Power Flow Using FACTS Devices in Power System
GAGANDEEP SINGH AULUCK
Electrical Engineering Department
RIMT-IET, Mandi-Gobindgarh
Punjab (India)
E-mail: gaganaulakh82@gmail.com

Abstract: The power flow studies with the implementation of FACTS devices are presented in this paper. In this paper thorough grounding on conventional power flow theory with particular reference to the Newton-Raphson method has been presented. The main aim of this work is to introduce a systematic and coherent way to study models and methods for the representation of FACTS controllers in the power flow studies. Aspects of modeling and implementation of the Thyristor Controlled Series Compensator (Series Controller) and Static VAR Compensator (Shunt Controller) FACTS controllers are presented with the help of MATLAB simulation & Newton-Raphson power flow technique in this paper. This technique exhibits very strong convergence characteristics, regardless of the network size and the number of controllable devices. The results of power flow have been obtained on the IEEE 5-Bus & 14-Bus system. In this paper the study has been carried to locate the optimal position of compensating devices in order to reduce the production cost along with the device cost. From the obtained results the effective regulation of active power has been achieved which leads to reduction in technical losses.

Key Words: FACTS, TCSC, SVC, Transmission, Distribution.

1. INTRODUCTION
With the ongoing expansion and growth of the electric utility industry, including deregulation in many countries, numerous changes are continuously being introduced to a once predictable business. Although electricity is a highly engineered product, it is increasingly being considered and handled as a commodity. Thus, transmission systems are being pushed closer to their stability and thermal limits while the focus on the quality of power delivered is greater than ever. In the evolving utility environment, financial and market forces are, and will continue to, demand a more optimal and profitable operation of the power system with respect to generation, transmission, and distribution. Now, more than ever, advanced technologies are paramount for the reliable and secure operation of power systems. To achieve both operational reliability and financial profitability, it has become clear that more efficient utilization and control of the existing transmission system infrastructure is required.

Improved utilization of the existing power system is provided through the application of advanced control technologies. Power electronics based equipment, or Flexible AC Transmission Systems (FACTS), provide proven technical solutions to address these new operating challenges being presented today. FACTS technologies allow for improved transmission system operation with minimal infrastructure investment, environmental impact, and implementation time compared to the construction of new transmission lines.

Traditional solutions to upgrading the electrical transmission system infrastructure have been primarily in the form of new transmission lines, substations, and associated equipment. However, as experiences have proven over the past decade or more, the process to permit, site, and construct new transmission lines has become extremely difficult, expensive, time-consuming, and controversial. FACTS technologies provide advanced solutions as cost-effective alternatives to new transmission line construction.

The power flow problem is formulated as set of nonlinear equations. Many calculation methods have been proposed to solve the problem. Among them, Newton Raphson method and fast decoupled load flow method are two very successful methods. In general, the decoupled power flow methods are only valid for weekly loaded network with large X/R ratio network. For system conditions with large angle across lines (heavily loaded network) and with special control that strongly influence active and reactive power flows, Newton-Raphson method may be required. Therefore, when the AC power flow
calculations is needed in systems with FACTS devices, Newton-Raphson method is a suitable power flow calculation in system with TCSC and SVC when high accuracy is required. The basic requirement of power system is to meet the demand that varies continuously. That is, the amount of power delivered by the power companies must be equal to that of consumer’s need. Unfortunately nobody guarantees that unexpected things such as generator fault or line fault and line tripping would not happen. Due to its fast control characteristics and continuous compensation capability, FACTS devices have been researched and adapted in power engineering area. There are so many advantages in FACTS device; it can increase dynamic stability, loading capability of lines and system security. It can also increase utilization of lowest cost generation. The key role of FACTS device is to control the power flow actively and effectively. In other words, it can transfer power flow from one line to another within its capability. This paper focuses on the development of new SVC and TCSC model and their implementation in the Newton-Raphson load flow algorithms.

2. OPTIMAL LOCATION OF FACTS DEVICES

Most of the work, in the past has utilized dynamic considerations for the placement of the FACTS devices, as these devices were utilized to mainly improve the stability of the power system networks. In this paper, the FACTS devices have been considered from a static point of view to reduce the total system real power Transmission loss (PL). Hence, a new method based on sensitivity approach, as described below, has been suggested for placement of the FACTS devices.

