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A Study on Integrated Performance of Tap-Changing Transformer and SVC in Association with Power System Voltage Stability

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***Abstract*—**Electricity market activities and a growing demand for electricity have led to heavily stressed power systems. This requires operation of the networks closer to their stability limits. Power system operation is affected by stability related problems, leading to unpredictable system behavior. Voltage stability refers to the ability of a power system to sustain appropriate voltage levels through large and small disturbances. Steady-state voltage stability is concerned with limits on the existence of steady-state operating points for the network. FACTS devices can be utilized to increase the transmission capacity, the stability margin and dynamic behavior or serve to ensure improved power quality. Their main capabilities are reactive power compensation, voltage control and power flow control. Among the FACTS controllers, Static Var Compensator (SVC) provides fast acting dynamic reactive compensation for voltage support during contingency events. In this paper, voltage stability assessment with appropriate representations of tap-changer transformers and SVC is investigated. Integrating both of these devices is the main topic of this paper. Effect of the presence of tap-changing transformers on static VAR compensator controller parameters and ratings necessary to stabilize load voltages at certain values are highlighted. The interrelation between transformer off nominal tap ratios and the SVC controller gains and droop slopes and the SVC rating are found. P-V curves are constructed to calculate loadability margins.

***Keywords*—**SVC, voltage stability, P-V curve, reactive power, tap changing transformer.

I. Introduction

PRESENT power systems are now large, complex and interconnected systems, which consist of thousand of buses and hundreds of generators [1]-[3]. New installations of power stations and other facilities are primarily determined based on environmental and economic reasons. In addition, new transmission lines are expensive and take considerable amount of time to construct. Given these conditions, in order to meet ever-increasing load demands, electric utilities have to rely on power export/import arrangements through the existing transmission system, deteriorating voltage profiles and system stability in some cases. This situation has resulted in an increased possibility of transient, oscillatory and voltage instability, which are now brought into concerns of many utilities especially in planning and operation [3]-[5]. Moreover, the trend of the deregulated power system has led to some unexpected problems, such as voltage instability, etc.

It has been well recognized that voltage stability is a very important issue for operating power networks when the continuous load increase along with economic and environmental constraints has led to systems to operate close to their limits including voltage stability limit [6], [7]. Voltage stability has become a critical issue due to the continuous load increase along with economical and environmental constraints, leading systems to operate close to their limits, with reduced stability margins [8]. Thus, an accurate knowledge of how far the current system's operating point is from the voltage stability limit is crucial to operators. They must assess whether the system has a secure and feasible operation point following a given disturbance, such as a transmission line outage or sudden change in system loading [9].

Reactive power compensation is an important issue in electrical power systems and shunt flexible ac transmission system (FACTS) devices play an important role in controlling the reactive power flow to the power network and hence the system voltage fluctuations and stability [10]. The recently developed FACTS technology provides a way to relieve the stability problem imposed by increasing load demand [11]. FACTS controllers provide fast and reliable control over the three main transmission parameters, i.e., voltage magnitude, phase angle and line impedance. For this reason, control of FACTS devices has received a lot of attention in power system stability enhancement. Using FACTS controllers, like Static Var Compensator (SVC) and Static Phase Shifter (SPS), to improve transient stability has been explored in the past years and is shown to be effective [12], [13]. The application of P-V curves also provides a means to evaluate the voltage stability of a power system for various conditions and contingencies.

In this paper the integration of the SVC and tap-changing transformer is suggested. 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. SVC parameters needed for this purpose are found. The influence of the presence of tap-changing transformers on compensator gains, reference voltage values and ratings of SVC are given in detail. SVC rating and controller references and gains are found in order to stabilize load voltage at certain specified values. Interaction between these two means parameters are highlighted.

