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# Reduction of Power System Oscillations Using Facts Controllers

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**ABSTRACT:** Several studies have investigated the potential of using FACTS Controllers' capability in damping inter-area oscillations. The uses of Thyristor Controlled Series Capacitor (TCSC) and Static Synchronous Series Compensator (SSSC) have been the subjects of several studies evaluating their respective effectiveness in enhancing power system dynamics. The recently proposed phase imbalanced series capacitive compensation concept has been shown to be effective in enhancing power system dynamics as it has the potential of damping power swing as well as sub synchronous resonance oscillations. In this project, the effectiveness of a *"hybrid"* series capacitive compensation scheme in damping power system oscillations is evaluated. A *hybrid* scheme is a series capacitive compensation scheme, where two phases are compensated by fixed series capacitor (C) and the third phase is compensated by a TCSC in series with a fixed capacitor (Cc). The effectiveness of the scheme in damping power system oscillations for various network conditions, namely different system faults and tie-line power flows is evaluated using the MATLAB simulation program.

**Index Terms:** FACTS Controllers, phase imbalance, series compensation, thyristor controlled series capacitor.

## I. INTRODUCTION

FLEXIBLE AC Transmission Systems (FACTS) technology provides unprecedented way for controlling transmission grids and increasing transmission capacity[1]. FACTS Controllers provide the flexibility of controlling both real and reactive power which could result in an excellent capability for improving power system dynamics. A problem of interest in the power industry at which FACTS Controllers could play a significant role in it is increasing damping of low frequency power oscillations that often arise between areas in large interconnected power networks. These oscillations are termed inter-area oscillations, which are normally characterized by poor damping [2]. Inter-area oscillations can severely restrict system operations by requiring the curtailment of electric power transfers level as an operational measure. These oscillations can also lead to widespread system disturbances, e.g. cascading outages of transmission lines and, therefore system wide voltage collapse .Several studies have investigated the potential of using FACTS Controllers' capability in damping inter-area oscillations. The use of Thyristor Controlled Series Capacitor (TCSC), and Static Synchronous Series Compensator (SSSC)have been the subjects of several studies evaluating their respective effectiveness in enhancing power system dynamics.

The recently proposed phase imbalanced series capacitive compensation concept has been shown to be effective in enhancing power system dynamics as it has the potential of damping power swing as well as sub synchronous resonance oscillations [7], [8]. Fig. 1 shows a scheme for a phase imbalanced capacitive compensation. It is a "hybrid" series compensation scheme, where the series capacitive compensation in one phase is created using a single-phase TCSC in series with a fixed capacitor (Cc), and the other two phases are compensated by fixed series capacitors (C). The TCSC control is initially set such that its equivalent compensations at the power frequency combined with the fixed capacitor yield a resultant compensation equal to the other two phases. Thus, the phase balance is maintained at the power frequency while at any other frequency, a phase imbalance is created. To further enhance power oscillations damping, the TCSC is equipped with a supplementary controller.

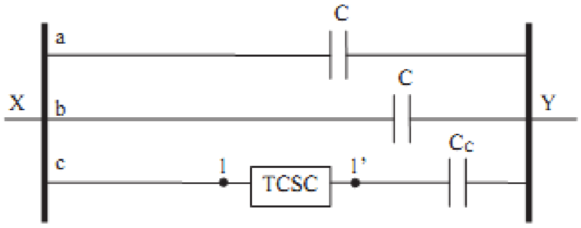



**Fig. 1.** A schematic diagram of the hybrid series compensation scheme.

The phase imbalance of the proposed scheme can be explained mathematically as follows: 1) At the power frequency, the series reactances between buses X and Y, in Fig. 1, in phases a, b, and c are given by:

$$X_{a^=} = X_b = 1/jw_0c -------(1)$$

$$X_C = 1/JW_0C_c - JX_{TCSC_0} -----(2)$$

where $-JX_{TCSC_0}$ is the effective capacitive reactance of the TCSC at the power frequency such that

$$X_a = X_b = X_c.$$

$$X_C = 1/JW_eC_c - JX_{TCSC_0} - J\Delta X_{TCSC} ----------(3)$$

The first terms in (2) and (3) are different because of the difference in frequency. The third term in (3) represents the change in the effective capacitive reactance of the TCSC due to the action of the TCSC supplementary controller. This scheme would, definitely, be economically attractive when compared with a full three-phase TCSC which has been used/proposed for power oscillations damping. Furthermore, reducing the number of thyristor valves to one third will also have a positive impact on system reliability. The effectiveness of the scheme in damping power swings and sub synchronous resonance oscillations is reported in [7], [8]. This paper evaluates the effectiveness of the scheme in damping power system oscillations. Time domain simulations were conducted on a benchmark network using the EMTP-RV.

