Analysis of the Effect of Tap Changing Transformer on Performance of SVC

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Abstract— Most of the world’s electric power supply systems are widely connected, involving connections inside utilities of own territories which extend to inter-utility interconnections and then to inter-regional and international connections. This is done for economic reasons, to reduce the cost of electricity and to improve reliability of power supply. Worldwide transmission systems are undergoing continuous changes and restructuring due to steady growth in demand for electric power, much of which has to be transmitted over long distances. Moreover, in today’s scenario power systems are more difficult to operate, the reason behind this is deregulation issues which requires an open access power delivery system which enables power delivery within and between the regions, facilitates access to interconnected competitive generation, little or no market based incentives for transmission investment & the other reliability, security and stability issues. These trends have led to extensive research interest in flexible ac transmission systems (FACTS), with the aim of developing new devices and technologies to control the flow of power, so as to allow more efficient usage of existing power generation and transmission power plants. The focus of this research work is on the application of Static VAR Compensator with tap-changing transformer to solve voltage regulation and power transfer capabilities.

Keywords— FACTS; Voltage stability; SVC; OLTC; PV curve

I. INTRODUCTION

The recent studies reveal that FACTS controllers could be employed to enhance power system stability in addition to their main function of power flow control. The literature shows an increasing interest in this subject for the last two decades, where the enhancement of system stability using FACTS controllers has been extensively investigated. SVC is a mature thyristor based controller that provides rapid voltage control to support electric power transmission voltages during and immediately after major system disturbances.

Several studies have shown that transformer with automatic tap-changing can be used for improvement of voltage stabilities \cite{4, 5}, for both steady state and transient voltage stabilities.

Some of these studies were interested in proposing new models of tap-changing transformers. On the other hand, Static VAR compensator is used for improvement of voltage stabilities \cite{6, 7, 8} due to line opening in the presence of induction motor or due to starting of induction motor or due to recoveries of short-circuit at induction motor terminals or due to heavy load abilities. With this static VAR compensator we can also use the series capacitor \cite{9}. The combination of the static VAR compensator and tap-changing transformer is suggested in \cite{10}.

Hiroshi Ohtsuki, Akihiko Yokoyama, Yasuji Sekine, presented the work on Reverse action of on-load tap-changer in association with voltage collapse \cite{4}. They discuss the reverse action that the secondary voltage of a transformer is pulled down when the tap position of on-load tap changer is raised to increase the secondary voltage.

S. Milan, Calovic, presented the work on Modeling and analysis of under load tap-changing transformer control systems \cite{5}. Here a nonlinear system model is derived, suitable for analysis of voltage and reactive power flow control applications of ULTC transformers in the consideration of mid-term and long-term dynamics and steady-state behavior of power systems.

M.Z. El-Sadek, et al, discussed the Enhancement of steady-state voltage stability by using static VAR compensators \cite{6}. Steady-state voltage instability can certainly be enhanced by static VAR compensators which can hold certain node voltages constant and create infinite buses within the system nodes. Static VAR compensator parameters needed for this purpose are found. Mark Ndubuka discussed the Voltage Stability Improvement using Static VAR Compensator in Power Systems \cite{7}. They investigate the effects of Static VAR Compensator (SVC) on voltage stability of a power system. The functional structure for SVC built with a Thyristor Controlled Reactor (TCR) and its model are described. The model is based on representing the controller as variable impedance that changes with the firing angle of the TCR.
Voltage collapse is the catastrophic rotor angle l. The proposed Scheme is transform of infinite operating conditions and after being testing from heavily stressed systems to keep desired voltages. system to meet the demands for reactive causing amount of electrical power to the loads. The main factor power system lacks the capability to profile suddenly in a major part of the power system.‖ Voltage control and instability are local problems. capability of the combined transmission and generation load dynamics to restore power consumption beyond the load, decrement of production and/or weakening of voltage (generator, line, transformer, bus bar, etc.), increment of load, decrement of production and/or weakening of voltage control. According to reference the definition of voltage instability is “Voltage instability stems from the attempt of load dynamics to restore power consumption beyond the capability of the combined transmission and generation system.” Voltage control and instability are local problems. However, the consequences of voltage instability may have a widespread impact. Voltage collapse is the catastrophic result of a sequence of events leading to a low-voltage profile suddenly in a major part of the power system. Voltage stability can also be called “load stability”. A power system lacks the capability to transfer an infinite amount of electrical power to the loads. The main factor causing voltage instability is the inability of the power system to meet the demands for reactive power in the heavily stressed systems to keep desired voltages.

II. VOLTAGE STABILITY

Power system stability is defined as a characteristic for a power system to remain in a state of equilibrium at normal operating conditions and to restore an acceptable state of equilibrium after a disturbance. Traditionally, the stability problem has been the rotor angle stability, i.e. maintaining synchronous operation. Instability may also occur without loss of synchronism, in which case the concern is the control and stability of voltage.

The voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system at normal operating conditions and after being subjected to a disturbance.”

