters of these controllers can be defined as

$$ a_k = \frac{\partial Q_l}{\partial X_k} = \text{Loss sensitivity with respect to control parameter } X_k \text{ of TCSC placed in line-k (K=1, \ldots, N_i)} $$

$$ b_k = \frac{\partial Q_i}{\partial \phi_k} = \text{Loss sensitivity with respect to control parameter } \phi_k \text{ of TCPAR placed in line-k (K=1, \ldots, N_i)} $$

$$ c_k = \frac{\partial Q_i}{\partial Q_i} = \text{Loss sensitivity with respect to control parameter Q of SVC placed at bus-i (i = 1, \ldots, N)} $$

These factors have been computed at a base case load flow solution, as given below. Consider a line-k connected between bus-i and bus-j and having series impedance $R_k + jX_k$, where, $X_k$ is the net reactance after considering the reactance of a series compensator, if present in the line. Let the complex voltages at the buses-i and j be $V_i \angle \delta_i$ and $V_j \angle \delta_j$, and respectively $\phi_k = \delta_i - \delta_j$ be the phase shift in the line-k including the effect of the phase shifter. The loss sensitivity with respect to $X_k$ and $\phi_k$ can be computed as

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respectively.

\[ Q_{k} = -V_{j}^{2} (B_{j} + B_{k}) - V_{j}^{2} (B_{j} + B_{k}) + V_{j} V_{k} B_{j} \cos (\delta_{j} - \delta_{k}) \]

For modeling to TCSC in the ORPD formulation.

\[ Q_{k} = -a^{2} V_{j}^{2} B_{j} + V_{j}^{2} B_{k} + 2 V_{j} V_{k} B_{j} \cos (\delta_{j} - \delta_{k} + \alpha) \]

For modeling to TCSC in the ORPD formulation.

\[
\frac{\partial Q_{L}}{\partial X_{k}} = \frac{\partial Q_{L}}{\partial \phi_{k}} = \frac{\partial Q_{L}}{\partial K}, \quad \frac{\partial Q_{L}}{\partial \phi_{k}} = \frac{\partial Q_{L}}{\partial K}
\]

For computing the loss sensitivity with respect to the SVC control parameter \( Q \), a general loss formula has been used, according to which

\[
Q_{L} = \sum_{j=1}^{N} \sum_{k=1}^{N} \gamma_{jk} (P_{j} P_{k} + Q_{j} Q_{k}) + \zeta (Q_{j} P_{k} - P_{j} Q_{k})
\]

Equation (3)

Where, \( \gamma, \zeta \) are the loss coefficients defined as:

\[
\gamma_{jk} = \frac{X_{jk}}{V_{j} V_{k}} \cos (\delta_{j} - \delta_{k})
\]

\[
\zeta_{jk} = \frac{X_{jk}}{V_{j} V_{k}} \sin (\delta_{j} - \delta_{k})
\]

Equation (4)

\[
P_{j} + jQ = \text{Complex power injected at bus-} j
\]

\[
X_{jk} = \text{Imaginary part of the j}^{'th} \text{element of [Z_{bus}]
}
\]

If SVC is placed at bus-\( i \), the sensitivity index with respect to SVG control parameter using above loss formula can be expressed as:

\[
\frac{\partial Q_{L}}{\partial Q_{i}} = 2 \sum_{j=1}^{N} \gamma_{ij} Q_{j} + \zeta_{ij} P_{j} \quad i = 1, \ldots, N
\]

Equation (5)

### 2.2 Criteria for optimal placement

Generally, FACTS controllers should be placed on the most sensitive bus or line. For instance SVC is employed at the most sensitive bus from the voltage control viewpoint whereas TCSC or TCPAR is placed in the most sensitive line for the effective power flow control. With the loss sensitivities computed as discussed earlier, following criteria have been used for optimal placement of the FACTS controllers.

1. TCSC should be placed in a line-m having most positive loss sensitivity index \( a_{m} \).
2. TCPAR should be placed in a line-n having largest absolute value of loss sensitivity index \( b_{n} \).
3. SVC should be placed at a bus-i having most negative loss sensitivity index \( C_{i} \).

