Electric Power Systems Research 45 (1998) 47–55

Combined use of tap-changing transformer and static VAR compensator for enhancement of steady-state voltage stabilities

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Received 17 November 1997; accepted 17 November 1997

Abstract

Both tap-changer transformers and static VAR compensators can contribute to power systems voltage stabilities. Combining these two methods is the subject of this paper. Effect of the presence of tap-changing transformers on static VAR compensator controller parameters and ratings required 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. For any large power system represented by its equivalent two nodes system, the power/voltage nose curves are found and their influence on the maximum power/critical voltage are studied.

Keywords: Voltage stability; Tap ratios; Power/voltage curves

1. Introduction

Several studies have shown that transformers with automatic tap-changing can be used for improvement of voltage stabilities [1–6], for both steady-state and transient voltage stabilities. Some of these studies were interested in proposing new models for tap-changing transformers [6,7]. On the other hand, static VAR compensator is used for improvement of voltage stabilities due to lines opening in the presence of induction motors [8] or due to starting of induction motors [9,10] or due to recoveries of short-circuits at induction motor terminals [11] or due to heavy loadabilities [12,13] or due to high impedance corridors due to switching of parallel circuits [8,13]. The combination of these two means of voltage instabilities is suggested in [14,15] as textbook exercises, but have not yet been studied in detail.

This is the main aim of this study. Effects of tap-changing transformers alone forms the first part of this paper. Static VAR compensator (SVC) [17] effects alone is given in another study [16]. The influence of the presence of tap-changing transformers on compensator gains, reference voltage values and ratings are given in detail. The studied system represents any large system seen from the load node under consideration.

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.

2. Studied system

A large power system which feeds a certain load of powers $(P+jQ)$ is used in this study Fig. 1. The system, at steady-state conditions, can be represented by its Thevenen's equivalent seen from node 5 as shown in Fig. 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_t.

In order to be able to use the approximate voltage drop formula [14]; $(X_S Q + R_S P)/V_T = |V_S| - |V_T|$, all the system voltage and impedances will be refered to the 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

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0378-7796/98/$19.00
PII S0378-7796(97)01222-4

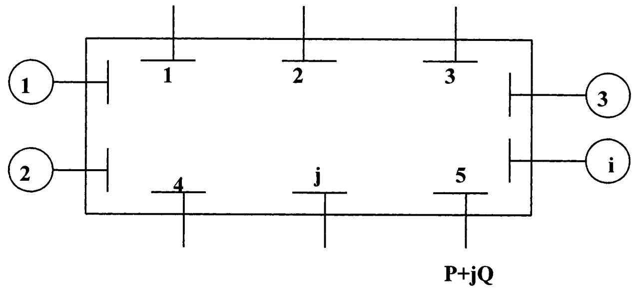

Fig. 1. Studied large power system.

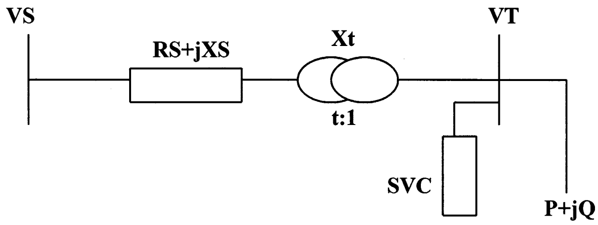

Fig. 2. Thevenen's equivalent system shows the load node terminals

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

Data used in this study: $V_S = 1.004$ p.u., $Z_S = 0.311\angle 78.84$ p.u., $X_t = 0.0126$ p.u. and $t = 0.8–1.2$.

3. Static VAR compensator and power system with tap-changing transformer model

A thyristor-controlled 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 currents 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 form the whole variable inductive or capacitive reactive power of that static compensator. Fig. 3 shows a block diagram of that compensator when connected to a large power system.

Fig. 4. shows the transfer function of a power system provided by tap-changing transformer and a static VAR compensator. The off-nominal tap ratio of the tap-changing transformer is 't'. Fig. 5 shows the simplified transfer function block diagram of that system with combined tap-changing transformer and static VAR compensator.