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II. Overview on the Static Voltage Stability

As defined in [3], “Voltage stability is the process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system”. There are two types of voltage stability based on the time frame of simulation: static voltage stability and dynamic voltage stability. Static analysis involves only the solution of algebraic equations and therefore is computationally less extensive than dynamic analysis. Voltage stability is inherently a dynamic problem. But since time domain simulations are time consuming and also they do not readily provide the sensitivity information or the degree of stability [7]. For these reasons generally for bulk system studies the static analysis is preferred in order to provide more insight into the voltage and reactive power problem. In static voltage stability, slowly developing changes in the power system occur that eventually lead to a shortage of reactive power and declining voltage. This phenomenon can be seen from the plot of the power transferred versus the voltage at receiving end. The plots are popularly referred to as P-V curve or “Nose” curve. As the power transfer increases, the voltage at the receiving end decreases. Eventually, the critical (nose) point, the point at which the system reactive power is short in supply, is reached where any further increase in active power transfer will lead to very rapid decrease in voltage magnitude. Before reaching the critical point, the large voltage drop due to heavy reactive power losses can be observed. The only way to save the system from voltage collapse is to reduce the reactive power load or add additional reactive power prior to reaching the point of voltage collapse [10].

In static voltage stability the slow changes in the power system eventually lead the system into instability situations with declining voltage and shortage of reactive power. This can be observed from the P-V curve analysis, wherein it demonstrates as the power transfer increases the voltage at the receiving end decreases as show in Fig. 1. The nose-point or bifurcation point pinpoints to the maximum limit beyond which the system collapses because of lack of enough reactive support to maintain the voltage profile. One solution to this problem is to reduce reactive power load or add additional reactive power prior to the collapse point.

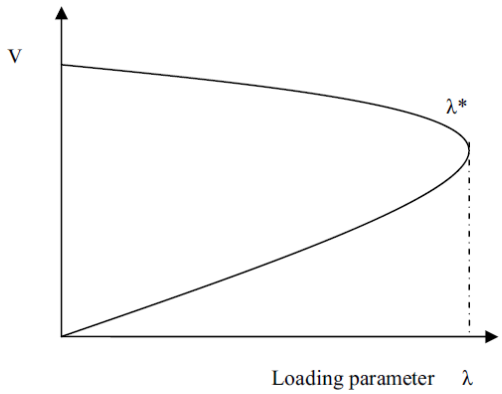

Fig. 1 Traditional P-V curve

III. On Load Tap-Changing Transformer

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 [14].

The action of an on-load tap changer might be dangerous for a power system under disturbance [15]. The stepping down of the tap changer increases the voltage in a distribution network; thus reactive power transfer increases from the transmission network to the distribution network. Fig. 2 illustrates the action of tap changer caused by a disturbance seen from the transmission network. The power system operates at point A in the pre-disturbance state. Due to the disturbance the operation point moves to point B, which is caused by decrement of secondary voltage and load dependence of voltage. The load curve represents the state of power system just after the disturbance. After a time delay the tap changer steps down to increase secondary voltage. The operation point seen from the transmission network moves along the post-disturbance P-V curve towards a maximum loading point, which causes decrement of the primary voltage. The tap changer operates until the secondary voltage reaches the nominal voltage at point D. The amount of load at points A and D is equal due to action of tap changer. The operation point D is stable, but quite closes the post-disturbance maximum loading point.

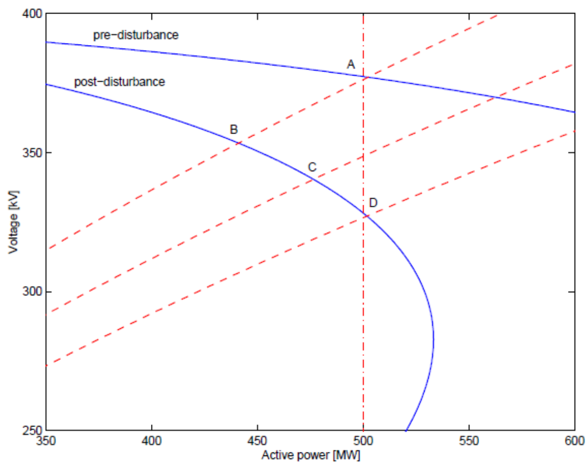

Fig. 2 The action of on-load tap changer caused by a disturbance

The voltage dependence of the loads can be seen when the on-load tap changer reaches the tap changer minimum limit, in which case on-load tap changer is not capable of maintaining constant secondary voltage. The step size of the on-load tap changer should also be taken into account in load-flow based long-term voltage stability studies [16]. The restoration of load may occur although distribution network voltage is not