Loss sensitivity indices

The proposed method utilizes the sensitivity of total transmission loss (PL) with respect to the control parameters of FACTS devices for their optimal placement. The control parameters for the two FACTS devices include line net series reactance (placed in line no-19) for TCSC and reactive power injection (placed at bus no-5) for SVC. Thus, the loss sensitivity factors with respect to the parameters of these devices can be defined as,

\begin{align}
    a_k &= \frac{\partial P_L}{\partial X_k} \text{ Loss sensitivity with respect to TCSC Placed in line } k (k = 1, \ldots, N_j) \\
    c_i &= \frac{\partial P_L}{\partial Q_i} \text{ Loss sensitivity with respect to SVC Placed at bus } i (i = 1, \ldots, N_i)
\end{align}

These factors can be computed at a base load flow solution as given below.

Consider a line-k connected between bus-I and bus-j and having series impedance \( R_k + jX_k \). \( X_k \) is the net reactance considering the reactance of the series compensator, if present, in the line. Let the complex voltage at the bus –I and –j are \( V_I \) and \( V_j \) respectively. \( \phi_k = \delta_j - \delta_i \) is the phase shifter.

3.

\[
    \frac{\partial P_L}{\partial X_k} = \left[ a^2 V_i + V_j^2 - 2aV_iV_j \cos(\delta_j - \delta_i) \right] \cdot \frac{2R_kX_k}{(R_i^2 + X_k^2)^2}
\]

Where \( k = 1 \ldots N \)

For computing the loss sensitivity index with respect to SVC an exact loss formula has been used, which expresses \( P_L \) as,

\[
    P_L = \sum_{j=1}^{N} \sum_{k=1}^{N} \left[ a_{jk} (P_JP_k + Q_JQ_k) + \beta_{jk} (Q_JP_k - P_JQ_k) \right]
\]

Where \( a, \beta \) is the loss coefficients defined as;

\[
    a_{jk} = \frac{r_{jk}}{V_jV_k} \cos(\delta_j - \delta_k)
\]

\[
    \beta_{jk} = \frac{r_{jk}}{V_jV_k} \sin(\delta_j - \delta_k)
\]

\[
    P_i + jQ_i = \text{Complex injected power at bus-I}
\]

\[
    r_{jk} = \text{Real Part of the jk element of } [Z_{bus}]\]

At bus-I, sensitivity index with respect to SVC parameter using above loss formula can be expressed as:

\[
    \frac{\partial P_L}{\partial Q_i} = 2 \sum_{j=1}^{N} (a_{ij}Q_j + \beta_{ij}P_j) \quad i = 1, \ldots, N
\]

Criteria for optimal placement

The FACTS devices should be placed on the most sensitive bus or line. With the loss sensitivity indices computed for each type of the FACTS devices, following criteria have been used for their optimal placement.

1. The TCSC should be placed in a line (m) having most positive loss sensitivity index \( (a_m) \).
2. The SVC should be placed at a bus -i having most negative sensitivity index \( c_i \).
Following additional criteria have also been used while deciding the optimal placement of FACTS devices.

i) The TCSC should not be placed between two generation buses, even though the line sensitivity is highest.

ii) The placement of SVC has been considered at load buses only.

3. POWER FLOW CONSIDERING FACTS DEVICES

The unified approach blends the AC network and power system controller state variables in a single system of simultaneous equations:

\[ f(X_{nAC}, R_{nF}) = 0, \]
\[ g(X_{nAC}, R_{nF}) = 0, \]

Where, \( X_{nAC} \) stands for the AC network state variables, namely, nodal voltage magnitude and phase angle and \( R_{nF} \) stands for the power system controller state variables.

\[
\begin{array}{cccccc}
X_1 & \ldots & x_{nAC} & r_1 & \ldots & r_{nf} \\
\vdots & & \vdots & \vdots & & \vdots \\
f_1 & & f_{nAC} & F_1 & & F_{nf} \\
\vdots & & \vdots & \vdots & & \vdots \\
\end{array}
\]

Fig. 1 Augmented Jacobian

3.1 SVC Model Implementation, Newton-Raphson Load Flow

1. SVC total susceptance model: A Changing susceptance \( B_{svc} \) represents the fundamental frequency equivalent susceptance of all shunt modules making up SVC. This model is an improved version of SVC models currently available in open literature.