4. System equations

The regulator transfer function is given by

$$G_1 = \frac{(1/\text{slope})}{(1 + T_1 S)}\frac{(1 + T_2 S)}{1 + T_3 S} \qquad (1b)$$

The slope is the regulator droop slope equal 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:

$$G_2 = K_d\,e^{-ST_d} \cong \frac{K_d}{(1 + T_d S)} \qquad (2)$$

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:

$$\mathrm{H} = K_H\,e^{-ST_H} \cong \frac{1}{1 + T_H S} \qquad (3)$$

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

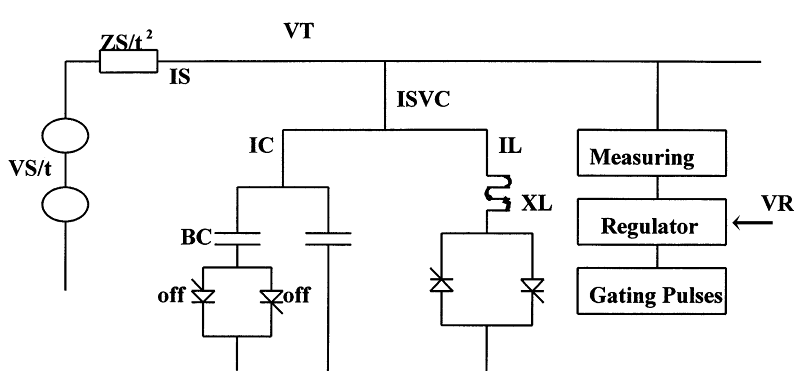

Fig. 3. Static VAR compensator and power system block diagram.

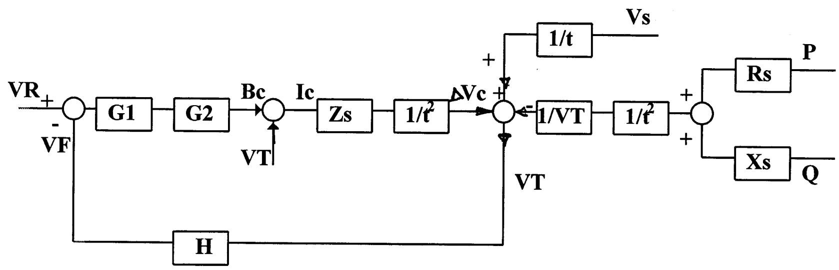

Fig. 4. Block diagram of a loaded power system, tap-changing transformer and SVC.

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

$$I_S = BV_T \tag{4}$$

The power system which is provided by a tap-changing transformer at the load inlet can be represented by its Thevenen's voltage V_S/t, system and transformer impedances $(R_S/t^2) + j(X_S + X_t)/t^2$. All refered to the load voltage side. The load voltage drop through system equivalent series impedance and through the tap-changing transformer link is given by:

$$\Delta V = \left|\frac{V_S}{t}\right| - |V_T| = \frac{\dfrac{(X_S + X_t)}{t^2}Q + \dfrac{R_S}{t^2}P}{V_T} \tag{5}$$

where V_T is the load node and SVC terminal voltage and 'S' is the Laplace operator, which vanishes in steady-state conditions.

$$\Delta V_C = I_S Z_S/t^2 = G(V_R - V_T H)Z_S/t^2 \tag{7}$$

Therefore, the load terminal voltage is given by:

$$V_T = \Delta V_C + \left(\frac{V_S}{t} - \frac{R_S/t^2}{V_T}P - \frac{(X_S + X_t)/t^2}{V_T}Q\right) \tag{8}$$

or:

$$V_T = G\frac{Z_S}{t^2}(V_R - V_T H) + \left(\frac{V_S}{t} - \frac{R_S/t^2}{V_T}P - \frac{(X_S + X_t)/t^2}{V_T}Q\right) \tag{9}$$

from which;

$$V_T^2\left(1 + G\frac{Z_S}{t^2}H\right) - V_T\left(\frac{V_S}{t} + G\frac{Z_S}{t^2}V_R\right) + (R_S/t^2)P + ((X_S + X_t)/t^2)Q = 0 \tag{10}$$

its solution is:

$$V_{T_1} = \left[\left(\frac{V_S}{t} + G\frac{Z_S}{t^2}V_R\right) \pm \sqrt{\left(\frac{V_S}{t} + G\frac{Z_S}{t^2}V_R\right)^2 - 4\left(1 + G\frac{Z_S}{t^2}H\right)\left(\frac{R_S}{t^2}P + \left(\frac{X_S + X_t}{t^2}\right)Q\right)}\right] \Big/ 2\left(1 + G\frac{Z_S}{t^2}H\right) \tag{11}$$

Defining

$$B_C = G_1 G_2(V_R - V_T H)$$

and

$$G = G_1 G_2 V_T$$

the compensator current I_S is given by:

$$I_S = G(V_R - V_T H) \tag{6}$$

and the SVC control system feedback voltage is given by:

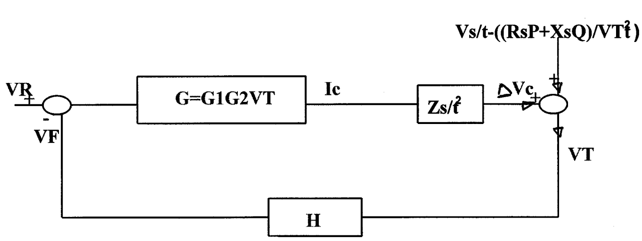

Fig. 5. Simplified transfer function block diagram of power system, tap-changing transformer and SVC.