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increased to nominal or pre-disturbance value. A thermostat typically controls heating and cooling loads. The energy consumed in the thermostatic loads is constant in the long run. Although heating loads are resistive, the thermostats increase the amount of load if the decrement of load voltage is long enough. The time constants of thermostatic loads are high, which makes this phenomenon slow. The thermostatic load is modeled as constant impedance load with a long time constant. A long interruption or voltage decrement might also cause a phenomenon called cold load pick-up, where the load becomes higher than nominal value due to manual connection of additional load to compensate decreased power supply.

IV. Study System

A large Power System which feeds a certain load or power $(P + jQ)$ is used in this study as shown in Fig. 3. The system, at steady-state conditions can be represented by its Thevenin's equivalent seen from node 5 as shown in Fig. 4. 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_t.

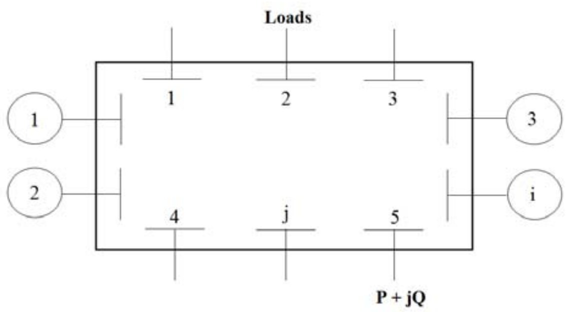

Fig. 3 Large power system

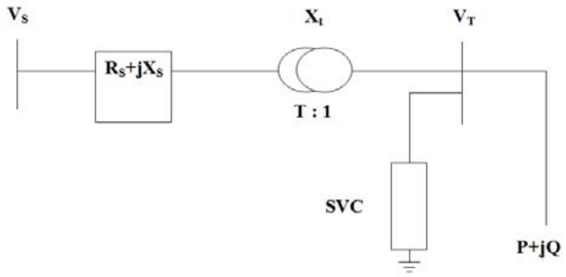

Fig. 4 Thevenin's equivalent system shows the load node terminals

In order to be able to use the approximate voltage drop formula; $(X_S Q + R_S P)/V_T = |V_S| - |V_T|$. All the system voltage and impedances will be referred to the system load side, i.e. $(V_S / t), (R_S / t^2), (X_S / t^2), (X_t / t^2)$.

The link voltage drop will therefore be.

$$\Delta V = \left|\frac{V_S}{t}\right| - |V_T| = \frac{\frac{(X_S + X_t)}{t^2} Q + \frac{R_S}{t^2} P}{V_T} \tag{1}$$

V. Integrated Tap-Changing Transformer with SVC

A. General Model

Advances in power electronics technology together with sophisticated control methods made possible the development of fast SVC's in the early 1970's [4]. The SVC consists of a group of shunt-connected capacitors and reactors banks with fast control action by means of thyristor switching. From the operational point of view, the SVC can be seen as a 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 [17]. Suitable control of this equivalent reactance allows voltage magnitude regulation at the SVC point of connection. SVC's achieve their main operating Characteristic at the expense of generating harmonic currents and filters are employed with this kind of devices. SVC's normally include a combination of mechanically controlled and thyristor controlled shunt capacitors and reactors. 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 [18]. As far as steady-stale analysis is concerned, both configurations can be modeled along similar lines.

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 $(I_L^2 X_L)$ which corresponds to variable virtual reactance of susceptance B_L given by: $V_T^2 B_C = I_L^2 X_L$, Together with the fixed capacitive reactive power , these from the hole variable inductive and capacitive reactive power of that static compensator. Fig. 5 shows a block diagram of that compensator when connected to a large power system.