Power system is voltage stable if voltages after a disturbance are close to voltages at normal operating condition. A power system becomes unstable when voltages uncontrollably decrease due to outage of equipment (generator, line, transformer, bus bar, etc.), increment of load, decrement of production and/or weakening of voltage control. P-V curve is one of the method to analyze voltage stability. The PV-curve presents load voltage as a function of load or sum of loads. It presents both solutions of power system. The power system has low current-high voltage and high current-low voltage solutions. Power systems are operated in the upper part of the PV-curve. This part of the PV-curve is statically and dynamically stable. The head of the curve is called the maximum loading point. The critical point where the solutions unite is the voltage collapse point. The maximum loading point is more interesting from the practical point of view than the true voltage collapse point, because the maximum of power system loading is achieved at this point. The maximum loading point is the voltage collapse point when constant power loads are considered, but in general they are different.
The voltage dependence of loads affects the point of voltage collapse. The power system becomes voltage unstable at the voltage collapse point. Voltages decrease rapidly due to the requirement for an infinite amount of reactive power. The lower part of the PV-curve (to the left of the voltage collapse point) is statically stable, but dynamically unstable. The power system can only operate in stable equilibrium so that the system dynamics act to restore the state to equilibrium when it is perturbed.

Figure 1 Example of P-V Curve

Figure 1.2 presents five PV-curves for the test system (V =400 kV and X =100 Ω). These curves represent different load compensation cases (tan = Q/P). The load compensation makes it possible to increase the loading of the power system according to voltage stability.

The automatic voltage control of power transformers is arranged with on-load tap changers. The action of tap changer affects the voltage dependence of load seen from the transmission network. Typically a transformer equipped with an on-load tap changer feeds the distribution network and maintains constant secondary voltage. When voltage decreases in the distribution system, the load also decreases. The tap changer operates after time delay if voltage error is large enough restoring the load.

Facts Controllers For Power System

FACTS Controller is “A power electronic based system and other static equipment that provide control of one or more AC transmission system parameters.”

In general FACTS controllers can be divided in to three categories:

1. shunt connected controllers
2. series connected controllers
3. combined shunt & series connected controllers

Key benefits of applying FACTS to eliminate transmission constraints:

1. Voltage stability
2. Increased loading and more effective use of transmission corridors
3. Added power flow control
4. Increased system security
5. Increased system reliability
6. Added flexibility in siting new generation
7. Elimination or deferral of the need for new transmission lines

A shunt connected static VAR generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus bar voltage). This is the general term used for a thyristor-controlled or thyristor-switched reactor or thyristor-switched capacitor or combination. SVC is based on thyristor without the gate turn off capability.

By placing the shunt compensator in the middle of a line and therefore dividing the line into two segments, the voltage at this point can be controlled such that it has the same value as the end line voltages. This has the advantage that the maximal power transmission is increased. If the shunt compensator is located in the end of a line in parallel to a load it is possible to regulate the voltage at this end and therefore to prevent voltage instability caused by load variations or generation or line outages.

III. INTRODUCTION ABOUT SYSTEM UNDER STUDY

A large Power System which feeds a certain load or power (P+jQ) is used in this study as shown in Fig. 3.1. The system, at steady-state conditions can be represented by its Thévenin’s equivalent seen from node 5 as shown in fig. 3.2. The tap-changing transformer is connected at the load terminal, its off-nominal tap ratio is ‘t’. Transformer reactance at unity off-nominal tap ratio is X. All the system voltage and impedance will be referred to the system load side.
Figure 2: Large power system.

Figure 3: Thevenin’s equivalent system shows the load node terminals.

\[ \Delta V = \frac{|V_s|}{I} \] 

Data used in this study: \( V_s = 1.004 \) p.u., \( Z_s = 0.3228 \) p.u., \( X_i = 0.0125 \) p.u., \( X_t = 0.3125 \) p.u., \( H = 1.0 \) p.u., \( R_s = 0.08126 \) p.u., \( X_c = 4.5 \) p.u. and \( t = 0.8 - 1.2 \).

Power System Model With Tap-Changing Transformer And Static Var Compensator

A thyristor-control reactor /fixed capacitor (TCR/FC) type is used. Its control system consists of a measuring circuit for measuring its terminal voltage \( V_t \), a regulator with reference voltage and a firing circuit which generates gating pulses in order to command variable thyristor current \( I_L \), through the fixed reactor reactance \( X_L \).

This variable current draws variable reactive power \( (I_L^2X_L) \) which corresponds to variable virtual reactance of susceptance \( B_L \) given by:

\[ V_t^2B_L = I_L^2X_L \]

Together with the fixed capacitive reactive power, these form the hole variable inductive and capacitive reactive power of that static compensator. Fig. 3.3 shows a block diagram of that compensator when connected to a large power system.