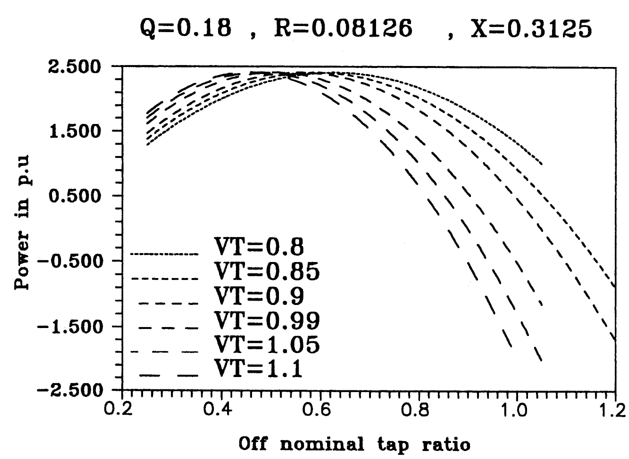

Fig. 6. Active power versus/transformer off-nominal tap ratio at constant terminal voltages with constant load reactive power.

$$V_{T_2} = \left[\left(\frac{V_S}{t} + G\frac{Z_S}{t^2}V_R\right) - \sqrt{\left(\frac{V_S}{t} + G\frac{Z_S}{t^2}V_R\right)^2 - 4\left(1 + G\frac{Z_S}{t^2}H\right)\left(\frac{R_S}{t^2}P + \left(\frac{X_S + X_t}{t^2}\right)Q\right)}\right] \Big/ 2\left(1 + G\frac{Z_S}{t^2}H\right) \quad (12)$$

and the compensator controller gain is given from Eq. (10) by:

$$G = \frac{-V_T^2 + V_T\frac{V_S}{t} - \left(\frac{R_S}{t^2}P + \frac{(X_S + X_t)}{t^2}Q\right)}{\frac{Z_S}{t^2}V_T(HV_T - V_R)} \quad (13)$$

While, the regulator reference voltage is given from Eq. (10) by:

$$V_R = \frac{V_T^2\left(1 + GH\frac{Z_S}{t^2}\right) - V_T\frac{V_S}{t} + \left(\frac{R_S}{t^2}P + \frac{(X_S + X_t)}{t^2}Q\right)}{V_T G\frac{Z_S}{t^2}} \quad (14)$$

The regulator slope is obtained from the known the V/I characteristic of SVC as:

$$\text{Slope} = \Delta V_C / I_{S(\max)} \quad (15)$$

After substitution of Eqs. (7) and (4) in Eq. (15), we get:

$$\text{Slope} = (V_R - V_T H)G\frac{Z_S}{t^2}/(B_C V_T) \quad (16)$$

Defining:

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

Eq. (16) becomes:

$$\text{Slope} = (G/B_C)AK \quad (17)$$

with:

$$B_C = 1/X_C \quad (18)$$

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).

5. Compensator rating

Compensator rating is given by ($B_C V_T^2$) or simply by B_C at $V_T = 1$ p.u. It can therefore be calculated from Eq. (17) by:

$$B_C = G(AK)/\text{Slope} \quad (19)$$

6. Results and discussion

6.1. System performance with different off-nominal tap ratios and without SVC

Having used the system under study with the above mentioned data, i.e. $V_S = 1.004$ p.u, $R_S = 0.08125$ p.u, $X_S = 0.3$ p.u and $X_t = 0.0126$ p.u, the load reactive power is assumed to be kept constant at $Q = 0.18$ p.u. In order to keep the terminal voltage constant at $V_T =$ 0.8 p.u up to 1.05 p.u for different system powers P, Fig. 6 shows the required corresponding off-nominal tap changer ratios. The figure shows that the maximum power is the same for all off-nominal tap ratio's. More or less values of that ratio will refer to lower load power at constant load voltage. Fig. 7 shows the reactive power which will be demanded by the load when its terminal voltage remain between 0.8 and 1.05 p.u and its consumed active power P is kept constant at 0.3 p.u.

