FIRING ANGLE SVC MODEL FOR ANALYZING THE PERFORMANCE OF TRANSMISSION NETWORK USING NEWTON RAPHSON LOAD FLOW

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ABSTRACT

This paper deals with Power flow, which is necessary for any power system solution and carry out a comprehensive study of the Newton-Raphson method of power flow analysis with and without SVC. Voltage stability analysis is the major concern in order to operate any power system as secured. This paper presents the investigation on N-R power flow enhancement of voltage stability and power loss minimization with & without FACTS controllers such as Static Var Compensator (SVC) device. The Static Var Compensator (SVC) provides a promising means to control power flow in modern power systems. In this paper the Newton-Raphson is used to investigate its effect on voltage profile and power system lossess with and without SVC in power system.. Simulations investigate the effect of voltage magnitude and angle with and without SVC on the power flow of the system. This survey article will be very much useful to the researchers for finding out the relevant references in the field of Newton-Raphson power flow control with SVC in power systems. In order to reach the above goals, these devices must be located optimally. In this paper the Optimal placement of SVC is carried out by Voltage collapse Prediction Index (VCPI).The size of the SVC is determined by suitable firing angle which reduces the losses in the system. Simulations have been implemented in MATLAB Software and the IEEE 14 and IEEE 57-bus systems have been used as case studies.

Key words: Flexible AC Transmission System (FACTS), Voltage collapse Prediction Index (VCPI), Static VAR Compensator (SVC) and Newton Raphson Method.

1. INTRODUCTION

The operation of power system is becoming more and more challenging because of continuously increasing load demand which is leading to an augmented stress of the transmission lines, voltage instability, increase in loss and cost. To meet the ever-increasing demand it is now essential to maximize the utilization of the existing transmission system. In recent years, due to advancement in high power solidstate switches, transmission controllers have been developed which provides more flexibility and controllability. A new solution for controlling power flow known as FACTS was introduced in 1988 by Hingorani [1]. FACTS devices have made the power system operation more flexible and secure. They have the ability to control, in a fast and effective manner. FACTS controllers minimizes loss, enhance the voltage profile and the load ability of power systems. FACTS devices include Thyristor Controlled Series Compensator (TCSC), Static VAR Compensator (SVC), Static Compensator (STATCOM), Unified Power Flow Controller (UPFC), etc.

In this paper, SVC is used for several reasons. The most widely used shunt FACTS devices within power networks is the SVC due to its low cost and good performance in system enhancement. It is more conventional and available. SVC can control voltage with higher level of accuracy. It is a shunt connected static VAR generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to provide voltage support and when installed in a proper location, it can also reduce power losses [27]. For these reasons, SVC is chosen over other FACTS devices in this paper.

2. LITERATURE SURVEY

In the literature many people proposed different concepts about the placement and sizing of the SVC.

Hadi Saadat Presented Real and Reactive Power flow equations in polar form by considering two bus power system. A Jacobean matrix is then constructed and Newton Raphson method is used to solve these equations [1]. Hingorani N.G et.al presented about the Fast development of power electronics introduces the use of flexible ac transmission system (FACTS) controllers in power systems. The main benefit of FACTS devices is reduction of operation and transmission investment costs, increasing the power transfer capabilities, system security, controlling power flow in the lines and in improving stability [2]. [3]-[4] papers refer that , SVCs are the combination of mechanically controlled and thyristor controlled shunt capacitors and reactors. Ref [5]-[6] papers proposed the most popular model of SVC's is the combination of either fix capacitor and thyristor controlled reactor or thyristor switched capacitor and thyristor controlled reactor .Ref[7]-[10] papers proposes Existing Basic model of SVC and the novel Firing angle model for Static VAR Compensator (SVC) FACTS devices. In that paper, it explains the power electronic development, fixed capacitor and reactor reactive power compensator has replaced with variable reactance reactive power compensator. Kumar, G.R et.al presented about load flow analysis with incorporated FACTS controllers in multimachine power systems from different operating conditions viewpoint. The Newton Raphson Methods have been proposed in literatures includes for different types of Modeling of Series FACTS controllers[11] .B.Venkateswara rao et.al explains the Implementation of Static VAR Compensator for Improvement of Power System Stability[12] Sahoo et.al (2007) proposed the basic modeling of the FACTS devices for improving the system performance[13].Zhang, X.P et.al explains Jacobian Matrix of Power flow Newton Raphson algorithm and Newton Raphson strong convergence characteristics [14].Gotham.DJ and G.T Heydt (1998) detailed about the optimal location of FACTS devices allows controlling its power flows and thus enhances the reliability of the power systems [15].Povh.D(2000) proposed the nice concepts of the modeling of the power systems and the impact of the FACTS devices on the transmission network [16]. Ref [17]-[20] papers presented the lot of techniques have been developed in predicting the closeness of the system to voltage instability in order to counteract this effect. The prediction is based on voltage collapse prediction index [VCPI] have been used to identify the bus which is more prone to voltage instability. Modelling of the FACTS devices with various techniques with complete computer programming and the operating state determine the maximum power

