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# A Novel Control Strategy for TCSC to Damp Subsynchronous Oscillations

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## 1.0 INTRODUCTION

Thyristor Controlled Series Compensators (TCSC) is the first FACTS controller under the new generation to have reached mature stage of development. The importance of adding series capacitor to ac transmission lines for increasing line loadability is known for a long time. But the potential risk of SSR oscillations had made it undesirable to widely use them in the system. Adding a thyristor controlled series compensator Laresen et al (1) is however a fairly recent phenomenon and provides greater flexibility in power transmission, There are several advantages in using TCSC and reducing the torsional oscillations caused by SSR is one among them.

In this paper a novel discrete control strategy to mitigate SSR oscillations is proposed for TCSC having discrete type of control over compensation level, since it behaves like a conventional series compensation under normal conditions. The control strategy is based on the Phase unbalance concept and is simple and easy to implement in the hardware.

This paper is organised as follows. The concept of Phase unbalance originally proposed by A.Edris (2) is described followed by theoretical analysis to support the design for practical implementation. An expression for the damping torque coefficient is given, which is useful to assess the damping effectiveness quantitatively, over a wide variety of system operating conditions and for arriving at an optimal design. Extension of this concept to TCSC with discrete control is subsequently explained.

Studies carried out on the IEEE second benchmark system for SSR demonstrate the utility of the damping torque coefficient derived at subsynchronous frequencies and also the control strategy applied to TCSC. Results are validated through EMTP simulations and discussed in the end of the paper.

## 2.0 ANALYSIS OF PHASE IMBALANCE

As per IEEE (3), SSR is defined as a condition wherein the electrical system (transmission lines and series compensation) exchanges energy with the mechanical system (turbine generator set) at one or more of the natural frequencies of the combined system below the synchronous frequency of the system. The positive sequence currents flowing in the stator winding at subsynchronous frequency, $\omega_e$ can lead to severe torsional interactions when its complement frequency $(\omega_o - \omega_e)$ is equal to, one of the torsional mode frequency $\omega_m$.

In the well known phase imbalance method (2), the network is modified by adding passive LC circuits in one or two phases as shown in Fig. 1. The unbalance

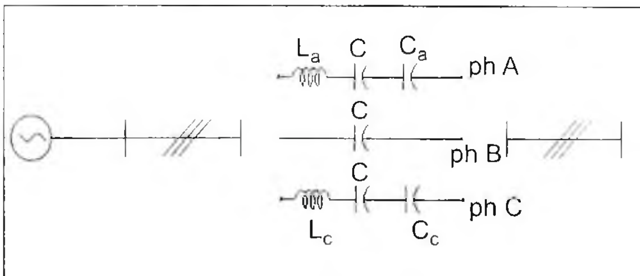


FIG. 1. SERIES RESONANT COMPENSATION SCHEME

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so created detunes the circuit, away from the SSR condition and damps the subsynchronous oscillations. The effectiveness of this method largely depends on the choice of LC circuits and the unbalance created.

## 3.0 ANALYSIS OF NETWORK WITH ASYMMETRY

In SSR phenomenon, the torsional interaction is more important than the induction generator effect. It is convenient to ignore the flux decay, damper circuits and transient saliency in the generator. The synchronous machine is represented as a positive sequence voltage source behind a transient reactance, which is given by,

$$e_{pos} = \varpi E' \sin(\omega_o t + \delta), \tag{1}$$

where, $E'$ - induced voltage proportional to the flux linkage, and $\varpi$ - pu speed.