Noting that the maximum power or reactive power value are not affected by the transformer tap ratio's.

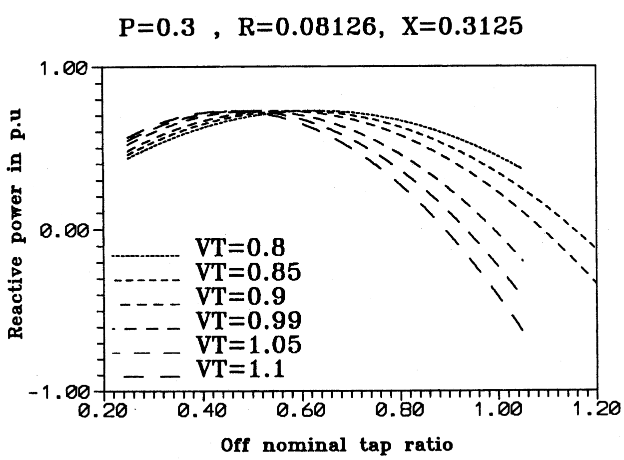

Fig. 7. Reactive power versus/transformer off-nominal tap ratio at constant terminal voltages with constant load active power.

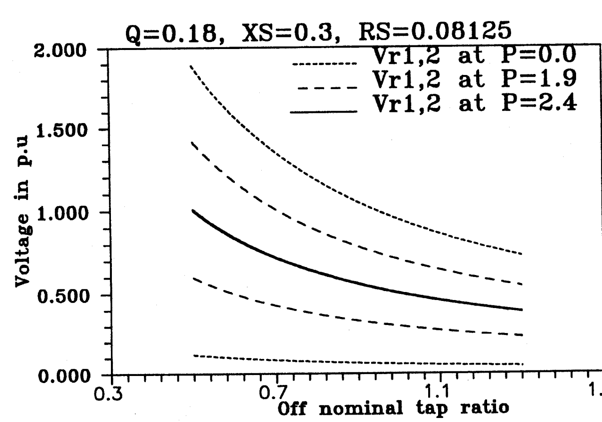

Fig. 8. Load voltage versus off nominal transformer tap ratio at constant reactive power with three powers $P = 0.0$, 1.9 and 2.4 p.u.