In addition to these, following criteria have also been incorporated while deciding the optimal placement of the FACTS controllers.

(i) The TCSC or TCPAR should not be placed between two generator buses, even if, the loss sensitivity for the line connecting them is highest.

(ii) The placement of SVC has been considered at load buses only, since the objective is voltage stabilization.

### 2.3 ORPD considering FACTS controllers

After optimal placement of the FACTS controllers, the conventional optimal reactive power dispatch (ORPD) formulation has been modified to include TCSC, TCPAR and SVC. In the present work, static models of these FACTS controllers have been considered in which a TCSC is represented as a static capacitor/reactor offering impedance \( \alpha \), a TCPAR as a transformer having complex tap ratio \( 1: a < \alpha \) and a series admittance \( Y_{k} \) and a SVC is represented as a reactive power source \( Q_{svc} \) with its limits as \( Q_{\text{svc}}^{\text{min}} \) and \( Q_{\text{svc}}^{\text{max}} \). Considering a general case when all the three types of FACTS controllers are present in the system, the modified ORPD formulation is as follows:

Minimize,

\[
Q_{L} = 2 \sum_{j=1}^{N_{g}} (Q_{LM} + Q_{ML}) + \sum_{i=N_{g}+1}^{N_{g}+N_{TCPAR}} Q_{TCPAR} + \sum_{i=N_{g}+N_{TCPAR}+1}^{N_{g}+N_{TCPAR}+N_{SVC}} Q_{TCPARi}
\]

Equation (6)

Where, \( Q_{L} = \) Total reactive power loss.

\( Q_{TCPAR} = \) Reactive power loss in line-i having TCPAR

\( Q_{SVC} = \) Reactive power loss in line-i having SVC

\( N_{g} = \) Number of lines with no FACTS controllers

\( N_{TCPAR} = \) Number of lines with TCSCs

\( N_{SVC} = \) Total number of lines in the network

Hence, the remaining \( (N_{g} - N_{TCPAR} - N_{SVC}) \) lines are consisting of TCPARs. The above minimization is subject to reactive power balance (equality constraint)

\[
\sum_{i=1}^{N_{g}} Q_{Gi} - Q_{L} - Q_{D} + \sum_{i=N_{g}+1}^{N_{g}+N_{TCPAR}} Q_{TCPAR} = 0
\]

Equation (7)
And a set of inequality constraints
\[ Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}; \quad i = 1, \ldots, N_q \]
\[ V_{i}^{\min} \leq V_{i} \leq V_{i}^{\max}; \quad i = 1, \ldots, N \]
\[ X_{cj}^{\min} \leq X_{cj} \leq X_{cj}^{\max}; \quad j = N_1 + 1, \ldots, N_1 + N_2 \]
\[ a_{i}^{\min} \leq a_{i} \leq a_{i}^{\min}; \quad i = N_1 + N_2 + 1, \ldots, N_f \]
\[ Q_{SVC}^{\min} \leq Q_{SVC} \leq Q_{SVC}^{\max}; \quad i = N_q + 1, \ldots, N_q + N_{SVC} \]

Where,
- \( Q_{0} \) = Total reactive power demand in the system.
- \( N_{svc} \) = Total number of SVCs.
- \( Q_{SVC} \) = Reactive power output of SVC placed at bus-i
- \( X_{cj} \) = Series reactance of TCSC placed in line-j
- \( a_{i} \) = Phase shift from TCPAR placed in line-i

In the present work, each type of FACTS controllers has been considered only one at a time, in order to establish their relative impact on voltage control. An actual power system may, however, have several such controllers in operation which can be modeled using the above general formulation.

### 3. TYPICAL RESULTS AND DISCUSSION

For investigating the effect of optimal placement and setting of FACTS controllers in minimizing the total reactive power loss studies are conducted on the IEEE 30-bus system. IEEE 30-bus system consists of 3 generators, 3 synchronous condensers, 37 lines and 4 transformers with OLTC arrangement. First of all, the reactive power loss sensitivity analysis was performed for the optimal placement of FACTS controllers. Then sensitivity indices were computed for each line/bus and their values were arranged in the priority order for the placement of TCSC, TCPAR and SVC respectively.