## II. STUDY BENCHMARK

To demonstrate the effectiveness of the proposed scheme in power system oscillations damping, the system shown in Fig. 2 is adopted as a test benchmark. It consists of three large generating stations (G1, G2 and G3) supplying two load centers (S1 and S2) through five 500 kV transmission lines. The two double-circuit transmission lines L1 and L2 are series compensated with fixed capacitor banks located at the middle of the lines. The compensation degree of L1 and L2 is 50%.The compensation degree is defined as the ratio $(X_C / X_L)*100\%$ $(XC_C + XTCSC)/X_L*100\%$ for the hybrid compensated phase. The total installed capacity and peak load of the system are 4500 MVA and 3833 MVA respectively. Shunt capacitors are installed at buses 4 and 5 to maintain their voltages within 1±0.05 p.u. Two loading profiles designated as Load Profiles A and B are considered in the investigations of this paper. In Load Profile A, $S_1 = 1400 + j200MVA$ and $S_2 = 2400 + j300$ while in Load Profile B, $S_1 = 2000 + j200MVA$. The power flow results for the bus voltages and the line real power flows of the system for these two loading profiles are shown in the Appendix. The EMTP-RV is used as the simulation study tool.

## III. MODELING OF THE SINGLE-PHASE TCSC

The single-phase TCSC is modeled in the EMTP-RV as a single module using an ideal thyristor pair and an RC snubber circuit as shown in Fig. 3. A Phase Locked Loop (PLL) is used to extract phase information of the fundamental frequency line current, which will be used to synchronize TCSC operation. The thyristor gating control is based on the Synchronous Voltage Reversal (SVR) technique [9] - [11]. The TCSC impedance is measured in terms of a boost factor kB, which is the ratio of the apparent reactance of the TCSC seen from the line to the physical reactance of the TCSC capacitor bank. A positive value of k B is considered for capacitive operation. A low-pass filter based estimation algorithm is used to estimate the voltage and the current phasors. A boost measurement block performs complex impedance calculations for the boost factor of the TCSC as $kB = \mathrm{Im}ag\{V_C^{\wedge} / I_c^{\wedge}\} / X_{CTCSC}$, where,

C V ˆ and C I ˆ are the estimated phase voltage and current and XCTCSC is the capacitive reactance of the TCSC capacitor branch at the fundamental frequency. A proportional-integral (PI) control based boost level controller is implemented to control the TCSC boost level to the desired value by adjusting the instant of the expected capacitor voltage zero crossing. The integral part of the controller helps in removing the steady state errors. The controller parameters were determined by performing repeated time domain simulations for the different operating conditions. This algorithm uses the difference between the actual boost level and the reference boost level (err) shown in Fig. 3 as an objective function. The algorithm starts with arbitrary initial values for the control parameters and calculates the values of the objective function each time. The control parameters are incremented for the next iteration and the procedure is repeated until the objective function approaches a minimum value (below a threshold value). The procedure described above is widely used by industry for tuning of controller parameters. The multiple simulations run based tuning procedure similar to the above was reported in [12].

