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

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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 is studied. © 1998 Elsevier Science S.A. All rights reserved.

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

I. 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 load abilities [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 form 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.

II. STUDIED SYSTEM

A large power system which feeds a certain load of powers (P + *j*Q) 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 *Xt*.

In order to be able to use the approximate voltage drop formula [14]; (XSQ + *RSP*)/VT = | VS| - | VT|, all the system voltage and impedances will be referred to the load side, i.e. (VS/t), (RS/t2), (XS/t2), *(Xt/t2).*
The link voltage drop will therefore

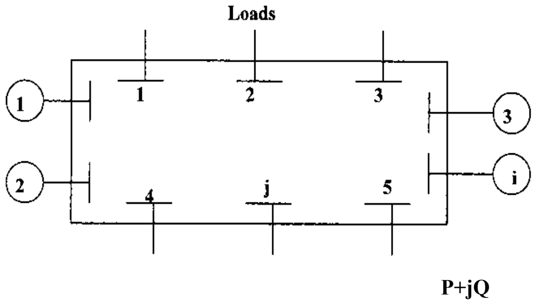


Fig. 1.: Studied large power system.

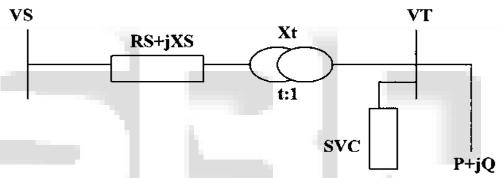


Fig. 2:Thevenen's equivalent system shows the load node terminals

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

Data used in this study: *V*S ⁄_1.004 p.u., *Z*S⁄_0.311⁄_78.84 p.u., *Xt*⁄_0.0126 p.u. and t⁄_0.8–1.2

III. 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 *BC*_*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.

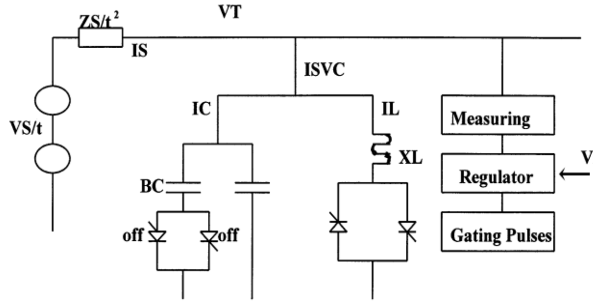


Fig. 3: Static VAR compensator and power system block diagram

IV. 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 DVC:D*I*max volt:ampere, *T*1 is a delay time, (*T*2, *T*3) are the regulator compensator time constants, *VR* 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.

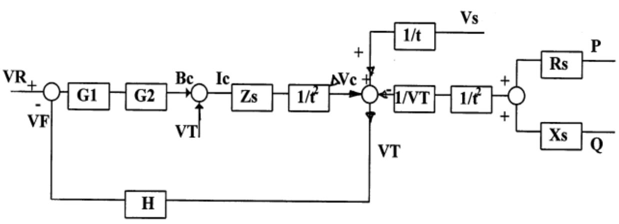


Fig. 4: Block diagram of a loaded power system, tap-changing transformer and SVC.

Multiplication of *B* by *VT* yields the SVC current flowing in the series link (*I*S), which is given by:

$$I_S = B V_T \qquad (4)$$

The power system which is provided by a tap-changing transformer at the load inlet can be represented by its Thevenen’s voltage *VS*:*t*, system and transformer impedances (*RS*:*t*2)_*j*(*XS*_*Xt*):*t*2. All referred to the load voltage side. The load voltage drop through system equivalent series impedance and through the tap changing transformer link is given by:

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

where *VT* is the load node and SVC terminal voltage and ‘S’ is the Laplace operator, which vanishes in steady-state conditions.