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carrying capability of the network elements is proposed by Acha et.al. [21]. The impact of multiple compensators in the system was proposed by Radman. G and R.S Raje [22]. The important concepts of the power systems with different load flow was proposed by Stagg. G.W et.al(1968) [23]. Tong Zhu and Gang Haung proposed (1999) the accurate points of the buses which were suitable for the FACTS devices installation [24]. P.Kessal and H. Glavitsch (1986) proposed increase the transmission capability, improvement of stability by installing FACTS devices in transmission network [25].

3. NEWTON RAPHSON METHOD OF POWER FLOW

The Newton-Raphson method is widely used for solving non-linear equations. It transforms the original non-linear problem into a sequence of linear problems whose solutions approach the solutions of the original problem. Load-flow studies [7] are very common in power system analysis. Load flow allows us to know the present state of a system, given previous known parameters and values. The power that is flowing through the transmission line, the power that is being generated by the generators, the power that is being consumed by the loads, the losses occurring during the transfer of power from source to load, and so on, are iteratively decided by the load flow solution, or also known as power flow solution. In any system, the most important quantity which is known or which is to be determined is the voltage at different points throughout the system. Knowing these, we can easily find out the currents flowing through each point or branch.

Since within the power flow problem real power and voltage magnitude are nominal for the voltage-controlled buses, the power flow equations [1] are developed in polar type. For the standard bus of the facility system shown in Figure 1

The current entering bus i is given by

\[ I_i = V_i \sum_{j=i}^{n} y_{ij} \cdot \sum_{j=1}^{n} y_{ij} V_j \quad j = i \]  \hspace{1cm} (1)

This equation can be written in terms of the bus admittance matrix as

\[ I_i = \sum_{j=1}^{n} Y_{ij} V_j \]  \hspace{1cm} (2)

In the above equation, j includes bus i. Expressing this equation in polar form, we have

\[ I_i = \sum_{j=1}^{n} |Y_{ij}| |V_j| \cdot \theta_{ij} + \delta_j \]  \hspace{1cm} (3)
The complex power at bus i

\[ P_i - jQ_i = V_i^* I_i \]  \hspace{1cm} (4)

Substituting from 2.3 for \( I_i \) in 2.4

\[ P_i - jQ_i = |V_i| \angle \theta_i \sum_{j=1}^{n} |Y_{ij}| |V_j| \angle \theta_j + \delta_j \]  \hspace{1cm} (5)

Separating real and imaginary parts

\[ P_i = \sum_{j=1}^{n} |V_i| |V_j| Y_{ij} \cos(\theta_i + \delta_i - \theta_j) = P_i(|V|, \delta) \]  \hspace{1cm} (6)

\[ Q_i = \sum_{j=1}^{n} |V_i| |V_j| Y_{ij} \sin(\theta_i + \delta_i - \theta_j) = Q_i(|V|, \delta) \]  \hspace{1cm} (7)

The power mismatch equations \( \Delta P \) and \( \Delta Q \) are expanded around a base point \((\theta(0), V(0))\) and, hence, the power flow Newton–Raphson algorithm is expressed by the following relationship.

\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} =
\begin{bmatrix}
\frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\
\frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V}
\end{bmatrix}
\begin{bmatrix}
\Delta \theta \\
\Delta V
\end{bmatrix}
\]  \hspace{1cm} (8)

Where

\( \Delta P \) is the change of real power at the bus.

\( \Delta Q \) is the change of reactive power at the bus.