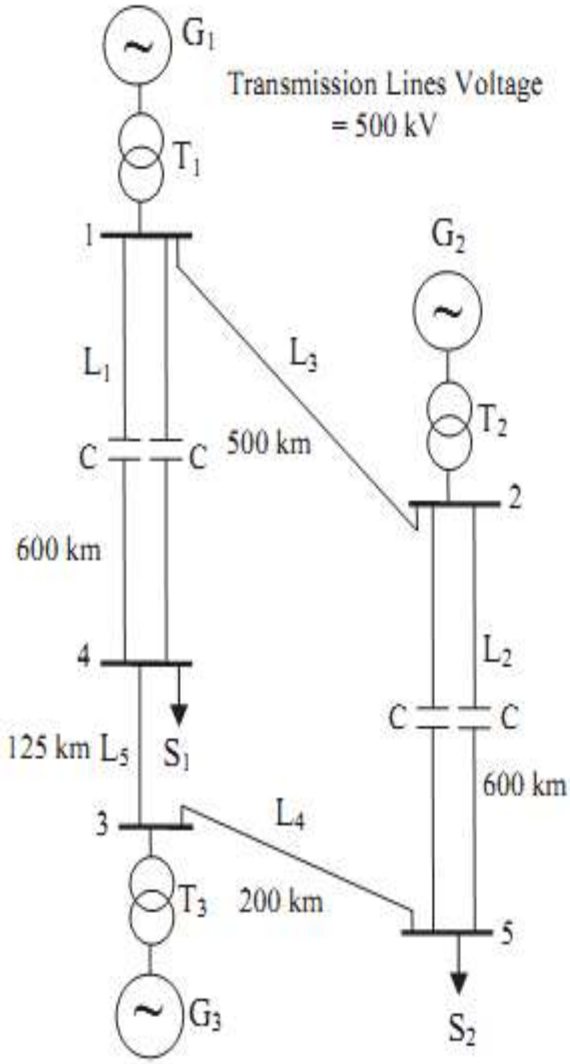



**FIG2:** TESTBENCHMARK

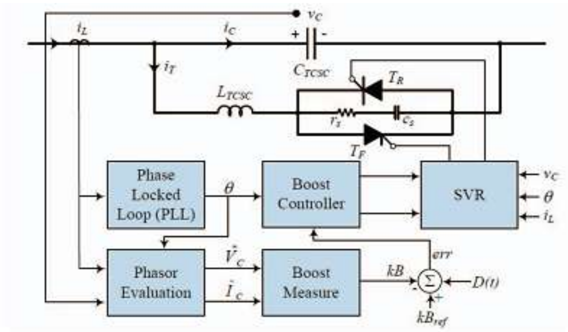



**Fig3.** Block diagram of a TCSC controller

In Fig. 3, D(t) is a supplemental signal generated from an m-stage lead-lag compensation based controller. As the real power flow in the transmission line is proportional to the inverse of the total line reactance, the power swing damping can be achieved by properly modulating the apparent TCSC reactance through this controller. The supplemental controller input (stabilizing) signals could be local (e.g. real power flows) or remote (e.g. load angles or speed deviations of remote generators). If a wide-area network of Synchronized Phasor Measurement (SPM) units is available, then the remote signals can be downloaded at the controller in real time without delay. Local signals are generally preferred over remote signals as they are more reliable since they do not depend on communications. Fig. 3, k Brief is the TCSC boost level set point. The Synchronous Voltage Reversal block solves for angle γ from the non-linear relation, [] )

$u_{CZ} = X_0 i_{LM} [\lambda\gamma - \tan(\lambda\gamma)]$, where u CZ is the estimated capacitor voltage at the desired instant when the capacitor voltage zero crossing occurs, I LM is the measured value of the line current iL, X0 is the TCSC capacitor reactance at the TCSC resonance frequency, λ is the ratio between the TCSC resonance frequency and the system fundamental frequency and γ is the angle difference between the firing time and the voltage zero-crossing. The value of γ is used to calculate the exact firing instants of the individual thyristors. The non-linear relationship between the boost factor and the thyristor firing angle Į is shown in Fig. 4.

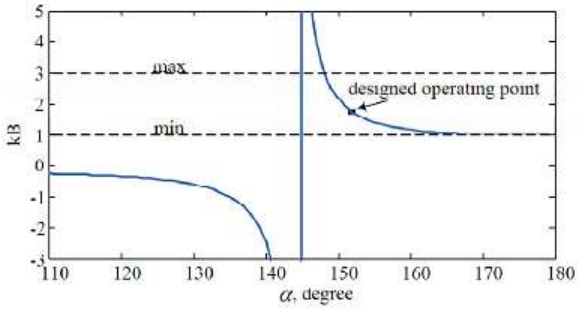



**Fig. 4.** TCSC boost factor as a function of the thyristor firing angle Į.

## IV. TIME DOMAIN SIMULATIONS

This section demonstrates the capability of the proposed hybrid series compensation scheme in power system oscillations damping. For this purpose, the scheme is assumed to be placed in the test benchmark replacing the fixed series capacitive compensation in L1 and L2. Moreover, it is assumed that each TCSC provides 50% of the total capacitive compensation and the disturbance is a three-cycle, three-phase fault at bus 4. Furthermore, the performance of the scheme is compared to the case with only fixed capacitor compensation which is labeled in the figures of the time responses as Fixed C.

