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THYRISTOR CONTROLLED SERIES CAPACITOR FOR DAMPING POWER SYSTEM OSCILLATIONS

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ABSTRACT
This paper describes the effects of resistor added to thyristor controlled series capacitor (TCSC) on damping power system oscillations. A new analytical model has been developed to consider the resistive component of TCSC circuit including the damping resistor. A modified TCSC for damping power system oscillations was proposed. Performances of the modified TCSC were examined using the analytical model.

KEY WORDS
FACTS, TCSC(Thyristor Controlled Series Capacitor), Damping Resistor, Power System Oscillations.

1. INTRODUCTION
A thyristor controlled series capacitor (TCSC) basically consists of a series capacitor connected in parallel with a thyristor-controlled reactor. Although the resistance exists in the inductor and anti-parallel thyristors of the TCSC circuit, it is negligibly small. Therefore little attention has been given to the effect of resistance on the overall performances of TCSC systems [1, 2]. However, the damping capability of resistance in the TCSC circuit could not be underestimated as shown later in this paper.

A prototype TCSC [3] shown in Fig. 1 was manufactured and installed in our laboratory-scale power system to investigate various capabilities of TCSC such as stability enhancement and flexible control of power flow, as well as an increase of power transfer. It was designed to be inserted into the 3300 V transmission line in our laboratory. The capacitor is chosen at 146 μF, i.e. 18.15 Ω. The reactor is chosen at 10 mH, i.e. 3.77 Ω. In order to check the effect of reactor size on the TCSC performances, two reactors of 10 mH per phase are prepared to constitute 5 mH, 10 mH and 20 mH. An additional resistor of 2 Ω is also prepared. It was shown from the experimental study on the laboratory system that resistive component of TCSC contributes to damp oscillations, although it has losses. However, the conventional analytical model of TCSC has not fully considered the effect of resistive component. Therefore a new analytical model of TCSC was developed to consider the resistive component. Losses are also calculated.

The purpose of this paper is to present a new analytical model of TCSC, propose a modified TCSC for damping enhancement and examine the contribution of resistive component in the TCSC on damping power system oscillations.

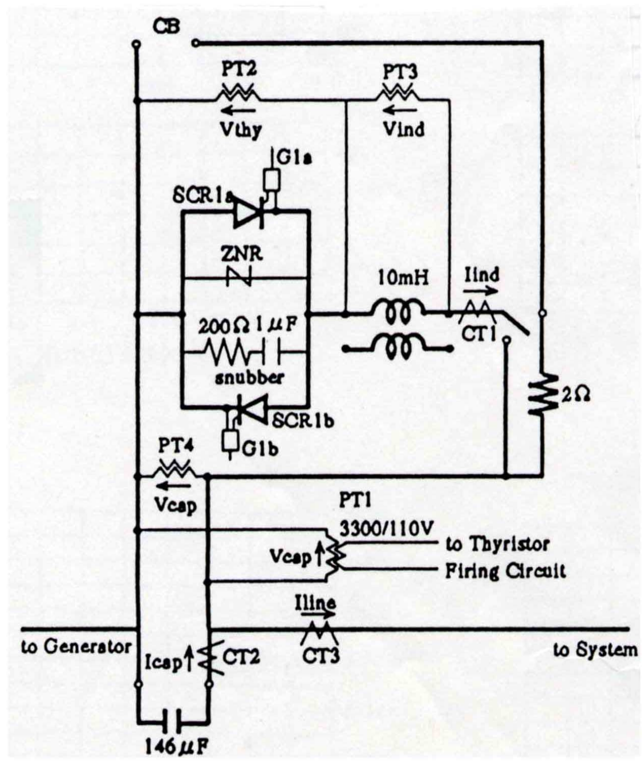


Fig. 1 Prototype TCSC

2. ANALYTICAL MODEL OF TCSC
Analytical equations for the steady state capacitor voltage, inductor current and line current of this system are newly developed using Laplace transformation for all of three basic modes of operation of TCSC; thyristors-blocked mode, thyristor-bypassed mode and vernier operating mode. The new analytical model assumes the line current to be pure sinusoidal and considers this current as a current source for TCSC. Analytical equations are derived separately for each of thyristors-on and thyristors-off modes of operation.