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

Therefore, the load terminal voltage is given by:

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

or:

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

from which;

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

its solution is:

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

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:

$$I_S = G(V_R - V_T H) \qquad (6)$$

and the SVC control system feedback voltage is given by:

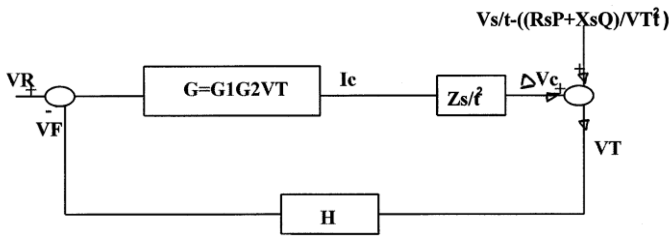


Fig. 5: Simplified transfer function block diagram of power system, tap-changing transformer and SVC.

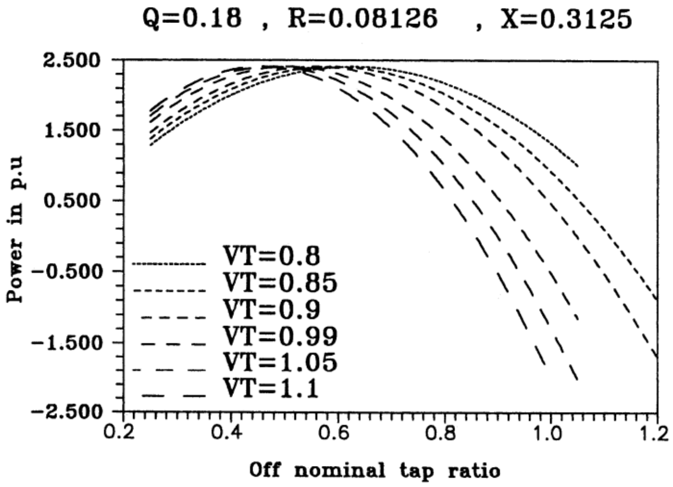


Fig. 6: Active power versus/transformer off-nominal tap ratio at constant terminal voltages with constant load reactive power.

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

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:

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

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:

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

Defining:

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

Eq. (16) becomes:

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

with:

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

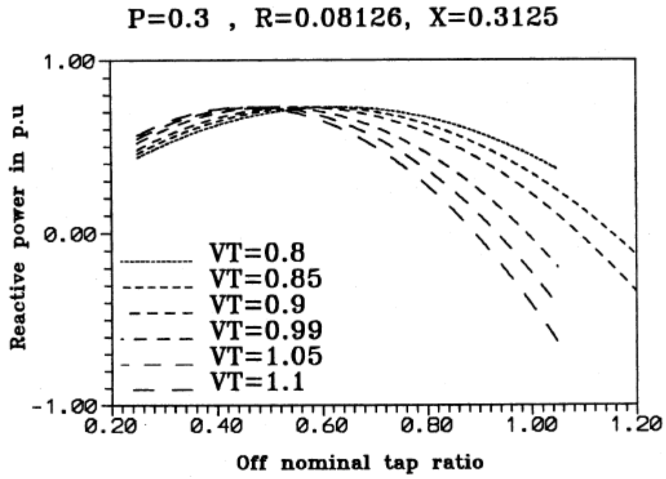


Fig. 7: Reactive power Vs transformer off-nominal tap ratio at constant terminal voltages with constant load active power.

$V_S = 1.004$ p.u.

$X_S = 0.3125$ p.u.

$X_t = 0.0126$ p.u.

$V_r =$ 1 p.u.

$H =$ 1 p.u.

$R_S = 0.08126$ p.u.

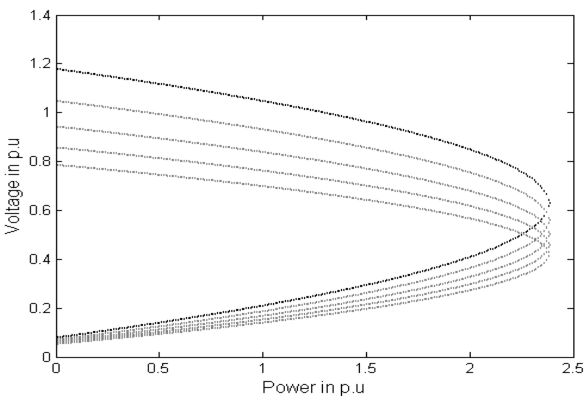
$Z_S = 0.3228$ p.u.

$X_C = 4.5$ p.u.

The load reactive power is assumed to be kept constant at Q = 0.18 p.u.