Assuming that the generator rotor oscillates about a constant speed sinusoidally, $\varpi = \varpi_o + A\sin(\omega_m t)$, we can show that the induced emf in the stator $e_{pos}(t)$ is given by Padiyar (4)

$$\begin{aligned} e_{pos}(t) &= \varpi_o E' \sin(\omega_o t + \delta_o) \\ &\quad - \frac{AE'}{2\omega_m}(\omega_o - \omega_m)\cos[(\omega_o - \omega_m)t + \delta_o] \\ &\quad - \frac{AE'}{2\omega_m}(\omega_o + \omega_m)\cos[(\omega_o + \omega_m)t + \delta_o] \end{aligned} \tag{2}$$

The emf has three sinusoidal components, viz., one of frequency $\omega_o$ and other two components of frequencies $\omega_o \pm \omega_m$., for small amplitude $(A)$ of oscillations. When these voltages are applied to an unbalanced transmission network, we have all the three sequence currents flowing in the network at these frequencies as given by,

$$\begin{bmatrix} i_{pos} \\ i_{neg} \\ i_{zero} \end{bmatrix} = [Y_{seq}] \begin{bmatrix} e_{pos} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \begin{bmatrix} e_{pos} \\ 0 \\ 0 \end{bmatrix} \tag{3}$$

where the $[Y_{seq}]$ is admittance matrix.

Among the three sequence currents flowing in the stator only the positive sequence currents produce torques at the subsynchronous frequency m, and lead to the possibility of negative damping effect on SSR oscillation. Equation (4) is further simplified as,

$$i_{pos} = Y_{11} \quad e_{pos} \tag{4}$$

Computation of $i_{pos}$ from eqn(5) is equivalent to computing the positive sequence current flowing in an equivalent balanced network, whose admittance is equal to $Y_{11}$ and we can write the expression for the damping coefficient torque $T_D$ [3] as,

$$\begin{aligned} T_D &= -\frac{(E')^2}{2\omega_m}\left[(\omega_o - \omega_m)G_{sub} - (\omega_o + \omega_m)G_{sup}\right] \\ &= -T_{Dsub} + T_{D\,sup} \end{aligned} \tag{5}$$

where,

$G_{sub} + jB_{sub} = Y_{11}(j(\omega_o - \omega_m))$ and

$G_{sup} + j\,B_{sup} = Y_{11}(j(\omega_o + \omega_m))$,

are the admittances computed at the subsynchronous and supersynchronous frequency respectively. If the network impedance is close to SSR resonance condition, then the network impedance is purely resistive at the subsynchronous frequency and inductive in the supersynchronous frequency range. Moreover as $G_{sub}$ is very large compared to $G_{sup}$, the damping coefficient is highly negative. It is therefore important to look into the effects of network unbalance on the factor $G_{sub}$. For simplicity the mutual coupling between phases is neglected and we define resonant frequency and impedances in phases a, b & c as,

$$\omega_{ea}^2 = \frac{1}{L_a C_a} \quad \text{with} \quad Z_{aa} = R + j\omega L_a + \frac{1}{j\omega C_a} \tag{6}$$

$$\omega_{eb}^2 = \frac{1}{L_b C_b} \quad \text{with} \quad Z_{bb} = R + j\omega L_b + \frac{1}{j\omega C_b} \tag{7}$$

$$\omega_{ec}^2 = \frac{1}{L_c C_c} \quad \text{with} \quad Z_{cc} = R + j\omega L_c + \frac{1}{j\omega C_c} \tag{8}$$

The expression of $G_{sub}$ is given for two cases.

Case 1: All three phase impedances are equal and close to the resonance frequency

$$(G_{\text{sub}})_{\text{bal}} = \frac{1}{3R} + \frac{1}{3R} + \frac{1}{3R} = \frac{1}{R} \tag{9}$$

Case 2: Unbalance in phases a & c impedance and phase b impedance is close to its resonance frequency web, ie., $(\omega_o - \omega_m) \sim \omega_{eb}$,

$$G_{\text{sub}} = \frac{R}{3\left[R^2 + \omega_{eb}^2 L_a^2 \left\{1 - \frac{\omega_{ea}^2}{\omega_{eb}^2}\right\}^2\right]} + \frac{1}{3R} + \frac{R}{3\left[R^2 + \omega_{eb}^2 L_c^2 \left\{1 - \frac{\omega_{ec}^2}{\omega_{eb}^2}\right\}^2\right]} \tag{10}$$

We can observe that $G_{\text{sub}}$ is less than $(G_{\text{sub}})_{\text{bal}}$ at a particular torsional mode frequency $\omega_m$, due to unbalance in phases a & c. Hence it is possible to quantify the reduction in $G_{\text{sub}}$ in terms of degree of unbalance caused by the impedance imbalance and in turn the damping torque coefficient $T_D$.