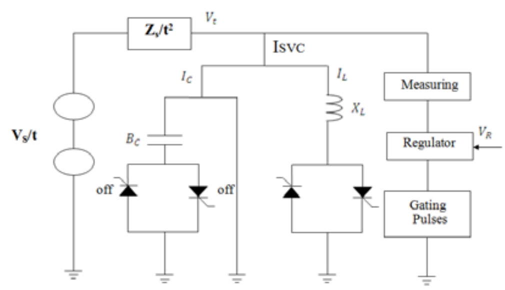

Fig. 5 SVC and power system schematic

Fig. 6 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. 7 shows the simplified transformer function block diagram of that system with combined tap-changing transformer and static VAR compensator [18].

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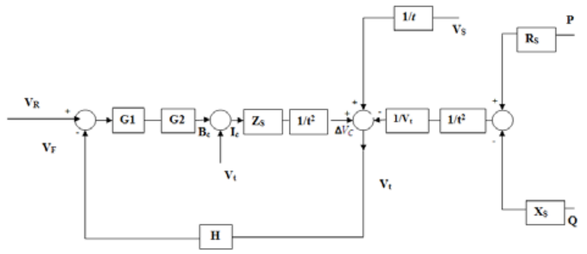


Fig. 6 Block diagram of a loaded power system, tap-changing transformer and SVC

B. System Equations

The regulator transfer function is given by

$$G_1 = \frac{(1/slope)(1+T_2S)}{(1+T_1S)(1+T_3S)} \qquad (2)$$

The slope is regulator drop slop equals to $\Delta V_C / \Delta I_{\max}$ Volt/ampere. T_1 is a delay time. (T_2, T_3) are the regulator compensator time constants. V_R is the reference voltage. The firing angle circuit can be represented by a gain K_d (nearly unity) and a time delay T_d as:

$$G_2 = K_d e^{-ST_d} \cong \frac{K_d}{(1+T_dS)} \qquad (3)$$

which is equal to 2.77×10^{-3} s for TCR and equal to 5.55×10^{-3} s for TSC. The limiter refers to the limits of the virtual compensator variable susceptance 'B'. The measuring circuit forms the feedback link and can be represented by a gain K_H equal nearly unity and a time delay T_H s as:

$$H = K_H e^{-ST_H} \cong \frac{1}{1+T_HS} \qquad (4)$$

is of the order of 20-50 ms, while T_H is usually from 8 – 16 ms. K_H usually takes a value around 1.0 p.u, T_2, T_3 are determined by the regulator designed for each studied system, as they are function in system parameters.

Multiplication of B by V_t yields the SVC current following in the series link (I_S), which is given by:

$$I_S = BV_t \qquad (5)$$

The power system which is provided by a tap-changing transformer at the load inlet can be represented by its Thevenin's voltage V_S / t, system and transformer impedance $(R_S / t^2) + j(X_S + X_t)/t^2$ [9]. All referred to the load voltage side. The load voltage drop to system equivalent series impedance and through the tap-changing transformer link is given by (1). In (1), V_t is the load node and SVC terminal voltage and '*S*' is the Laplace operator, which vanishes in steady-state condition.

Defining:

$$B_C = G_1G_2(V_R - V_T H) \qquad (6)$$

$$G = G_1G_2V_t \qquad (7)$$

The compensator current I_S is given by:

$$I_S = G(V_R - V_t H) \qquad (8)$$

and the SVC control system feedback voltage is given by:

$$\Delta V_C = I_S Z_S / t^2 = G(V_R - V_t H) Z_S / t^2 \qquad (9)$$

Therefore, the load terminal voltage is given by:

$$V_t = \Delta V_C + \left(\frac{V_S}{t} - \frac{R_S / t^2}{V_T} P - \frac{(X_S + X_t)/t^2}{V_t} Q\right) \qquad (10)$$

From which:

$$V_t^2\left(1 + G\frac{Z_S}{t^2}H\right) - V_t\left(\frac{V_S}{t} + G\frac{Z_S}{t^2}V_R\right) + \left(\frac{R_S}{t^2}P\right) + \left(\left(\frac{(X_S + X_t)}{t^2}\right)Q\right) = 0 \qquad (11)$$

which the compensator controller gain is given from (11) by:

$$G = \frac{-V_t^2 + V_t\frac{V_S}{t} - \left(\frac{R_S}{t^2}P + \frac{(X_S + X_t)}{t^2}Q\right)}{\frac{Z_S}{t^2}V_t(HV_t - V_R)} \qquad (12)$$