\( \frac{\partial P}{\partial \theta} \) is the change in real power w.r.t angle at the buses

\( \frac{\partial P}{\partial V} \) is the change in real power w.r.t change in voltage magnitude at the buses

\( \frac{\partial Q}{\partial \theta} \) is the change in reactive power w.r.t angle at the buses

\( \frac{\partial Q}{\partial V} \) is the change in reactive power w.r.t change in Voltage magnitude at the buses

\( \Delta V \) is the change in voltage at the bus

\( \Delta \theta \) is the change in angle at the bus

4. SHUNT COMPENSATION

Shunt compensation is widely used in power system to enhance loadability and to improve voltage stability. At buses where reactive power demand increases, bus voltage can be controlled by connecting capacitor banks in parallel to a lagging load. Capacitor banks supply part of or full reactive power of load, thus reducing magnitude of the source current necessary to supply load. Consequently the voltage drop between the sending end and the load gets reduced, power factor will be improved and increased active power output will be available from the source. Depending upon load demand, capacitor banks may be permanently connected to the system or can be varied by switching ON or OFF the parallel connected capacitors either manually or automatically (M.L.Soni, P.V.Gupta and U.S.Bhatnagar, 1994).

Shunt compensation is of two types:
4.1. Shunt Capacitive Compensation
This method is used to improve the power factor. Whenever an inductive load is connected to the transmission line, power factor lags because of lagging load current. To compensate, a shunt capacitor is connected which draws current leading the source voltage. The net result is improvement in power factor.

4.2. Shunt Inductive Compensation
This method is used either when charging the transmission line, or, when there is very low load at the receiving end. Due to very low, or no load – very low current flows through the transmission line. Shunt capacitance in the transmission line causes voltage amplification (Ferranti effect). The receiving end voltage may become double the sending end voltage (generally in case of very long transmission lines). To compensate, shunt inductors are connected across the transmission line.

The Examples of shunt compensation are Thyristor controlled reactor (TCR), Static Synchronous Compensator (STATCOM), Thyristor Switched reactor (TSR), Thyristor Switched Capacitor (TSC) and etc.

5. STATIC VAR COMPENSATOR (SVC)
A static var compensator (SVC) is the first generation shunt compensator. It has been around since 1960s. In the beginning it was used for load compensation such as to provide var support for large industrial loads, for flicker mitigation etc. However with the advancement of semiconductor technology, the SVC started appearing in the transmission systems in 1970s. Today a large number of SVCs are connected to many transmission systems all over the world. An SVC is constructed using the thyristor technology and therefore does not have gate turn off capability.

A typical SVC consists of Thyristor-Switched Reactors (TSRs) and Thyristor-Switched Capacitors (TSCs) or a fixed Capacitor in parallel. The output of the compensator is controlled in steps by sequentially switching of TCRs and TSCs. The need for harmonic filtering as part of the compensator scheme could be eliminated by stepwise switching of reactors rather than continuous control. The figure shows the basic construction model of SVC device.

![Figure2 The basic construction model of SVC device.](http://www.iaeme.com/IJEET/index.asp)
6. FIRING ANGLE MODEL STATIC VAR COMPENSATOR

The SVC consists of a group of shunt-connected capacitors and reactors banks with fast control action by means of thyristor switching. The firing angle model for SVC is shown in figure 2.

![Firing Angle Model of SVC](image)

**Figure 3** The Firing angle model of SVC

SVC's normally include a combination of mechanically controlled and thyristor controlled shunt capacitors and reactors [3], [4]. The most popular configuration for continuously controlled SVC's is the combination of either fix capacitor and thyristor controlled reactor or thyristor switched capacitor and thyristor controlled reactor [5], [6]. As far as steady-state analysis is concerned, both configurations can be modeled along similar lines. The SVC structure shown in Fig. 2 is used to derive 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 [5],

\[
X_{Leq} = X_L \frac{\pi}{2(\pi - \alpha) + \sin(2\alpha)} \tag{9}
\]

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

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

\[
X_{eq} = \frac{X_C X_L}{\frac{X_C X_L}{\pi(2(\pi - \alpha) + \sin(2\alpha))} - X_L} \tag{10}
\]

In general, the transfer admittance equation for the variable shunt compensator is,

\[
I_{svc}(i) = jB_{svc} V(i) \tag{11}
\]

Where

The SVC equivalent susceptance is given by (4) whilst its profile, as function of firing angle,

\[
B_{svc} = B_c - B_{TCR} = -\frac{1}{X_L} (X_L - X_c \frac{2(\pi - \alpha) + \sin 2\alpha}{\pi}) \tag{12}
\]

\[
X_L = wL X_C = \frac{1}{wc} \tag{13}
\]

and the reactive power equation is,
From the equation (14), the linearized SVC equation is given by as

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

(15)