## 4.0 EXTENSION OF UNBALANCE CONCEPT TO TCSC

TCSC with discrete control, is made up a number of capacitor modules connected in series to the transmission line, as shown in Fig. 2. The phase imbalance concept discussed above can be readily extended to TCSC, by introducing asymmetry under transient conditions in the system. Instead of adding passive LC resonant circuits, an unbalance is created in TCSC by either inserting/bypassing capacitor modules in individual phases during the disturbances and by removing it when there is no SSR. This is possible due to the thyristor control, which otherwise would not be possible using mechanical breakers. Asymmetry so created reduces the torsional interactions. A control strategy for TCSC is discussed in the following section.

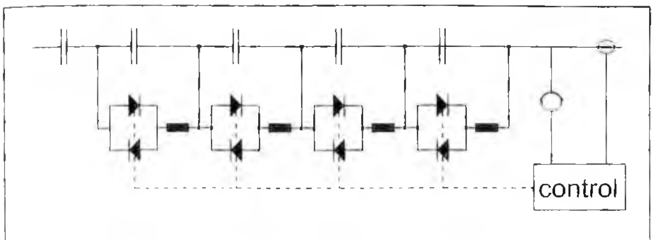


FIG. 2. TCSC CONFIGURATION

## 5.0 TEST SYSTEM

The IEEE Second Benchmark model for SSR studies IEEE(5) as shown in Fig 3 is chosen as the test example. The system consists of a synchronous generator connected to an infinite bus over two parallel transmission lines, one of which is capacitor compensated. The generator is represented as a four mass spring system:- high pressure turbine(HP), low pressure turbine(LP), the generator(GEN), and the exciter(EXC), coupled on a single shaft. The modal frequencies for the mechanical system are 24.65 Hz, 32.39 Hz and 51.10 Hz [5]. It is reported in [5] that the torsional modes at 24.65 Hz (mode 1) and 32.39 Hz (mode 2) go unstable over certain range of compensation. Particularly the mode 1 is vulnerable at higher levels of compensation. The damping torque coefficient is calculated for two cases as mentioned above - one with balanced compensation on all phases and the other with unbalance in two phases.

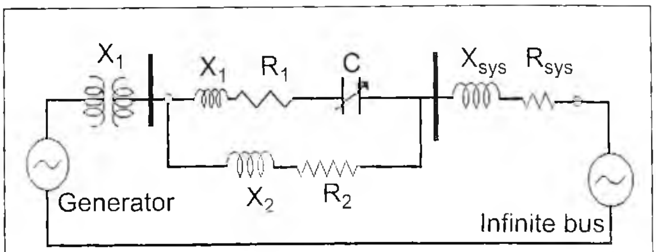


FIG. 3. IEEE SECOND BENCHMARK SYSTEM

### Case 5.1 Analysis of $T_D$ with balanced compensation level.

The variation of damping coefficient $T_D$ is shown in Fig. 4 for exciting the rotor at different modulating frequencies m - 0 to 50 Hz and having different balanced levels of compensation - 5% to 85%. We can observe that with increase in the level of compensation, the peak value of $T_D$ increases and also the frequencies at which it occurs shifts to the lower