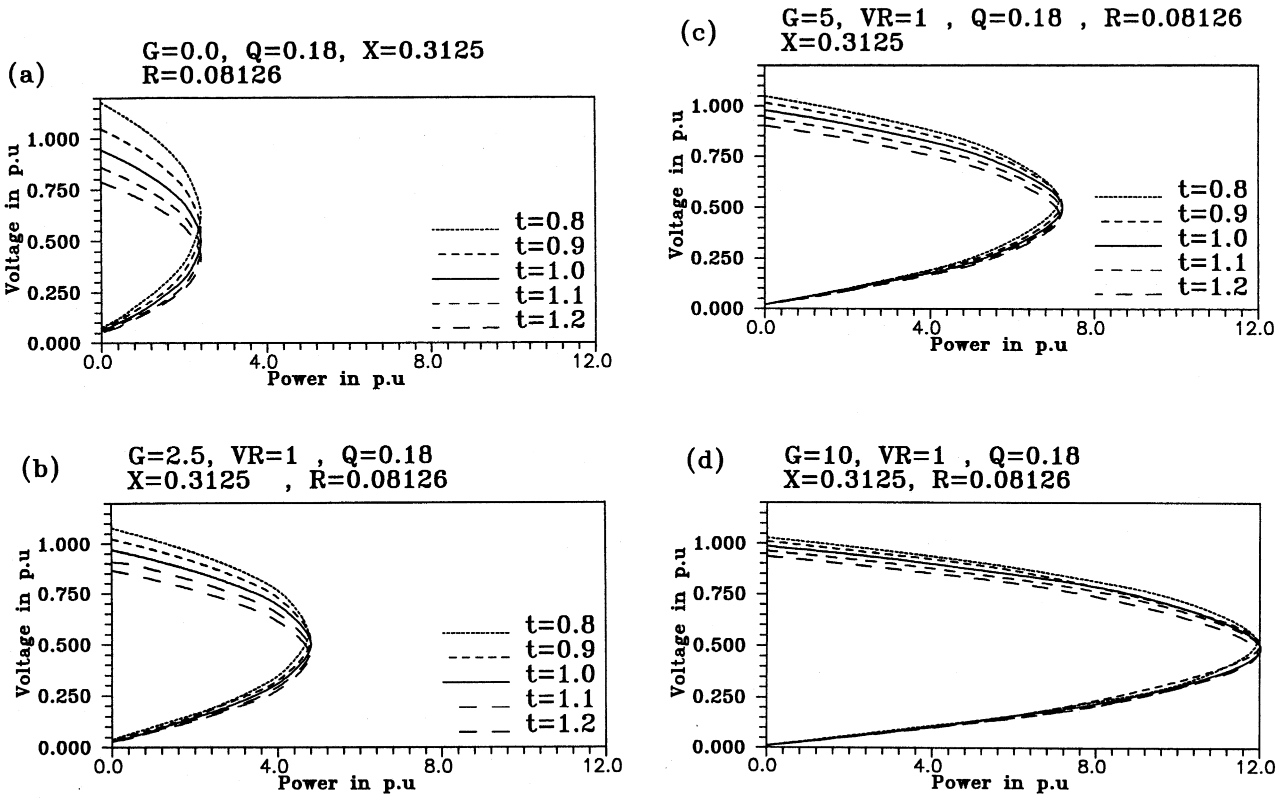

Fig. 9. Voltage/power response with different off-nominal tap ratios (0.8–1.2) and with constant Q and different compensator gains: (a) $G=0.0$; (b) $G=2.5$; (c) $G=5.0$; (d) $G=10$.

These values are constant at all tap ratio's. The load reactive power is assumed to be kept constant at $Q=0.18$, the load voltage V_T against off nominal tap ratio is plotted in Fig. 8 for three load powers $P=0.0$, 1.9 and 2.4 p.u. The latter value corresponds to the critical load power.

Two values of the voltage are detected at each off-nominal tap ratio. One of them is stable value and the other is unstable voltage value. At the critical power, which corresponds to two coincident critical voltages having the same value, the two voltages are found to be coincident at all off-nominal tap ratios of the tap-changing transformer. This ensures that the tap-changing does not affect the critical voltage values and keeps the system state as it is from the point of view of degree of stability but with different voltage levels in the same stability region.

Table 1
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

7. Load power/voltage response with presence of tap-changing transformer and static VAR compensator

The famous nose curve of the voltage/power relation is plotted in Fig. 9 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 $G=0.0$ (without compensator action), $G=2.5$, 5 and 10. The feedback loop is in operation and the system impedance is taken as: $Z_S=0.311\angle 74.84=0.08125+j0.3$, 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. 9 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.

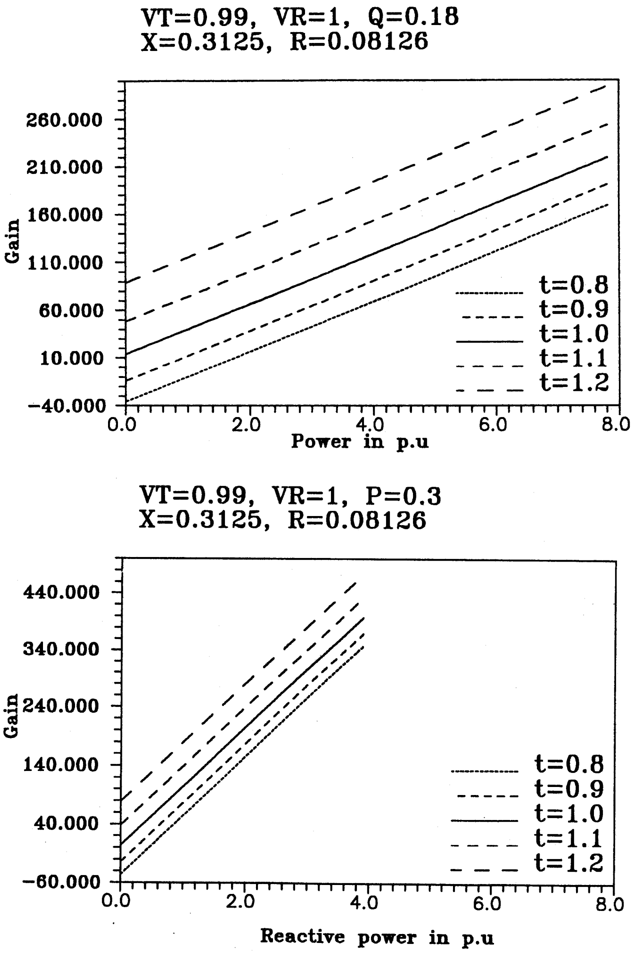

Fig. 10. (a) Gain/power responses for constant load voltage and constant load reactive power in presence of tap-changing transformer. (b) Gain/Reactive power responses for constant load voltage and constant load active power in presence of tap-changing transformer.