The regulator slope is obtained from the known $\frac{V}{I}$ characteristics of SVC as:

$$Slope = \Delta V_C / I_{S(\max)} \qquad (13)$$

After substituting of (9) and (5) in (13), we get:

$$Slope = (V_R - V_t H) G \frac{Z_S}{t^2} / (B_C V_t) \qquad (14)$$

Defining:

$$AK = (V_R - V_t H)\frac{Z_S}{t^2}\frac{1}{V_t} \qquad (15)$$

Equation (14) becomes:

$$Slope = (G / B_C) AK \qquad (16)$$

with:

$$B_C = 1 / X_C \qquad (17)$$

where X_c is the compensator fixed reactance, B_c is its rating in p.u. referred to its own rating (at 1.0 p.u. terminal voltage basis).

Compensator rating is given by $(B_C V_T^{\,2})$ or simply by B_C at $V_t = 1$ p.u.

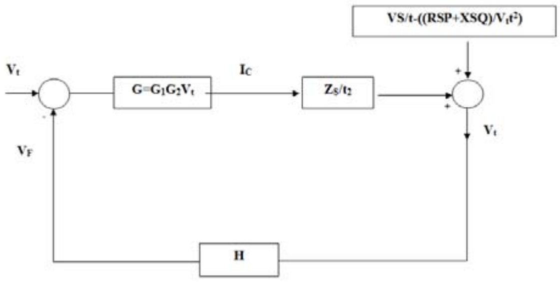


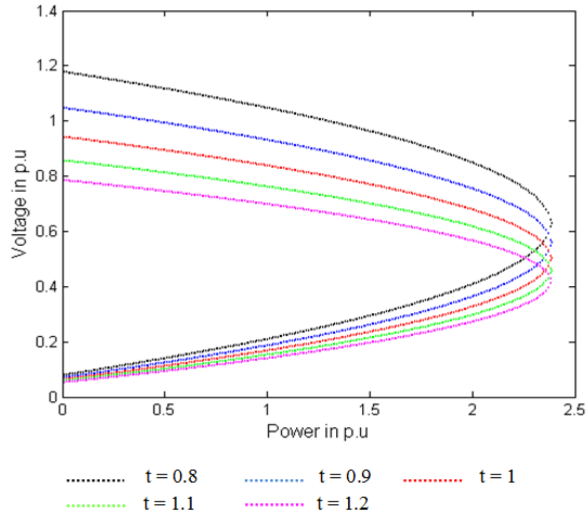
Fig. 7 Simplified transfer function block diagram of a loaded power system, tap-changing transformer and SVC

VI. Simulation Results

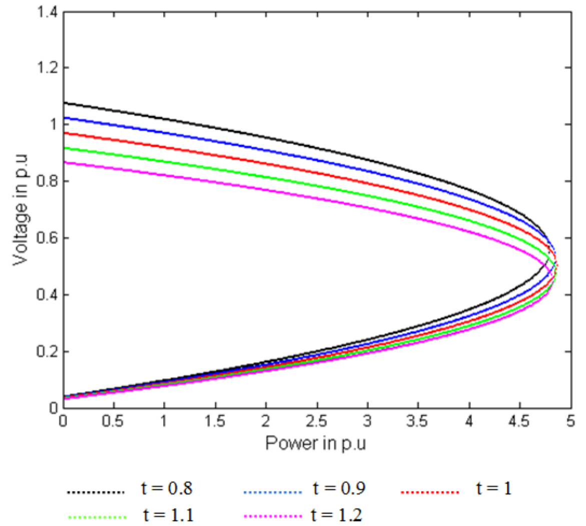
A. P-V Curve with the Presence of Tap-Changing Transformer and SVC

The famous nose curve of the Voltage/Power relation is plotted in Fig. 8. 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, i.e. $G = 0.0$ (without compensator action), $G = 2.5, G = 5, G = 10$. The feedback loop is in the operation and the system impedance is taken as: $Z_S = 0.311\measuredangle 74.84$, while the transformer reactance at $t = 1$ is $X_t = 0.0126$ p.u.