In the following text, I_{line}, V_{cap}, I_{ind}, C, L, and R are line current, capacitor voltage, inductor current, fixed capacitor, reactor, and resistor, respectively. The inductor current I_{ind} is the same as the thyristor current. The resistor R indicates the total of parasitic resistance of reactor, thyristor resistance and external resistance, if any. It is assumed that losses in the fixed capacitor can be neglected.

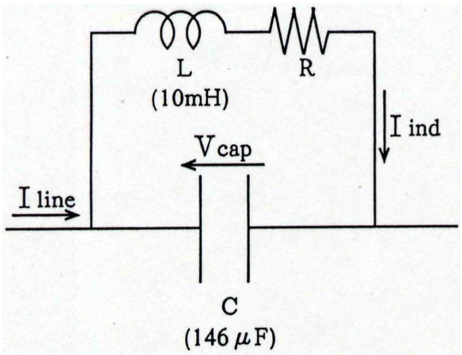


Fig 2. Equivalent circuit of TCSC at thyristors-on mode

First, Fig. 2 shows the equivalent circuit of TCSC at thyristors-on mode. The following equation is obtained.

$$I_{line} = I_{ind} + C\frac{dV_{cap}}{dt} \quad (1)$$

$$V_{cap} = RI_{ind} + L\frac{dI_{ind}}{dt} \quad (2)$$

The instant that TCSC changes from thyristors-off mode to thyristors-on mode is assumed as the beginning of time (t=0). Initial values of phase angle of line current and capacitor voltage are indicated as α_{0on} and V_{0on}, respectively. The line current is assumed as

$$I_{line} = I_m \sin(\omega_b t + \alpha_{0on}) \quad (3)$$

where $\omega_b = 120\pi$.
Using Laplace transformation, the inductor current is

$$I_{ind} = \omega_0^2\{E\sin\omega_b t + F\cos\omega_b t + (G\sin zt - F\cos zt)e^{-xt}\} \quad (4)$$

where

$$\omega_o = 1/\sqrt{LC}$$
$$x = R/2L$$
$$y = \omega_0^2 - \omega_b^2$$
$$z = \sqrt{\omega_0^2 - x^2}$$
$$X = 2\omega_b x$$
$$E = I_m\frac{X\sin\alpha_{0on} + y\cos\alpha_{0on}}{y^2 + X^2}$$
$$F = I_m\frac{y\sin\alpha_{0on} - X\cos\alpha_{0on}}{y^2 + X^2}$$
$$G = \frac{1}{z}(CV_{0on} - \omega_b E - xF)$$

Differentiating (4) and substituting it into (2) yields

$$\begin{aligned} V_{cap} = {} & R\omega_0^2[\mathrm{E}\sin\omega_b t + F\cos\omega_b t \\ & + \{G\sin zt - F\cos zt\}e^{-xt}] \\ & + L\omega_0^2[\omega_b E\cos\omega_b t + \omega_b F\sin\omega_b t \\ & + \{(zG + xF)\cos zt + (zF - xG)\sin zt\}e^{-xt}] \end{aligned} \quad (5)$$

Secondly, Fig. 3 shows the equivalent circuit of TCSC at thyristors-off mode.The following equation is obtained.