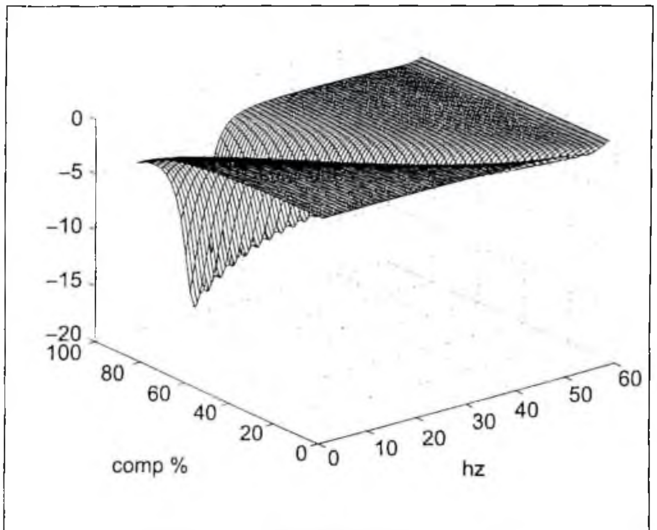


FIG. 4. VARIATION OF TD FOR DIFFERENT COMPENSATION LEVELS

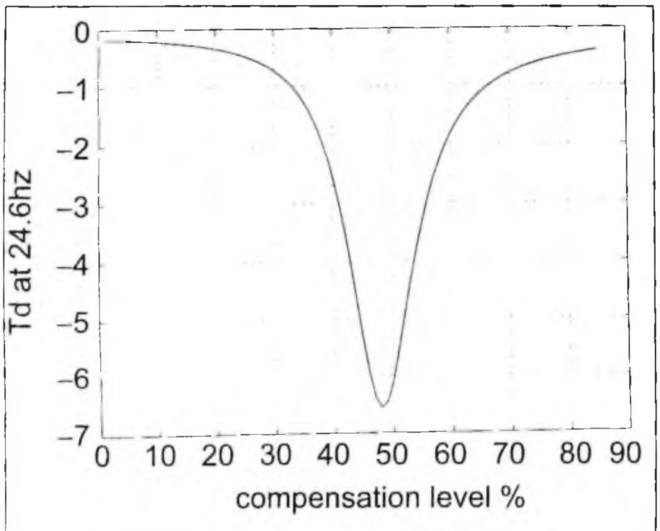


FIG. 5. VARIATION OF TD AT 24.6 HZ FOR DIFFERENT COMPENSATION LEVELS

side of the frequency range. Since we are interested in the damping effect of the torsional modes (at 24.6 Hz and 32.39 Hz for the system), the comparison of $T_D$ at 24.6 Hz is shown in Fig. 5. We can see that

- the magnitude of $T_D$ at 55% level (3.55) is greater than the magnitude of $T_D$ at 25% (0.5) and 75% (0.66) levels of compensation, which implies that there is poor damping in the case of 55%.
- the worst case is at 48% ($T_D = 6.46$) compensation level

Time domain simulation on EMTP is carried out with both the generator and the electrical network modeled in three phases, including the dynamics of the generator-turbine and the network. The disturbance considered for the study is a three phase to ground fault on the high voltage side of the generator step-up transformer, with one cycle clearing time (fault duration is 17 ms). At 55% compensation, we observe growing oscillations in the shaft torque as shown in Fig. 6 which agrees with the analytical prediction.

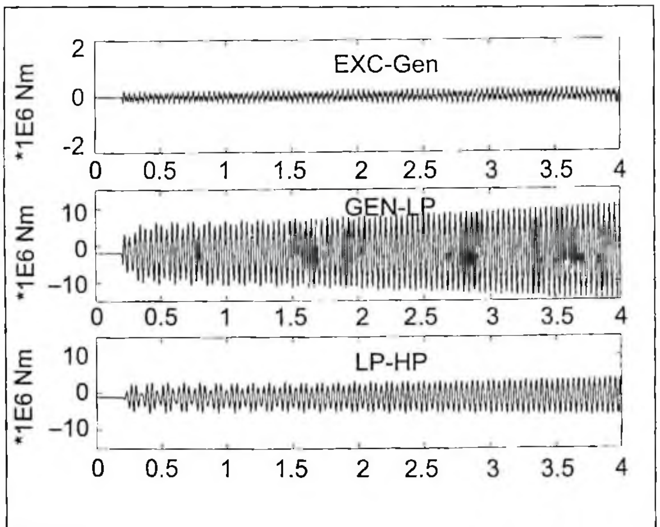


FIG. 6. SHAFT TORQUE VARIATION FOR A 3-PH TO GROUND FAULT, AT 55% COMPENSATION LEVEL

## Case 5.2 Analysis of $T_D$ with unbalance in compensation level.

The damping torque coefficient $T_D$ is computed for varying compensation levels in phases a & c in the range 10%–85%, keeping the compensation in phase-b constant at 55% compensation. Table 1 gives the maximum value of $T_D$ and the frequency at which it occurs. It also shows $T_D$ at 24.6 Hz (one of the torsional modes). We can observe the following,