**CASE STUDY I:** Load Profile A

In this case, four different combinations of stabilizing signals (tabulated in Table I) are examined in order to determine the combination that would result in the best system transient time responses. The final results of the time-domain simulation studies (controllers tuning) are shown in Fig. 5 which illustrates the generator load angles, measured with respect to generator 1 load angle, during and after fault clearing. The transfer functions of the TCSC supplemental controllers for the four combinations are given in Table II. Comparing the responses of the fixed series capacitor compensation to the hybrid TCSC compensation scheme in Fig. 5, the positive contribution of the proposed hybrid scheme to the damping of the system oscillations is very clear. As it can be seen from Fig. 5, the power swing damping controller effectively damps the system oscillations. It can also be seen from Fig. 5 that the best damping of the relative load angle responses are achieved with the į21-į21 combination. The second best damped responses are obtained with the į31-į21 combination. These results should be expected due to the direct relationship between the relative load angles and the generators that yield the problem. It can also be seen from Fig. 5 that the worst damped responses are obtained with PL1- į21 combination which results also in the increase of the first swings.

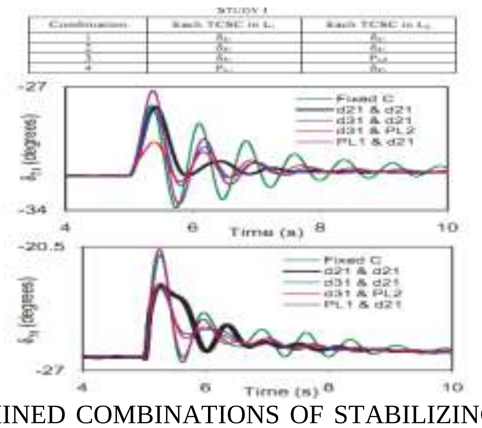



TABLE I: THE FOUR EXAMINED COMBINATIONS OF STABILIZING SIGNALS FOR CASE Fig. 5. Generator load angles, measured with respect to generator 1 load angle, during and after clearing a three-phase fault at bus 4 (Load ProfileA).

**CASE STUDY II:** Load Profile B

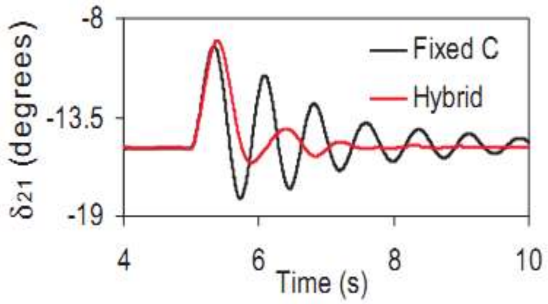
In this case, $\delta_{21}$ is used as the supplementary controllers stabilizing signal. The transfer functions of the TCSC supplemental controllers are given in Table III. Fig. 6 illustrates the generator load angles, measured with respect to generator 1 load angle, during and after fault clearing. It can be seen from Fig. 6 that, at this loading profile, the hybrid single-phase-TCSC scheme provides again a better damping performance to system oscillations compared to fixed capacitor compensation. It is observed, however, that there is a slight increase in the first swing of $\delta_{21}$.