Table 1, 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.

8. Static VAR compensator parameters in the presence of load tap-changing transformers

8.1. Compensator controller gains 'G'

Having seen the importance of application 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 Fig. 10(a) for different transformer off-nomi-

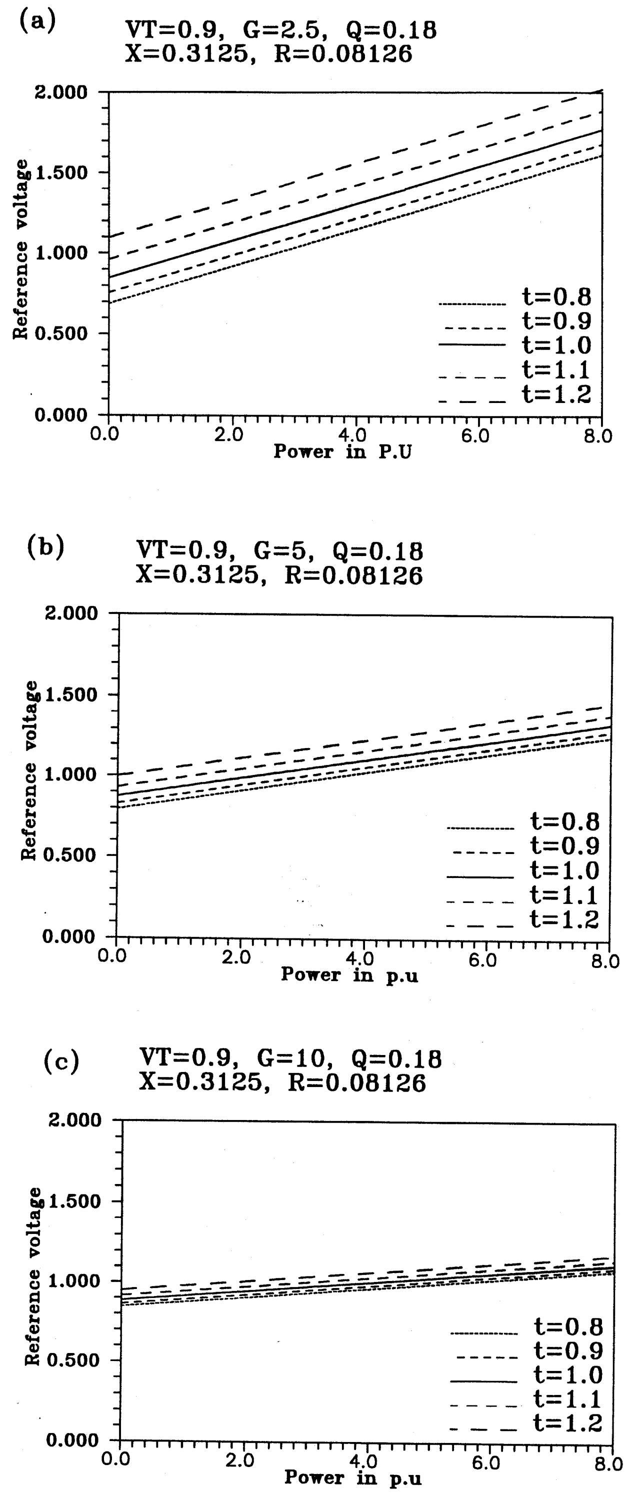

Fig. 11. SVC controller reference voltage/power relation required to keep the load voltage constant at different off nominal tap-changing ratio's and various compensator controller gains: (a) $G=2.5$; (b) $G=5$; (c) $G=10$.

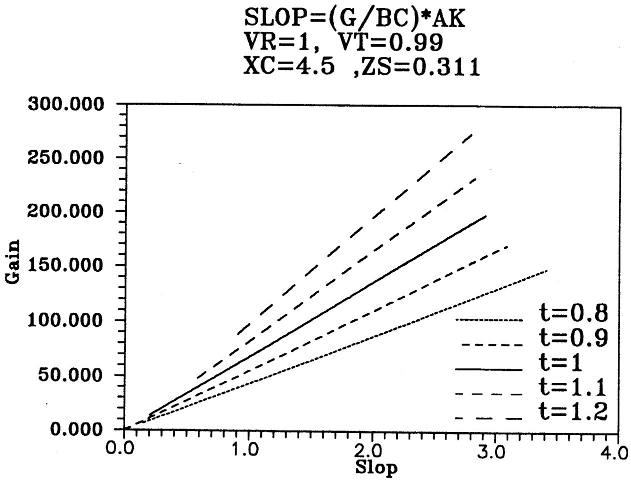

Fig. 12. SVC controller droop slope/gain relation in the presence of tap changing transformer in order to maintain the load voltage constant.

nal tap ratios $t = 0.8–1.2$. 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 ratios, 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 210, respectively, for the studied system.