![Block diagram of a loaded power system, tap-changing transformer and SVC](image)

Fig. 3.4 shows the transfer function of the power system provided by the tap changing transformer and a static VAR compensator. The off-nominal tap ratio of the tap-changing transformer is ‘t’. Fig. 3.5 shows the simplified transformer function block diagram of that system with combined tap-changing transformer and static VAR compensator.
Figure 6. Simplified transfer function block diagram of a loaded power system, tap-changing transformer and SVC

IV. RESULTS AND DISCUSSION

(A) P-V curve with the presence of tap changing transformer and SVC

The famous nose curve of the Voltage/Power relation is plotted in Fig. 4.1. When the transformer off-nominal tap ratios are varied within the known practical range (t = 0.8-1.2) and with various static compensator gains

(a) CASE 1 WHEN G=0

(b) CASE 2 WHEN G=2.5

(c) CASE 3 WHEN G=5

Figure: 7 Voltage/Power response with different off-nominal tap ratios (0.8-1.2), with constant Q and with G = 0.0

Figure: 8 Voltage/Power response with different off-nominal tap ratios (0.8-1.2), with constant Q and with G = 2.5

Figure: 9 Voltage/Power response with different off-nominal tap ratios (0.8-1.2), with constant Q and with G = 5.0
(d) CASE 4 WHEN G = 10

Table-1.2, however, shows the maximum load power corresponding to various values of SVC controller gains. Once more, this value is same at all off-nominal transformer tap ratio. Therefore, at a gain of 5 the maximum transmitted power can be increased to 360% and a gain of 10 can increase it by 600% of its value without static VAR compensator. This is important result illustrates the limited effects of the tap-changing transformer compared to the static VAR compensator, significant effects, at different controller gains.

(B) Influence of Tap-Changing Transformer on SVC Controller Gain versus Slope Relation.

![Figure 10 Voltage/Power response with different off-nominal tap ratios (0.8-1.2), with constant Q and with G = 10](image)

![Figure 11 SVC controller drop Slope/Gain relation in the presence of tap-changing transformer in order to maintain the load voltage constant.](image)

From all these curves we notice that the off-nominal tap ratio variation does not affect the critical power value at various SVC gain, i.e. this value remains constant at all off-nominal transformer’s ratios. However off-nominal tap ratio affects largely the load voltage magnitude at no-load conditions. At lower values, they affect the load at other loadings conditions.

The compensator application increases the maximum power largely as shown in the figures 4.1, 4.2, 4.3, 4.4, for different SVC controller gains. The same previous features of their variations with different off-nominal tap ratios are noticed. The same maximum power and different critical voltages largely affect the no-load conditions than the heavy loadings.

<table>
<thead>
<tr>
<th>Sr.No.</th>
<th>Compensator Gain (G)</th>
<th>Approximate Maximum Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>2.39</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>4.8</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>7.3</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>12.3</td>
</tr>
</tbody>
</table>

![Table II Maximum Load Power as Affected by Compensator Controller Gains](image)
For a slope of 0.2, the SVC controller gain/compensator rating \((1/X_C)\) relation is plotted in fig. 4.12 with three off-nominal tap ratio’s as \(t = 0.8\), 1 and 1.2. The plot shows different compensator power ratings are required at each compensator controller gain, in order to keep load voltage constant in the presence of automatic tap-changing transformer of different off-nominal tap ratios.

![Fig. 4.12 Compensator design parameter/controller gain relation in the presence of tap-changing transformer](image)

TABLE III

<table>
<thead>
<tr>
<th>Sr.No.</th>
<th>Gain (P.U.)</th>
<th>Off-nominal tap ratio (t = 0.8) (P.U.)</th>
<th>Off-nominal tap ratio (t = 1.0) (P.U.)</th>
<th>Off-nominal tap ratio (t = 1.2) (P.U.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>1.2</td>
<td>0.7</td>
<td>0.56</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>1.7</td>
<td>1.08</td>
<td>0.75</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>2.43</td>
<td>1.57</td>
<td>1.07</td>
</tr>
<tr>
<td>4</td>
<td>150</td>
<td>2.7</td>
<td>1.74</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table-1.3 shows the needed SVC ratings corresponding to different controller gain, and different transformer off-nominal tap ratios.

V. CONCLUSION

Presence of only tap-changing transformers does not improve voltage stability significantly. They do affect the voltage levels and slightly the critical voltages, but do not affect the maximum powers corresponding to these critical voltages. Therefore, tap-changing transformer at the load terminals can slightly contribute to its voltage stability.

Presence of Static VAR Compensator with different controller gains can increase the maximum load powers several times as compared to its original value without Static VAR Compensator.

There is an interaction between the transformer off-nominal tap ratio and the compensator controller gains and reference voltages, in order to keep the load node voltage constant at all loading conditions.

The compensator ratings is affected with presence of tap-changing transformer, the fixed reactance of the TCR type compensator changes significantly with the presence of tap-changing transformer. Certain transformer off-nominal tap ratios minimizes the SVC needed ratings, i.e. in the presence of tap-changing transformer, the SVC rating required to keep the load voltage constant at certain value is reduced significantly.

REFERENCES