In order to kept the terminal voltage constant at $V_t = 0.8$ p.u up to 1.05 p.u for different system power P.

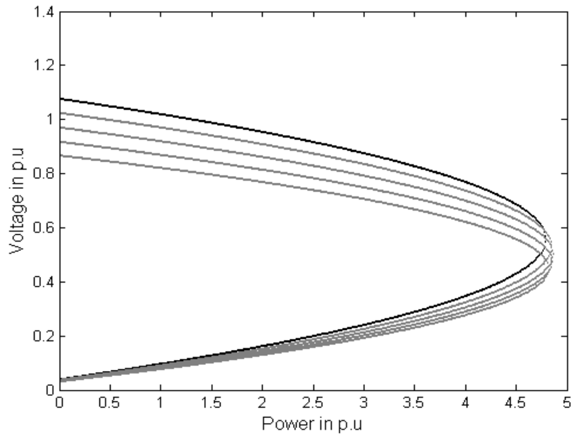
A. CASE 1 WHEN G= 0.0



------ t = 0.8 ------ t = 0.9 ------ t = 1
------ t = 1.1 ------ t = 1.1

Fig. 8: Voltage/Power response with different off-nominal tap ratios (0.8-1.2), with constant Q and with G = 0.0

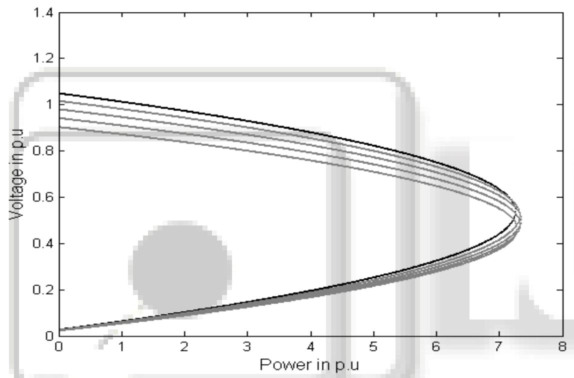
B. *CASE 2 WHEN G= 2.5*



------ t = 0.8 ------ t = 0.9 ------ t = 1
------ t = 1.1 ------ t = 1.1

Fig. 9: Voltage/Power response with different off-nominal tap ratios (0.8-1.2), with constant Q and with G = 2.5

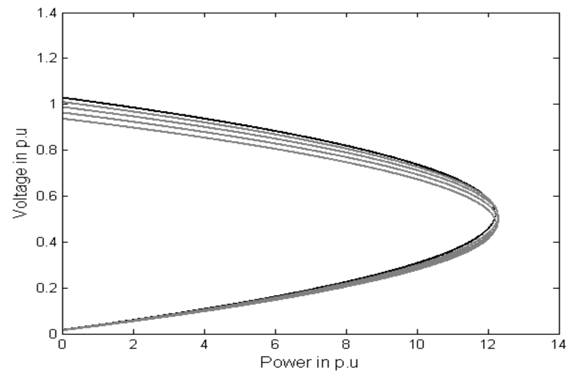
C. *CASE 3 WHEN G= 5*



------ t = 0.8 ------ t = 0.9 ------ t = 1
------ t = 1.1 ------ t = 1.1

Fig. 10: Voltage/Power response with different off-nominal tap ratios (0.8-1.2), with constant Q and with G = 2.5

D. *CASE 4 WHEN G=10*



------ t = 0.8 ------ t = 0.9 ------ t = 1
------ t = 1.1 ------ t = 1.1

Fig. 11: Voltage/Power response with different off-nominal tap ratios (0.8-1.2), with constant Q and with G = 10

V. ADDITION OF SERIES CAPACITOR IN THE CIRCUIT

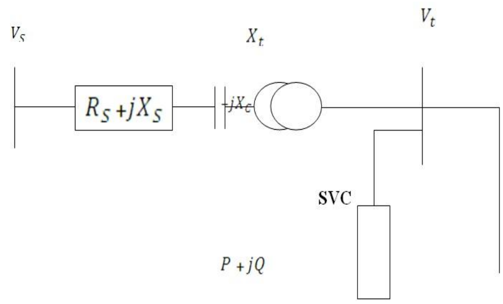


Fig. 12: Thevenen's equivalent system in the presence of series Capacitor, Tap-Changing Transformer and SVC.