7. VOLTAGE COLLAPSE PREDICTION INDEX (VCPI)

The technique [VCPI] is derived from the basic power flow equation. The technique is applicable for any number of buses in a system. It needs the voltage phasor information of the participating buses in the system and the network admittance matrix. Using the measured voltage phasors and the network admittance matrix of the system, the voltage collapse prediction index (VCPI) is calculated at every bus. The values of these indexes determine the proximity to voltage collapse at a bus. The detailed derivation of the technique [VCPI] is given in Appendix 7 of the Ref [17] paper. The power flow equations are resolved by Newton Raphson methodology that creates a partial matrix. By setting the determinant of the matrix to zero, the index at bus k is written as follows:

\[
VCPI_k = 1 - \frac{\sum_{m \neq k} V_m'}{V_k'}
\]

(16)

Where,

\[
V_m' = \frac{Y_{km}}{\sum_{j=1, j \neq k}^{N} Y_{kj}} V_m
\]

(17)

Vk is the voltage phasor at bus k
Vm is the voltage phasor at bus m
Ykm is the admittance between bus k and m
Ykj is the admittance between bus k and j
k is the monitoring bus
m is the other bus connected to bus k
N is the bus set of the system

The value of VCPI varies between zero and one. If the index is zero, the voltage at bus k is taken into account stable and if the index is unity, a voltage collapse is claimed to occur. VCPI is calculated solely with info of voltage phasor of taking part buses and impedance of relating lines. The calculation is straightforward while not matrix conversion. The technique offers quick calculation which may be applied for on-line watching of the power system

8. SIMULATION RESULTS

The proposed system is applied is two different test cases which are IEEE 14 and IEEE 57 bus systems by using MATLAB software.
8.1. Test case 1: IEEE 14 Bus System
The single line diagram of IEEE 14 bus system is shown in the figure 1 and the voltage profile for IEEE 14 bus system without SVC is shown in figure 2.

![Figure 4 Single line diagram of IEEE 14 bus system.](image)

![Figure 5 Voltage profile of IEEE 14 bus system without SVC](image)

8.1.1. Single SVC Placement
The placement of shunt compensating device which is SVC is determined by VCPI. The highest value of VCPI reveals the suitable location of SVC. The placement of single SVC by using VCPI is implemented on IEEE 14 bus system. The VCPI values of the IEEE 14 bus system is shown in the table 1. From the table 1, the single SVC is placement is decided at 14th bus. The VCPI is high at 14th bus, so shunt compensating device such as SVC is optimally placed at 14th bus of the system. By placing SVC at 14th bus location of the transmission network the real and reactive power losses are reduced. The real and reactive power losses are reduced to 9.44 MW and 49.44 MVar. The voltage profile, total real and reactive power losses without placing of SVC and with the placing of single SVC are shown in the figure 3, 4 and 5 respectively.
Table 1 Voltage Collapse Prediction Index (VCPI) of IEEE 14 bus system

<table>
<thead>
<tr>
<th>Bus no</th>
<th>VCPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1760</td>
</tr>
<tr>
<td>2</td>
<td>0.0679</td>
</tr>
<tr>
<td>3</td>
<td>0.2060</td>
</tr>
<tr>
<td>4</td>
<td>0.1529</td>
</tr>
<tr>
<td>5</td>
<td>0.1300</td>
</tr>
<tr>
<td>6</td>
<td>0.2591</td>
</tr>
<tr>
<td>7</td>
<td>0.2319</td>
</tr>
<tr>
<td>8</td>
<td>0.2184</td>
</tr>
<tr>
<td>9</td>
<td>0.2874</td>
</tr>
<tr>
<td>10</td>
<td>0.2967</td>
</tr>
<tr>
<td>11</td>
<td>0.2827</td>
</tr>
<tr>
<td>12</td>
<td>0.2920</td>
</tr>
<tr>
<td>13</td>
<td>0.2993</td>
</tr>
<tr>
<td>14</td>
<td>0.3408</td>
</tr>
</tbody>
</table>

Figure 6 Voltage profile of IEEE 14 bus with and without single SVC.
8.1.2. Placement of Two SVC’s

With the inclusion of two SVC’s in the bus system i.e one SVC is locate at 14th bus and second SVC is locate at 13th bus then the power flows are further improved and losses further are reduced which is shown in the table 2. The voltage profile, total real and reactive power losses without placing of SVC and with the placing of two SVC’s are shown in the figure 6,7 and 8 respectively.
Figure 9 Voltage profile of IEEE 14 bus with and without two SVCs

Figure 10 Total Real power losses of IEEE 14 bus with and without two SVCs

Figure 11 Total Reactive power losses of IEEE 14 bus with and without two SVCs
From the above table, it is shown that without SVC the Real and Reactive power losses are 9.682 MW and 50.04 MVar. In case placing single SVC the losses are Reduced i.e Real and Reactive power losses are 9.44 MW and 49.44 MVar and for two SVC’s 9.32 MW & 48.44 MVar.