2. SVC firing angle model: The equivalent susceptance \( B_{eq} \) which is function of a changing firing angle \( \alpha \), is made up of the parallel combination of TCR equivalent admittance and a fixed capacitive susceptance. This is a new and more advanced SVC representation than those that are currently available in open literature. This model provides information on the SVC firing angle required to achieve a given level of compensation.

In this work SVC firing angle model has been tested on IEEE 5 Bus System and IEEE 14-Bus System. Static VAR Compensator Equivalent Susceptance Advances in the power electronics technology together with sophisticated control methods made possible the development of fast SVC’s in the early 1970’s. The SVC consists of a group of shunt-connected capacitor and reactor banks with fast control action by the means of thyristor switching. From the operational point of view, the SVC can be seen as variable shunt reactance that adjusts automatically in response to changing system operative conditions. Depending on the nature of the equivalent SVC’s reactance, i.e. capacitive or inductive, the SVC draws either capacitive or inductive current from the network. Suitable control of this equivalent reactance allows voltage magnitude regulation at the SVC points of connection. SVC’s achieve their main operating characteristics at the expense of generating harmonic current and filter are employed with this kind of devices.
the combination of either fix capacitor and thyristor controlled reactor. As for as steady state analysis is concerned, both configuration can be modeled along similar lines. SVC structure shown in the figure above is used to drive a SVC model that considers the TCR firing angle \( \alpha \) as state variable. This is a new and more advanced SVC representation than those currently available in open literature.

The Variable TCR equivalent reactance, \( X_{Leq} \), at fundamental frequency, is given by

\[
X_{Leq} = \frac{\pi}{2(\pi - \alpha) + \sin 2\alpha}
\]

(9)

Where \( \alpha \) the thyristor is’s firing angle.

The SVC effective reactance \( X_{eq} \) is determined by the parallel combination of \( X_c \) and \( X_{Leq} \),

\[
X_{eq} = \frac{X_c X_{Leq}}{X_c (2(\pi - \alpha) + \sin 2\alpha) - X_L}
\]

(10)

Depending on the ratio \( X_c/X_L \) there is a value of firing angle that causes a steady state resonance to occur.

The SVC equivalent susceptance is given as

\[
B_{eq} = \frac{1}{X_{eq}} = \frac{1}{X_c} \frac{X_{Leq}}{X_c (2(\pi - \alpha) + \sin 2\alpha) - X_L}
\]

(11)

\( B_{eq} \) varies in a continuous, smooth fashion in both operative regions as shown in graph below:

![Graph showing the changing reactance XTCSC](image)

Fig .4. SVC equivalent susceptance as function of firing Angle

FA model is an optimized iterative process, consists in handling the TCR firing angle \( \alpha \) as state variable in the power flow formulation.

Injected Bus Power by SVC:

\[
Q_k = -\frac{V_k^2}{X_c X_L} \left[ X_L - \frac{X_c [2(\pi - \alpha_{svc}) + \sin(2\alpha_{svc})]}{\pi} \right]
\]

(12)

The Linearised SVC equation for ith iteration is given as:

\[
\begin{bmatrix}
\Delta P_k \\
\Delta Q_k
\end{bmatrix} =
\begin{bmatrix}
0 & 0 \\
-\frac{2V_k^2}{\pi X_L} \cos(2\alpha_{svc} - 1) & 0
\end{bmatrix}
\begin{bmatrix}
\Delta \theta_k \\
\Delta \alpha_{svc}
\end{bmatrix}
\]

(13)

At the end of iteration I, the variable firing angle \( \alpha \) is updated according to equation mentioned below:

\[
\alpha^{i+1} = \alpha^i + \Delta \alpha^i
\]

The firing angle model is better than variable susceptance model as variable susceptance model requires an additional iterative procedure, after the load flow solution has converged, to determine the firing angle.

### 3.2 TCSC Model Implementation in Newton-Raphson Load Flow

Variable Series Impedance Power Flow Model: The TCSC power flow model presented in this section is based on the simple concept of variable series reactance, the value of which is adjusted automatically to constrain flow across the branch to a specified value.