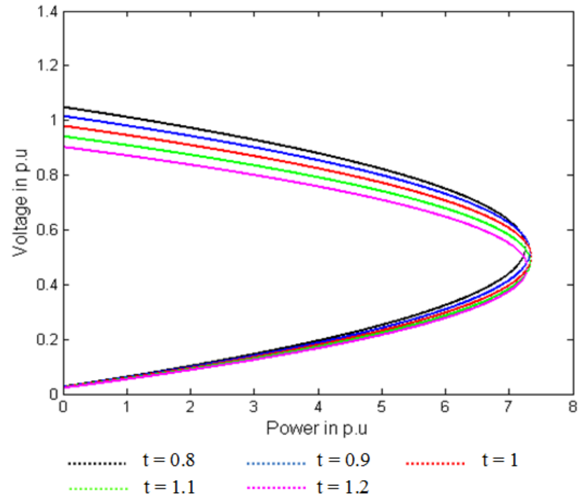
From all these curves we notice that the off-nominal tap ratio variation does not affect the critical power value at various SVC gains, i.e. this value remains constant at all off-nominal transformer ratio’s. However, off-nominal tap ratio’s affect largely the load voltage magnitudes at no load conditions. At lower values, they affect the load voltages at other loading conditions. The compensator application increases the maximum power largely as shown in Fig. 8 for different SVC controller gains. The same pervious features of their variations with different off-nominal tap ratio’s are noticed. The same maximum power and different critical voltages largely affect the no load conditions than the heavy loadings.



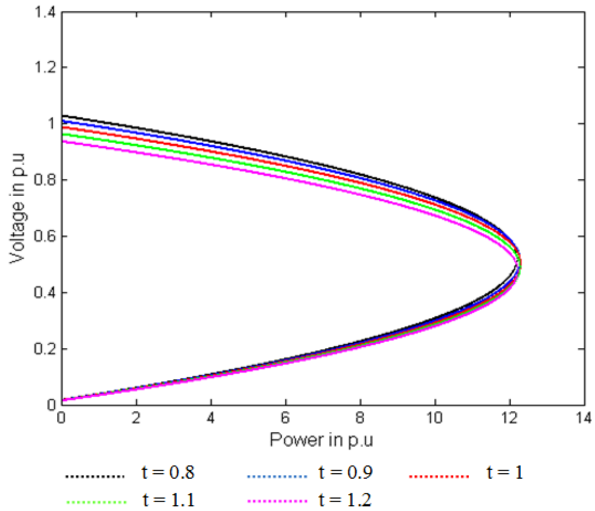
(a)



(b)



(c)



(d)

Fig. 8 P-V curve with different off-nominal tap ratios (0.8-1.2), with constant Q and with different compensator gains: (a)- G=0.0, (b)- G=2.5, (c)- G=5.0, (d)- G=10

B. VQ Curve with the Presence of Tap-Changing Transformer and SVC

A V-Q curve expresses the relationship between the reactive support Q at a given bus and the voltage at that bus. In Fig. 9, it can be determined by connecting a fictitious generator with zero active power Q produced as the terminal voltage V being varied. It must be noted at this point that the VQ curve is a characteristic of both the network and the load. As the curve aims at characterizing the steady state operation of the system, the load must be accordingly represented through its steady-state characteristic.

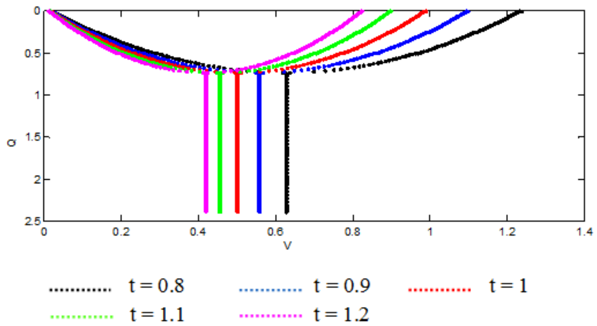


Fig. 9 VQ curve with different off-nominal tap ratios (0.8-1.2).