8.2. Test case 2: IEEE 57 bus
The single line diagram of the IEEE 57 bus system is shown in the figure 9. The improvement of voltage profile, the reduction of total real and reactive power losses, are shown in the figure 9.
8.2.1. Single SVC Placement

The placement of single SVC by using VCPI is implemented on IEEE 57 bus system. By placing single SVC at 33rd bus location of the transmission network, the real and reactive power losses are reduced. The real and reactive power losses are reduced to 27.864 MW and 119.27 MVar from 27.964 MW and 121.67 MVar. The voltage profile, total real and reactive power losses without placing of SVC and with the placing of single SVC are shown in the figure 10,11 and 12 respectively.

![Voltage profile of IEEE 57 bus with and without single SVC](image13)

**Figure 13** Voltage profile of IEEE 57 bus with and without single SVC

![Total Real power losses of IEEE 57 bus with and without single SVC](image14)

**Figure 14** Total Real power losses of IEEE 57 bus with and without single SVC
8.2.2. Placement of Two SVC’s

With the inclusion of two SVC’s in the bus system i.e one SVC is locate at 33rd bus and second SVC is locate at 51th bus then the power flows are further improved and losses further are reduced which is shown in the table 3. The voltage profile, total real and reactive power losses without placing of SVC and with the placing of two SVC’s are shown in figures 13,14 and 15 respectively.
Figure 17 Total Real power losses of IEEE 57 bus with and without two SVCs

Figure 18 Total Reactive power losses of IEEE 57 bus with and without two SVCs
Table 3 Comparative system parameters of IEEE 57 bus with and without single & two SVCs

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Without SVC</th>
<th>With SINGLE SVC</th>
<th>With TWO SVC’S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Voltage(p.u)</td>
<td>0.936 at bus 31</td>
<td>0.9638 at bus 26</td>
<td>0.9618 at bus 26</td>
</tr>
<tr>
<td>Maximum Voltage(p.u)</td>
<td>1.06 at bus1</td>
<td>1.0412 at bus 49</td>
<td>1.0392 at bus 49</td>
</tr>
<tr>
<td>Real power losses(MW)</td>
<td>27.964</td>
<td>26.864</td>
<td>26.424</td>
</tr>
<tr>
<td>Reactive power losses(MVar)</td>
<td>121.67</td>
<td>119.27</td>
<td>115.27</td>
</tr>
<tr>
<td>Location of SVC</td>
<td>--------------</td>
<td>33rd bus</td>
<td>33rd bus, 51 bus</td>
</tr>
<tr>
<td>SVC 1 firing angle(deg)</td>
<td>-------------</td>
<td>122.3</td>
<td>126.3</td>
</tr>
<tr>
<td>SVC2 firing angle(deg)</td>
<td>-------------</td>
<td>------</td>
<td>124.3</td>
</tr>
<tr>
<td>Size of SVC1(kVar)</td>
<td>--</td>
<td>3.82</td>
<td>1.74</td>
</tr>
<tr>
<td>Size of SVC2(KVar)</td>
<td>--</td>
<td>------</td>
<td>2.35</td>
</tr>
</tbody>
</table>

From the above table, it is shown that without SVC the Real and Reactive power losses are 27.964 MW and 121.67 MVar. In case placing single SVC the losses are Reduced i.e Real and Reactive power losses are 26.864 MW and 119.27 MVar and for two SVC’s 26.424 MW & 115.27 MVar.

9. CONCLUSION

In this paper, the optimal location and optimal sizing of SVC device is find out to minimize voltage deviation and the active power losses in the power system network using Newton Raphson Technique. The Firing Angle Model of Static VAR Compensator (SVC) using Newton Raphson method has been implemented on IEEE 14 and 57 bus test systems to investigate the performance of power transmission line in absence as well as in presence of single and double SVC devices. It is found that during presence of single SVC there is reduction of real and reactive power losses and also voltage profile improvement as compared to absence of SVC and with double SVCs also there is reduction in losses and there is more improvement in voltage profiles. The results obtained by application of the N-R technique during firing-angle model based control are found to be very much similar with the reactance model. It is noted that as compared to Reactance method, the implementation of the firing-angle based control of SVC using NR technique is much easier. It is also noted that the firing-angle calculation of SVC using firing-angle model based control is much easier as compared to impedance model based control and this proposed method is better than earlier published works like reactance models and power injection models.
REFERENCE


Firing Angle SVC Model for Analyzing the Performance of Transmission Network using Newton Raphson Load Flow