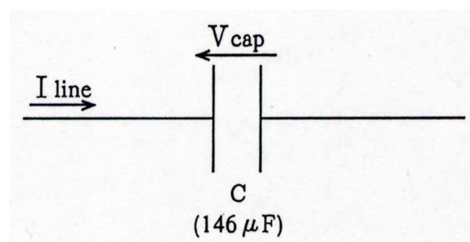


Fig. 3 Equivalent circuit of TCSC at thyristors-off mode

$$I_{line} = C\frac{dV_{cap}}{dt} \quad (6)$$

$$I_{ind} = 0 \quad (7)$$

The instant that TCSC changes from thyristors-on mode to thyristors-off mode is assumed as the beginning of time (t=0). Initial values of phase angle of line current and capacitor voltage are indicated as α_{0off} and V_{0off}, respectively. The line current is assumed as

$$I_{line} = I_m\sin(\omega_b t + \alpha_{0off}) \quad (8)$$

Using Laplace transformation, the capacitor voltage is

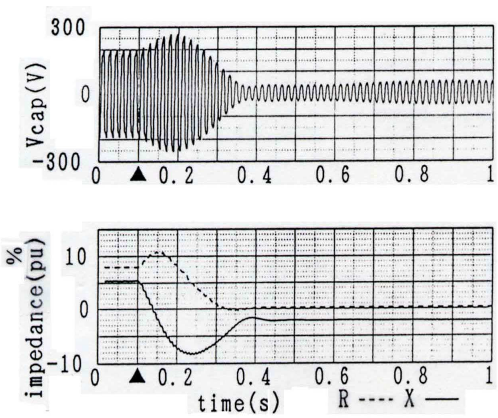
$$V_{cap} = \frac{I_m}{\omega_b C}\{-\cos(\omega_b t + \alpha_{0off}) + \cos\alpha_{0off}\} + V_{0off}$$

(9)

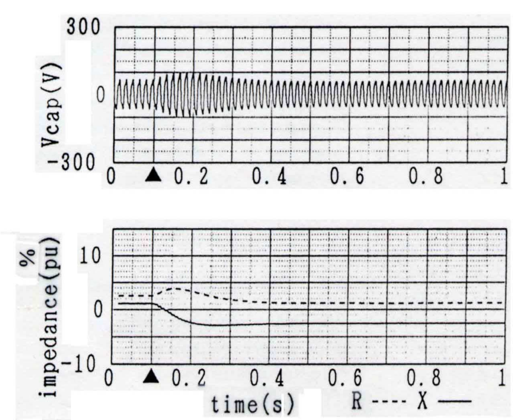
Thus, analytical equations for expressing time-domain characteristics of TCSC at both of thyristors-on and thyristors-off modes have been derived. Losses in the TCSC circuit can be also calculated by the following equation.

$$LOSS \quad = \quad 10 \times \sum_{i=1}^{n} R \times I_{ind}(i)^2 \times \Delta t \qquad (10)$$

where Δ t is the sampling time and n is the number of samples during the period of 0.1s.



(a) R = 0.57 Ω



(b) R = 2.57 Ω

Fig. 4 Experimental results of step responses of TCSC at the rated line current

3. A MODIFIED TCSC

Fig. 4 shows the experimental results of step responses of TCSC at the rated line current for the cases of R = 0.57 Ω and R = 2.57 Ω, while L = 10 mH. The firing angle order was instantaneouly stepped from the reactive reactance to the cpacitive reactance. That is, reactances change from 5.1 to -2.0 [%pu] for the case of R = 0.57 Ω, and from 1.1 to -2.5 [%pu] for the case of R = 2.57 Ω, respectively. In these figures, the capacitor voltage and the equivalent impedance are shown. The way how the equivalent impedance is obtained is presented in the Appendix. The triangle mark indicates the time of step-up order.

The effects of resistance on the transient performances appear in that the capacitor voltages decrease and then the equivalent reactances decrease. Furthermore both voltage and reactance reach steady-state much faster by increasing R. These results suggest that the addition of resistance to TCSC may contribute to damping oscillations.

A new structure of TCSC is shown in Fig. 5. A damping resistor is added to a thyristor branch of TCSC. An additional thyristor switch is connected in parallel with the resistor to bypass the resistor at the steady state and to insert the resistor at the oscillatory state. That is, the resistor is bypassed at the steady state to avoid the increase of losses and is inserted to be used to damp oscillations at the transient state.