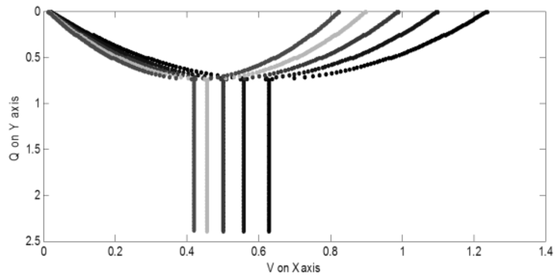


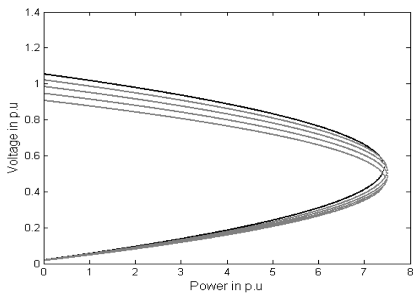
Fig. 13: V-Q curve

A V-Q curve expresses the relationship between the reactive support Q at a given bus and the voltage at that bus. 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.

VI. PLOTS BETWEEN LOAD POWER AND VOLTAGE RESPONSE WITH PRESENCE OF SERIES CAPACITOR, TAP-CHANGING TRANSFORMER AND STATIC VAR COMPENSATOR

When the transformer off-nominal tap ratios are varied within the known practical range (t=0.8-1.2), taking the static compensator gain as G = 5 and by taking the capacitor with X_c 25%, 50% and 75% of transmission line X_s i.e. (X_c= 0.0781, 0.1562, 0.2343).

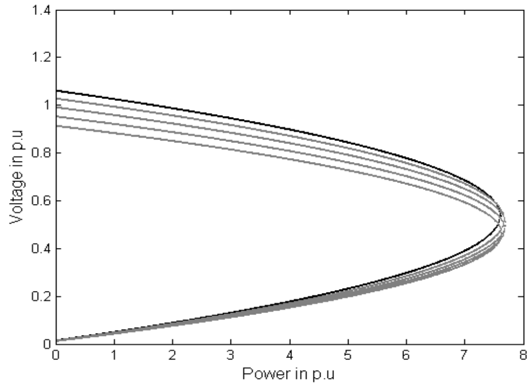
A. *CASE 1 WITH X_c IS 25% OF X_s i.e. X_c= 0.0781*



------ t = 0.8 ------ t = 0.9 ------ t = 1
------ t = 1.1 ------ t = 1.1

Fig. 14: Power/Voltage with Xc = 0.0781

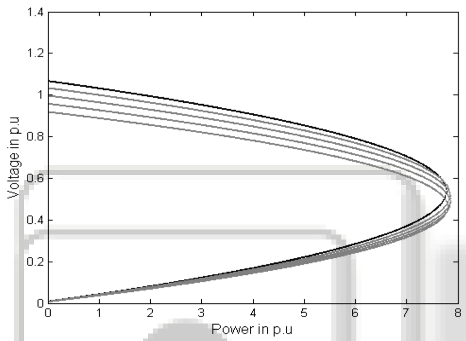
B. CASE 2 WITH X_c IS 50% OF X_s i.e. $X_c = 0.1562$



------ t = 0.8 ------ t = 0.9 ------ t = 1
------ t = 1.1 ------ t = 1.1

Fig 15: Power/Voltage with Xc = 0.1562

C. CASE 3 WITH X_c IS 75% OF X_s i.e. $X_c = 0.2343$



------ t = 0.8 ------ t = 0.9 ------ t = 1
------ t = 1.1 ------ t = 1.1

Fig 16: Power/Voltage with Xc = 0.2343

As we can see in these three plots that by the use of Capacitor in the circuit, the peak-load voltage can be increased by increasing the capacitor rating.

VII. 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] By using the series capacitor with the tap-changing transformer and SVC the Peak-load voltage can significantly be increased.

[3] Presence of Static VAR Compensator with different controller gains can Increase the maximum load powers several times its original value without Static VAR Compensator.

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