The changing reactance XTCSC shown in figure below:

![Graph showing the transfer admittance matrix](image)

For Induct Operation, we have:

\[
B_{kk} = B_{mm} = -\frac{1}{X_{r_{csc}}}
\]

(15)

\[
B_{km} = B_{mk} = \frac{1}{X_{r_{csc}}}
\]

(16)

And for capacitive operation the signs are reversed

The active and reactive power equation at bus k is:

\[
P_k = V_k V_m B_{km} \sin(\theta_k - \theta_m)
\]

(17)

\[
Q_k = -V_k^2 B_{kk} - V_k V_m B_{km} \cos(\theta_k - \theta_m)
\]

(18)
The set of Linearised power flow equation is:

\[
\begin{align*}
\Delta P_i & = \sum \left( \frac{\partial P_i}{\partial V_i} \Delta V_i + \frac{\partial P_i}{\partial Q_i} \Delta Q_i \right), \\
\Delta Q_i & = \sum \left( \frac{\partial Q_i}{\partial V_i} \Delta V_i + \frac{\partial Q_i}{\partial Q_i} \Delta Q_i \right), \\
\Delta P_{\text{TCSC}} & = \sum \left( \frac{\partial P_{\text{TCSC}}}{\partial V_i} \Delta V_i + \frac{\partial P_{\text{TCSC}}}{\partial Q_i} \Delta Q_i \right)
\end{align*}
\]

Where \( \Delta P_{\text{TCSC}} \) is the active power flow mismatch for the series reactance; \( \Delta X_{\text{TCSC}} \), given by:

\[
\Delta X_{\text{TCSC}} = X_{\text{TCSC}}^{(i)} - X_{\text{TCSC}}^{(i+1)}
\]

4. Load Flow Test Case
Sensitivity index of the transmission line no-19 has been come out most positive so TCSC should be placed on the transmission line no-19 only making the operation highly cost effective. And sensitivity index of bus no-5 has been come out as most negative among all the indices. So SVC should be placed at the bus no-5 only.

5. Discussion on Load Flow Results with TCSC Model
On the basis of sensitivity indices obtained, Transmission line no 6 has been considered as most sensitive line to get placed with TCSC and bus no 3 with SVC device. After placing these devices, above results have been obtained from Matlab simulation. After analyzing the results it can be observed that TCSC maintains active power from Bus no-3 to Bus no-4 at 21 MW. We have set the starting value of the TCSC at 50% of the value of the transmission-line power.

TABLE.1 VOLTAGE PROFILE OF 5-BUS SYSTEM

<table>
<thead>
<tr>
<th>Bus No</th>
<th>Base Load Flow</th>
<th>Load Flow with TCSC on TL-6</th>
<th>Load Flow With SVC on Bus-3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Magnitude (p.u.)</td>
<td>Phase angle (deg)</td>
<td>Magnitude (p.u.)</td>
</tr>
<tr>
<td>1</td>
<td>1.06</td>
<td>0</td>
<td>1.06</td>
</tr>
<tr>
<td>2</td>
<td>1.00</td>
<td>-2.06</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>0.987</td>
<td>-4.64</td>
<td>0.987</td>
</tr>
<tr>
<td>4</td>
<td>0.984</td>
<td>-4.96</td>
<td>0.9844</td>
</tr>
<tr>
<td>5</td>
<td>0.972</td>
<td>-5.77</td>
<td>0.972</td>
</tr>
</tbody>
</table>

TABLE.2 POWER FLOW RESULTS OF 5-BUS SYSTEM

<table>
<thead>
<tr>
<th>TL No</th>
<th>Active/ Reactive Powers</th>
<th>Base Load Flow</th>
<th>Load Flow with TCSC on TL-6</th>
<th>Load Flow With SVC on Bus-3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Sending End</td>
<td>Receiving End</td>
<td>Loss</td>
</tr>
<tr>
<td>6</td>
<td>P</td>
<td>0.1939</td>
<td>-0.1935</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0286i</td>
<td>-0.0469i</td>
<td>0.018</td>
</tr>
<tr>
<td>7</td>
<td>P</td>
<td>0.066</td>
<td>-0.0656</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0052i</td>
<td>-0.0517i</td>
<td>0.046</td>
</tr>
<tr>
<td></td>
<td>Total Loss</td>
<td>6.1222</td>
<td>-10.7773i</td>
<td>6.1272</td>
</tr>
</tbody>
</table>