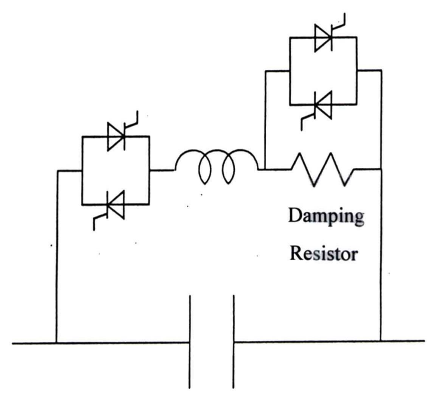
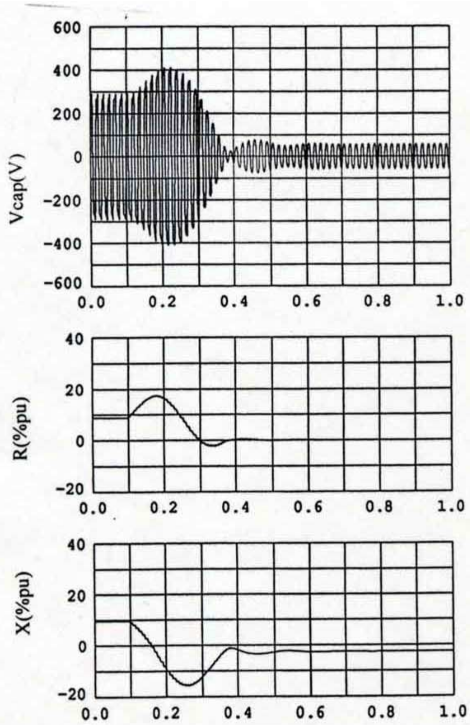


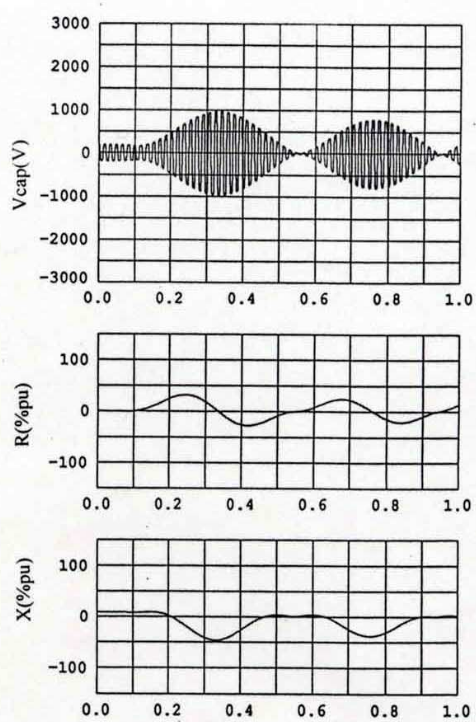
Fig. 5 A modified TCSC

4. SIMULATION RESULTS

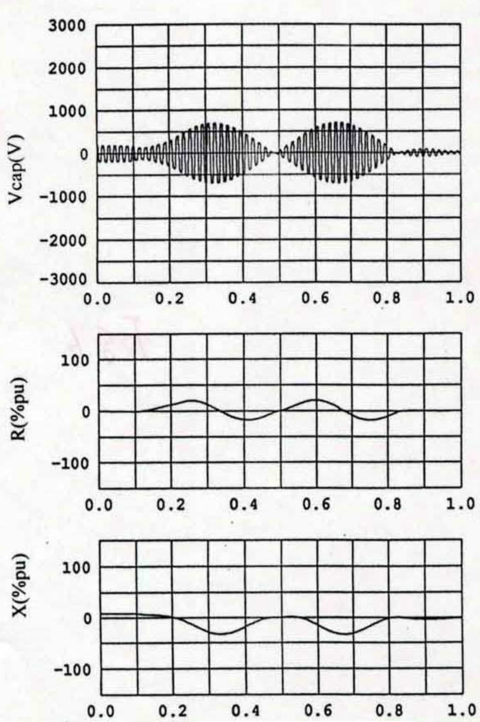
Fig. 6 shows the simulation results of step responses of the modified TCSC. The capacitor is chosen at 146 μ F and the reactor is chosen at 10 mH. The firing angle order was instantaneouly stepped from the reacitive reactance to the capacitive reactance at the time of 0.1s. Capacitor voltages and equivalent impedances are shown.