- an increase in the maximum value of $T_D$ from $-2.533$ to $-5.96$ and a decrease in the frequency at which it occurs from 25.96 Hz to 15.74 Hz resp., as the compensation in phase-*c* increases.
- The critical levels are 30% to 35% because the maximum $T_D$ occurs around the torsional frequency of 24.6 Hz.
- the value of $T_d$ at 24.6 Hz (shown in Table 1) for 35% compensation is lower than for the case of having balanced 55% compensation in all phases at 24.6 Hz. (see Fig. 5)

TABLE 1
MAXIMUM VALUE OF $T_D$ FOR 0% IN PH-A AND 55% IN PH-B

| Phase-c comp. (%) | $T_D$ at 24.6 Hz, pu | Maximum | |
|---|---|---|---|
| | | $T_D$, pu | Freq. (Hz) |
| 1 | −2.03 | −2.533 | 25.96 |
| 5 | −2.11 | −2.575 | 25.91 |
| 10 | −2.24 | −2.638 | 25.77 |
| 15 | −2.39 | −2.713 | 25.624 |
| 20 | −2.58 | −2.805 | 25.433 |
| 25 | −2.795 | −2.917 | 25.194 |
| 30 | −3.02 | −3.032 | 24.86 |
| 35 | −3.2 | −3.211 | 24.49 |
| 40 | −3.22 | −3.39 | 24.05 |
| 45 | −2.96 | −3.595 | 23.427 |
| 50 | −2.47 | −3.811 | 22.76 |
| 55 | −1.925 | −4.036 | 21.90 |
| 60 | −1.497 | −4.28 | 20.99 |
| 65 | −1.211 | −4.54 | 20.04 |
| 70 | −1.04 | −4.82 | 18.99 |
| 75 | −0.937 | −5.15 | 17.94 |
| 80 | −0.88 | −5.53 | 16.84 |
| 85 | −0.85 | −5.96 | 15.74 |

So the effect of detuning away from the torsional mode frequency can be observed with having unbalance compensation levels. Fig. 7 shows the variation of $T_D$ at 24.6 Hz for varying compensation levels in phases $a$ & $c$ in the range 10%–85% keeping the compensation in phase-$b$ constant at 55% compensation. We can observe the following,

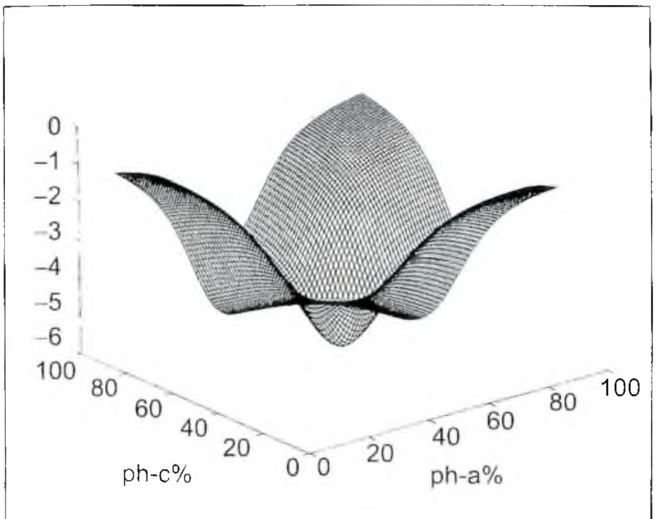


FIG. 7 VARIATION OF $T_D$ AT 24.6 HZ FOR 55% IN PHASE-$B$ AND DIFFERENT COMPENSATION LEVELS IN PHASES $A$ & $C$

- The maximum value of $T_D$ is −5.41, for having 48% and 47% compensation levels in phases $a$ and $c$ respectively. This value is less than the value of TD for the balanced case of 48% compensation level (see Fig. 5).
- There is symmetry between phases $a$ and $c$. The change observed in TD when we increase or decrease compensation in phase '$a$', is also seen when we do a similar change in phase '$c$' compensation.
- Minimum negative damping is observed when we have either maximum or minimum compensation on both the phases or maximum compensation in one phase and minimum in the other phase.