Fig. 10(b) Shows the same plots with variable load reactive power when its active power is kept constant.

8.2. Compensator controller reference voltage in presence of tap-changing transformer

In the presence of tap-changing transformer having off nominal tap ratios in the known practical ranges (0.8–1.2), the voltage/power responses are plotted in Fig. 11 for different controller gains, in order to keep the load node voltage constant at $V_T = 0.99$ p.u. Three controller gains are considered $G = 2.5$, 5 and 10. Examining these plots shows that increasing the regulator gains require very close reference voltages at different off-nominal transformer tap ratios. On the other hand a lower tap ratio of 0.8 require lower reference voltages than those with higher ratio's 1.2, in order to keep the terminal voltage constant. These results are logic as increasing the SVC controller gains increase its effectiveness in controlling the load voltage and consequently decreases its dependence on the off-nominal transformer tap-ratio.

8.3. Influence of tap-changing transformer on SVC controller gain/slope relation

Fig. 12 shows the SVC controller droop slope/gain relation plots for five off nominal transformer tap ratios that are 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 slopes should be adjusted with different transformer tap ratios, in order to keep the load voltage constant at 0.99 p.u. X_C of the compensator is selected to be 4.5, i.e its rating is 0.22 p.u. This means that using automatic tap changing transformer needs inherent adaptive controllers parameters. For a slope of 2.0, the SVC controller gain/compensator rating $(1/X_C)$ relation is plotted in Fig. 13(a) with three off-nominal tap ratios $t = 0.8$, 1 and 1.2. The graph shows different compensator reactive power ratings are required at each compensator controller gain, in order to keep the load voltage constant, in the presence of automatic tap-changing transformer of different off-nominal tap ratio's. Table 2 shows the needed SVC ratings corresponding to different controller gains and different transformer off-nominal tap ratio's. Fig. 13(b) shows the reactance of the SVC with the gain at the same three tap-ratios 0.8, 1 and 1.2 in order to keep the load voltage constant at $V_T = 0.99$.

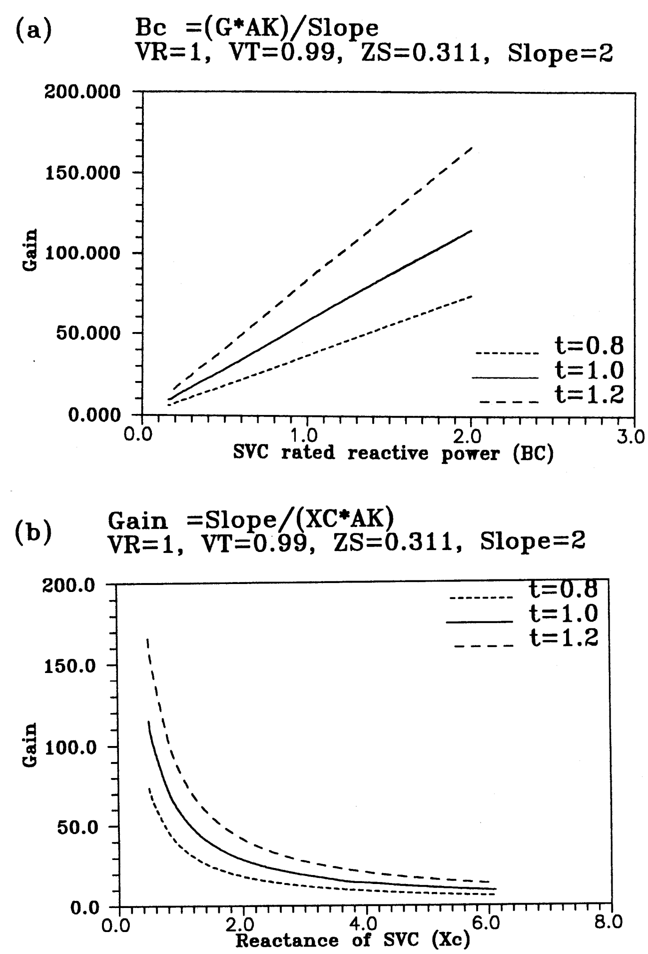

Fig. 13. Compensator design parameter/controller gain relations in the presence of tap-changing transformer: (a) compensator reactive power rating; (b) compensator reactive power reactance (X_C)/gain.