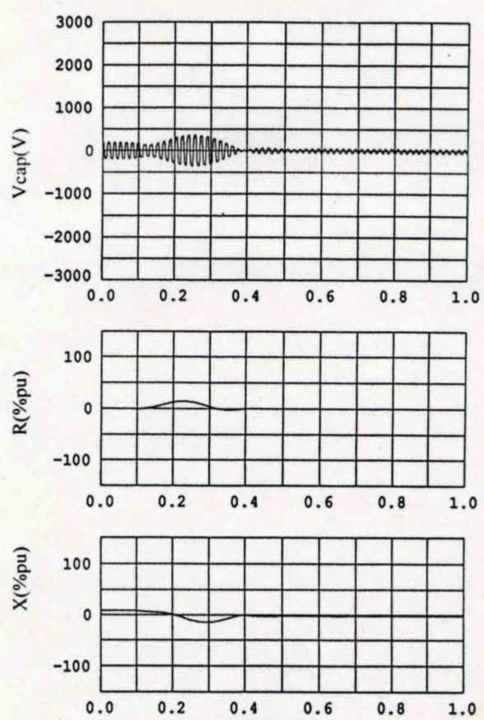
time(s)
(a) R = 0.57 Ω



time(s)
(b) R = 0.0343 Ω



time(s)
(c) Insertion of Damping Resistor from 0.1s to 0.2s



time(s)
(d) Insertion of Damping Resistor from 0.1s to 0.6s

Fig. 6 Simulation results of step responses of the modified TCSC

Fig. 6(a) shows the results for the conventional structure of TCSC, which is assumed to have a parasitic resistance of $0.57\,\Omega$ that is the same as the laboratory TCSC, for comparison. On the other hand, Fig. 6(b) shows the responses when a parasitic resistance is assumed to be $0.0343\,\Omega$ which is chosen so that the Q-factor of the reactor becomes the same as the Kayenta ASC [1]. It can be seen that the less resistance invites larger oscillations. Fig. 6(c) shows the responses when the damping resistor is inserted from 0.1s to 0.2s. Fig. 6(d) shows the responses when the damping resistor is inserted from 0.1s to 0.6s. The damping resistor is chosen at $0.5357\,\Omega$ so that the total resistance becomes $0.57\,\Omega$. Therefore the results of Figs. 6(a) and (d) are close, although both scales are different and both figures look different. From Figs. 6(c) and (d), it can be seen that the damping resistor acts well and that the more the applied time is, the better the performance is. Steady state losses, however, increase as the resistive component increases. Therefore, further study will be needed on the optimal value of the damping resistor.

5. CONCLUSION

Effects of the resistive component of TCSC on damping power system oscillations were investigated in this paper. Results obtained in this study are summarized as follows:

(1) An analytical model of TCSC to consider its resistive component fully is newly derived. An equation for losses is also presented.

(2) Effects of resistive component of TCSC on damping oscillations are clarified both experimentally and analytically.

(3) A new structure of TCSC for damping oscillations is presented and examined.

APPENDIX
EQUIVALENT IMPEDANCE OF TCSC

The equivalent impedance of TCSC is obtained in the following manner. From capacitor voltage and line current calculated from the analytical equations stated above, the fundamental components of them are obtained by Fourier analysis. Then the equivalent impedance *Z*, its resistive component *R* and its reactive component *X* are given by the following equations.

$$Z = \frac{|V_{cap}|}{|I_{line}|} \tag{A1}$$

$$\theta = \angle V_{cap} - I_{line} \tag{A2}$$

$$R = Z\cos(\theta) \tag{A3}$$

$$X = Z\sin(\theta) \tag{A4}$$

If *X* is negative, it means the reactance is capacitive, while if *X* is positive, the reactance is inductive.

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