5. Discussion on Load Flow Results with TCSC Model
On the basis of sensitivity indices obtained, Transmission line no 6 has been considered as most sensitive line to get placed with TCSC and bus no 3 with SVC device. After placing these devices, above results have been obtained from Matlab simulation. After analyzing the results it can be observed that TCSC maintains active power from Bus no-3 to Bus no-4 at 21 MW. We have set the starting value of the TCSC at 50% of the value of the transmission-line power.
inductive reactance i.e. $X=0.015$ p.u. Convergence is obtained in 6 iteration to a power mismatch tolerance of 1e-12. The connected TCSC device upholds the target value of 21 MW, which is achieved with 70% series capacitive compensation of the transmission line 3-4. It can also be observed that nodal voltage magnitudes and reactive power flows do not change appreciably compared with the base case.

5.1 Discussion on Load Flow Results with SVC Model

The inductive and capacitive reactance is taken to be 0.288p.u. and 1.07 p.u., respectively. The SVC firing angle is set initially at 140 deg, a value that lies on the capacitive region of the SVC characteristics. The SVC upholds its target value and, as expected, identical power flows and bus voltages are obtained. Power flows and nodal voltages are shown in table drawn below. Convergence is achieved in 5 iterations, satisfying a pre-specified tolerance of 1e-12 for all the variables involved. SVC injects 20.5 MVAR into bus no 3 and keeps the nodal voltage magnitude at 1 p.u. The action of SVC results in an overall improved voltage profile as detailed in the Table drawn below. The svc generates reactive power in excess of the local demand, which stands at 15 MVAR and, compared with the base case, there is an almost four times export increase of reactive power to bus no-4. Also there is an export of reactive power to bus no-2 via transmission line 3-2 with larger amount of reactive power available at the bus being absorbed by the generator. It draws 77.1 MVAR as opposed to 61.59 MVAR in the base case.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sending End</td>
<td>Receiving End</td>
<td>Loss</td>
<td>Sending End</td>
</tr>
<tr>
<td>19</td>
<td>P</td>
<td>0.017</td>
<td>-0.0174</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>Q</td>
<td>+0.01</td>
<td>-0.0127i</td>
<td>+0.001i</td>
</tr>
<tr>
<td>20</td>
<td>P</td>
<td>0.059</td>
<td>-0.0581</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Q</td>
<td>+0.04</td>
<td>-0.0416i</td>
<td>+0.002i</td>
</tr>
<tr>
<td></td>
<td>Total Loss</td>
<td>15.1549+34.6678i</td>
<td>15.1623+34.5359i</td>
<td>15.0800+34.0456i</td>
</tr>
</tbody>
</table>

5.2 Discussion on Load Flow Results with TCSC Model

On the basis of sensitivity indices obtained, Transmission line no 19 has been considered as most sensitive line to get placed with TCSC and bus no 5 with SVC device. After placing these devices, above results have been obtained from Matlab simulation.
the transmission line 12-13. It can also be observed that nodal voltage magnitudes and reactive power flows do not change appreciably compared with the base case.

5.3 Discussion on Load Flow Results with SVC Model

The inductive and capacitive reactances are taken to be 0.288p.u. and 1.07 p.u., respectively. The SVC firing angle is set initially at 140 deg, a value that lies on the capacitive region of the SVC characteristics. The SVC upholds its target value and, as expected, identical power flows and bus voltages are obtained. Power flows and nodal voltages are shown in table drawn above. Convergence is achieved in 7 iterations, satisfying a pre specified tolerance of 1e-12 for all the variables involved. SVC injects 18.5 MVAR into bus no 5 and keeps the nodal voltage magnitude at 1 p.u. The action of SVC results in an overall improved voltage profile as detailed in the Table drawn above. The svc generates reactive power in excess of the local demand, which stands at 1.6 MVAR. It can be analyzed that the reactive power loading of Line No-2 (Between Bus-1 & Bus-5) has been reduced to 22% in comparison with base case and, compared with the base case, there is an almost two times export increase of reactive power to bus no-2. Voltage regulation is achieved by controlling the production, absorption and flow of reactive power throughout the network. Reactive power flows are minimized so as to reduce system losses. This fact is justified in the Table where the decrement of 0.5% in total system losses has been mentioned by embedding the SVC on the key location in the 14-Bus system.

REFERENCES