Table 2
Compensator rating at different gains (compensator rating in p.u)

Gain	Off nominal tap ratio = 0.8	Off nominal tap ratio = 1	Off nominal tap ratio = 1.2
50	1.2	0.7	0.5
70	2.0	1.0	0.6
100	—	1.8	1.0
150	—	—	1.7

Fig. 14 shows the compensator gain relations with different load powers or with corresponding compensator reactance X_C, in the presence of different transformer off nominal tap ratios (0.8–1.2). The load reactive power is assumed to be kept constant at 0.18 p.u. SVC controller gain versus its rating in p.u is plotted in Fig. 14 with different transformer tap ratio's. The range of change of compensator rating for certain given load power is shown in the presence of different transformer taps. Once more, for the same SVC controller gain, higher SVC rating is required with lower transformer off-nominal tap ratio and vice versa. On contradictory higher load power can be taken at that load fixed terminal voltage in the presence of lower off nominal transformer tap ratio.

9. Conclusions

(1) 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.

(2) Presence of static VAR compensator with different controller gains can increase the maximum load powers several times its original value without static VAR compensator.

(3) 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.

(4) 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 ratio's 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 values is reduced significantly.

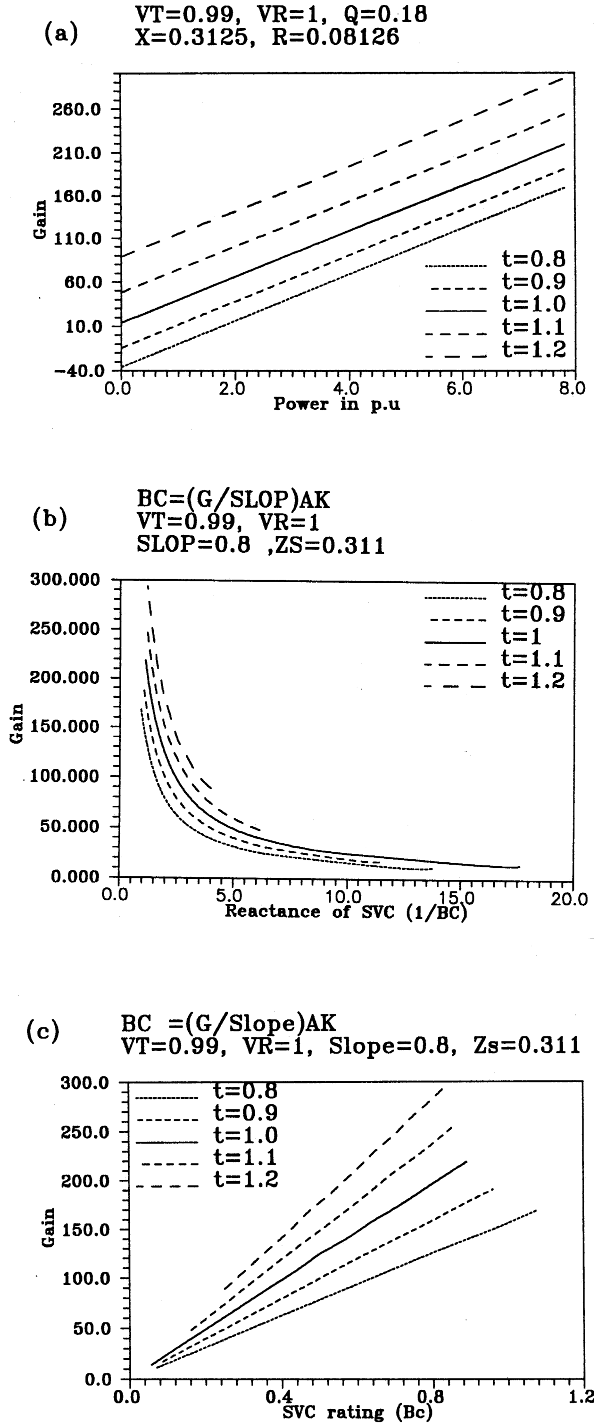

Fig. 14. (a) Gain/power relation with different transformer taps. (b) Gain/SVC reactance with different transformer taps. (c) Gain/SVC rating (B_C) with different transformer taps.

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