Table I, however, shows the maximum load power corresponding to various values of SVC controller gains. Once more, this value is the same at all off-nominal transformer tap ratio's. 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 important result illustrates the limited effects of the tap-changing transformer compared to the static VAR compensator significant effects, at different controller gains.

TABLE I
MAXIMUM LOAD POWER AS AFFECTED BY COMPENSATOR CONTROLLER GAINS

Compensator Gain(G)	Maximum Power
0.0	2.0
2.5	4.8
5.0	7.2
10.0	12.0

C. SVC Parameters in the Presence of Load Tap-Changing Transformer

1. Compensator Controller Gains, "G"

Here we see that the importance of the static VAR compensator over the automatically tap-changing transformer, the Gain/Power characteristics which can keep the load voltage constant at 0.99 p.u, is plotted in the Fig. 10. For different transformer off-nominal tap ratio's t = 0.8-1.2. The reactive power is kept constant at 0.18 p.u. It is clear here that to obtain the same value of load power with different off-nominal tap ratio's different SVC controller gains should be adjusted adaptively. Negative values can be required at lower load powers. At P = 4.0 p.u. for example, with t = 0.8-1.2, the gain should be varied between 60 and 200, respectively, for the studied system.

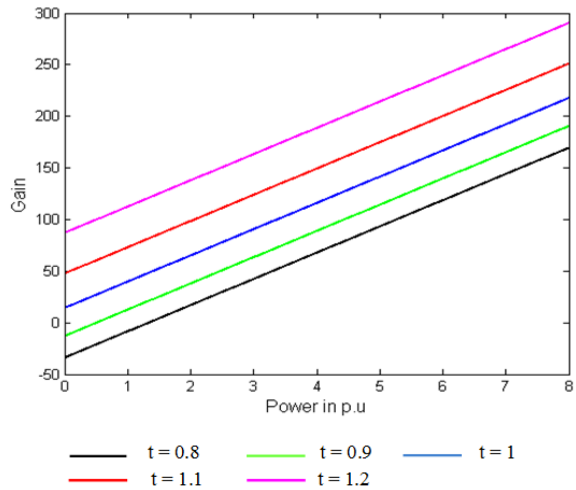


Fig. 10 Gain/Active Power response for constant load voltage (V_t = 0.99) and constant load reactive power (Q = 0.18) in presence of tap-changing transformer

Similarly as the plot of Gain/Active power, the Gain/Reactive power plot is also showing that when the active power is kept constant at 0.3 p.u, it is clear that to obtain the same value of load power with different off-nominal tap ratio's different SVC controller gains should be adjusted adaptively (As shown in Fig. 11).

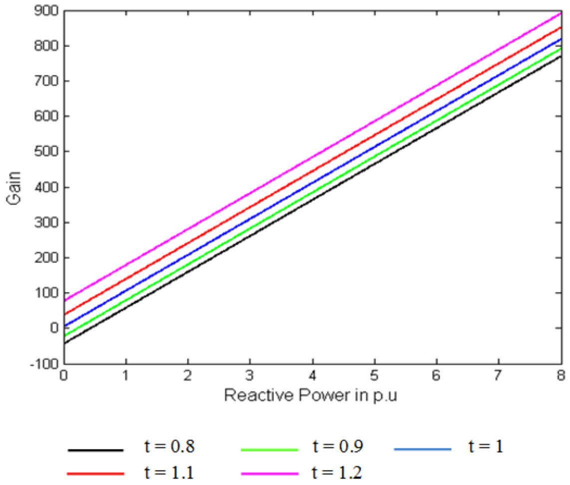


Fig. 11 Gain/Reactive Power response for constant load voltage (V_t = 0.99) and constant load active power (P = 0.3) in presence of tap-changing transformer.