#### Table 1
Priority list of Sensitivity Indices for IEEE 30-Bus System

<table>
<thead>
<tr>
<th>Priority</th>
<th>TCSC placement</th>
<th>TCPAR placement</th>
<th>SVC placement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( a_k )</td>
<td>( b_k )</td>
<td>( c_i )</td>
</tr>
<tr>
<td>I</td>
<td>Line 1-2</td>
<td>3.1157</td>
<td>3.7064</td>
</tr>
<tr>
<td>II</td>
<td>Line 2-5</td>
<td>0.8176</td>
<td>1.7807</td>
</tr>
<tr>
<td>III</td>
<td>Line 1-27</td>
<td>0.7500</td>
<td>1.7065</td>
</tr>
<tr>
<td>IV</td>
<td>Line 27-11</td>
<td>0.6220</td>
<td>1.5465</td>
</tr>
<tr>
<td>V</td>
<td>Line 11-13</td>
<td>0.4413</td>
<td>1.3166</td>
</tr>
</tbody>
</table>

#### Table 2
Comparison of Total Q-losses for IEEE 30-Bus System

<table>
<thead>
<tr>
<th>Case</th>
<th>( Q_{loss}(\text{p.u.}) )</th>
<th>%Loss reduction compared to base case</th>
<th>FACTS device Optimal setting (In p.u. unless specified)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
<td>0.50845</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional ORPD</td>
<td>-3.82827</td>
<td>852.93</td>
<td>Q_{SVC} = 0.111</td>
</tr>
<tr>
<td>Complete ORPD</td>
<td></td>
<td></td>
<td>X_{c} = 5.081 * 10^{-2}</td>
</tr>
<tr>
<td>Including FACTS Controllers:</td>
<td></td>
<td></td>
<td>( \alpha = 7.146 * 10^{-2} \text{ rad.} )</td>
</tr>
</tbody>
</table>
Top five priority lines/buses based on the values of these indices, computed at the base case operating point, are as shown in Table 1. It is observed that top five priority lines for the placement of TCSC and TCPAR are the same. However, using the criteria for optimal placement of these controllers, the line having 4th priority i.e. the line connecting buses 27 and 11 (having a series reactance of 0.0379 p.u.) is considered for the placement of TCSC and TCPAR. Whereas, the optimal placement of SVC was considered at bus 30, having the first priority based on the value of index c_i.

After optimal placement of FACTS controllers, the conventional ORPD and the ORPD considering FACTS controllers were run to determine the optimal settings of SVC, TCSC and TCPAR along with reactive power sources and transformer taps. For simulating the three types of FACTS controllers in ORPD model, the capacity of SVC was assumed to be ± 3.0 p.u., TCSC capacitive reactance was assumed to be in the range of 0.0 -0.02 p.u. (On system base) assuming a maximum of about 60% compensation of the line reactance of 0.0379 p.u. and TCPAR variation was considered was considered within ± 0.5 radian (about ± 30°). A comparison of effectiveness of these controllers in reducing reactive power losses has been made in Table 2, which also shows their optimal settings.

It is observed that the conventional ORPD (i.e. with reactive power generation rescheduling and OLTC control) itself helps in bringing down the Q_{loss} to from 0.50845 p.u. to -3.82827 p.u. However, SVC further helps in reducing the Q_{loss} to -3.898582 p.u. Similarly TCSC or TCPAR (along with ORPD) too reduces the total Q_loss from the base case value of 0.50845 p.u. to -1.99885 p.u. and 0.34651 p.u. respectively.

4. CONCLUSIONS
This study reveals that rescheduling of reactive power outputs of sources and transformers OLTC control drastically reduces the total reactive power losses of the system. Among three FACTS controllers considered, SVC is found to be the most effective in reducing the reactive power loss in the IEEE 30-bus system.

5. REFERENCES