### 5.3 Extension to TCSC-Validation using EMTP

EMTP simulations are carried out to demonstrate the control strategy adopted for TCSC. The nominal compensation provided by TCSC is 55%. When there is a disturbance the torsional oscillations are undamped as shown in Fig. 8. Five cases $a$–$e$ of asymmetry (as listed below) are considered The desired asymmetry in the level of compensation is made in the phases at the time of fault application The change is effected either by switching in or switching out the capacitor modules. The disturbance is a three phase to ground fault lasting for 17 ms duration.

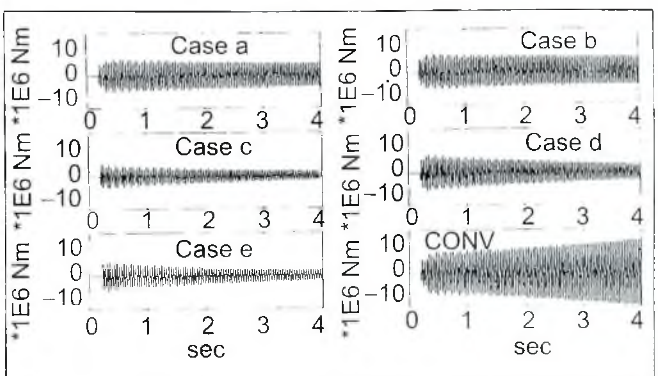


FIG. 8. GEN-LP SHAFT TRANSIENT TORQUE FOR A 3-PH TO GROUND FAULT FOR CASES $A$-$E$. CONV- FOR 55% COMPENSATION IN ALL PHASES

Case (a) 10% in phase '$a$', 55% in phase '$b$' and 55% in phase '$c$'

Case (b) 75% in phase '$a$', 55% in phase '$b$' and 55% in phase '$c$'

Case (c) 10% in phase '*a*', 55% in phase '*b*' and 10% in phase '*c*'

Case (d) 75% in phase '*a*', 55% in phase '*b*' and 75% in phase '*c*'

Case (e) 0% in phase '*a*', 55% in phase '*b*' and 75% in phase '*c*'

The oscillations in the GEN-LP shaft torque are shown in Fig. 8 for all these cases. These oscillations are damped when there is a change in the compensation during transient period. The damping is more in cases *c* & *e* when compared to cases *a*, *b* & *d*. Though the damping is found to be almost same for the cases (c) and (e), the case (e) is better of the two for two reasons. One is that we can maintain more power flow (for three phases) during the transient in the case (e), compared to the normal (balanced) condition. But in case (c) the power flow is considerably reduced due to reduced compensation in both the phases. Secondly, 10% module may not be available for implementing, as it depends on the discrete steps adopted in the TCSC system. Instead complete bypass can be resorted to as in case (e) and easy to implement. Thus EMTP results confirm the damping of torsional oscillations by the proposed scheme.

## 5.0 CONCLUSION

A theoretical analysis is presented to quantitatively assess the damping of torsional modes under unbalanced network conditions due to asymmetric LC resonant circuits.. An expression for the damping torque coefficient is given in terms of equivalent network admittance evaluated at sub and supersynchronous frequencies. This coefficient is a useful measure in assessing the degree of asymmetry required for a given system. .

The application of the unbalance concept to TCSC with discrete control is described for mitigation of SSR. The studies on the test system show that the change in the compensation level is to be made on both phases for better damping, instead of changing in only one phase. The best choice is found to have maximum in one phase and complete bypass of compensation in the other phase, during transients for damping transient torques. The strategy proposed is simple and easy to implement in the hardware.

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