2. Influence of Tap-Changing Transformer on SVC Controller Gain/Slope Relation

Fig. 12 shows the SVC controller drop slope/gain relation plots for five off-nominal transformer tap ratio's that are t = 0.8, 0.9, 1, 1.1 and 1.2. They are plotted for reference voltage $V_R = 1.0$ p.u and load terminal voltage $V_t = 0.99$ p.u. For the same gain value, different slops should be adjusted with different transformer tap ratios in order to keep load voltage constant at 0.99 p.u. X_C of the compensator is selected to be 4.5 p.u. i.e its rating is 0.22 p.u. This means using automatic tap-changing transformer needs inherent adaptive controller parameters.

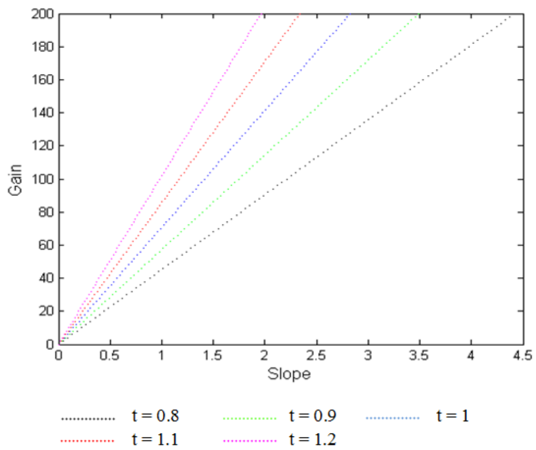


Fig. 12 SVC controller drop Slope/Gain relation in the presence of tap-changing transformer in order to maintain the load voltage constant

For a slope of 0.2, the SVC controller gain/compensator rating ($1/X_C$) relation is plotted in Fig. 13 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.

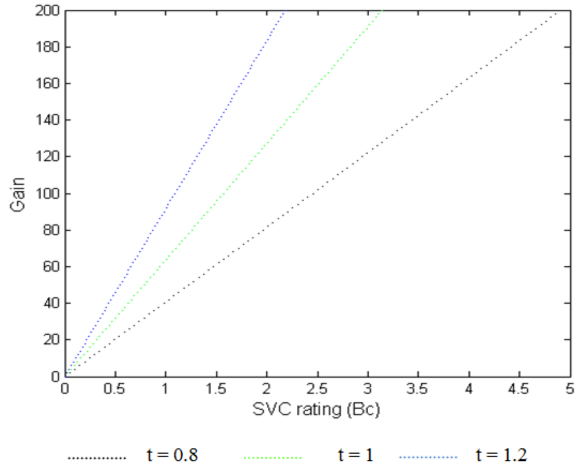


Fig. 13 Compensator design parameter/controller gain relation in the presence of tap-changing transformer

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

TABLE II
COMPENSATOR RATING AT DIFFERENT GAINS (COMPENSATOR RATING IN P.U.)

Gain	**Off-nominal tap ratio t = 0.8**	**Off-nominal tap ratio t = 1**	**Off-nominal tap ratio t = 1.2**
50	1.2	0.7	0.56
70	1.7	1.08	0.75
100	2.43	1.57	1.07
150	2.7	1.74	1.2

Fig. 14 shows that the reactance of the SVC with the gain at the tap ratios t=0.8, 0.9, 1, 1.1 and 1.2 in order to kept the load voltage constant at $V_t = 0.99$ p.u.

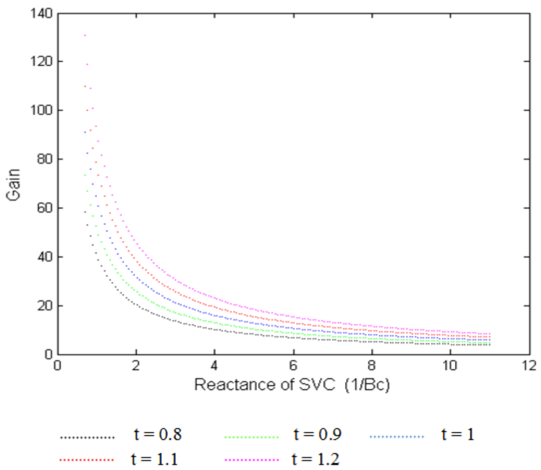


Fig. 14 Compensator reactive power reactance (X_C) / Gain

VII. 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 does 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 its original value without Static VAR Compensator. 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.

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