**TABLE II:** TRANSFER FUNCTIONS OF THE TCSC SUPPLEMENTAL CONTROLLERS FOR

| Combi-nation | Each TCSC in $L_1$ | Each TCSC in $L_2$ |
|---|---|---|
| 1 | $G(s)=0.25\frac{10}{(s+10)}\frac{3s}{(3s+1)}$ | $G(s)=-0.15\frac{10}{(s+10)}\frac{3s}{(3s+1)}$ |
| 2 | $G(s)=0.05\frac{10}{(s+10)}\frac{3s}{(3s+1)}$ | $G(s)=-0.15\frac{10}{(s+10)}\frac{3s}{(3s+1)}$ |
| 3 | $G(s)=0.1\frac{10}{(s+10)}\frac{3s}{(3s+1)}$ | $G(s)=-0.4\frac{10}{(s+10)}\frac{3s}{(3s+1)}$ |
| 4 | $G(s)=-0.25\frac{10}{(s+10)}\frac{3s}{(3s+1)}$ | $G(s)=-0.25\frac{10}{(s+10)}\frac{3s}{(3s+1)}$ |

TABLE III
TRANSFER FUNCTIONS OF THE TCSC SUPPLEMENTAL CONTROLLERS FOR CASE STUDY II

| | |
|---|---|
| Each TCSC in $L_1$ | $G(s)=0.3\frac{10}{(s+10)}\frac{3s}{(3s+1)}$ |
| Each TCSC in $L_2$ | $G(s)=-0.15\frac{10}{(s+10)}\frac{3s}{(3s+1)}$ |




CASESTUDYI

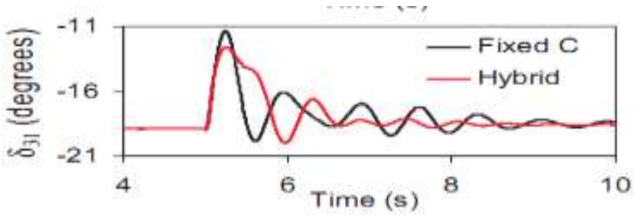



**Fig. 6**. Generator load angles, measured with respect to generator 1 load angle during and after clearing a three-phase fault at bus 4 (Load Profile B).

**CASE STUDY III:**

A Dual-Channel Controller Any of the four signals, $\delta_{21,}\delta_{31}$, PL1 and PL2 contains the system's two natural modes of oscillations and can be used to add damping to these modes as it has been demonstrated in Case study I. The sum of two properly selected signals ,however, should result in a more effective damping. The reason is that the two natural modes of oscillations are, in general, not in phase. A dual-channel controller would adjust separately the gain and phase of each mode of oscillations and, thus, provides a better damping. The performance of the dual-channel TCSC supplemental controller shown in Fig. 7 in damping power system oscillations is examined using the six pairs of signals given in Table IV. Investigations are conducted on the test benchmark system at Load profile B.

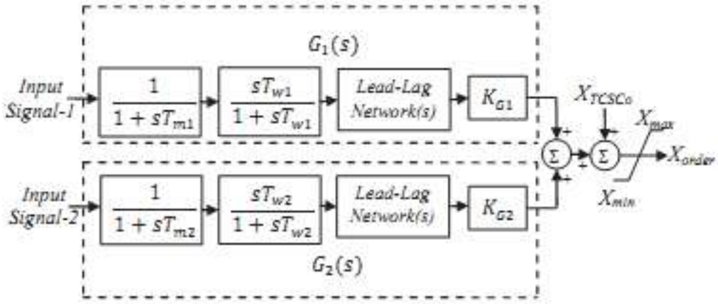



Fig. 7. Structure of a dual-channel power oscillations damping controller.

TABLE IV
THE SIX EXAMINED COMBINATIONS OF STABILIZING SIGNALS FOR CASE STUDY III

| Pair number | Each TCSC (input signal-1, input signal-2) |
|---|---|
| 1 | $\delta_{21}, \delta_{31}$ |
| 2 | $\delta_{21}, P_{L1}$ |
| 3 | $\delta_{21}, P_{L2}$ |
| 4 | $\delta_{31}, P_{L1}$ |
| 5 | $\delta_{31}, P_{L2}$ |
| 6 | $P_{L1}, P_{L2}$ |

The final results of the time-domain simulation studies (controllers tuning) show that the best and second best damped responses are obtained with pairs 2 and 5. The transfer functions of the TCSC supplemental controllers for the six pairs of signals are given in Table V. Fig. 8 illustrates the generator load angles, measured with respect to generator 1 load angle, during and after fault clearing. These results (in red color) are compared to the hybrid case of Fig. 6 (referred to as single channel).

**TABLE V** TRANSFERFUNCTIONS OF THE TCSC SUPPLEMENTAL CONTROLLERS

| | |
|---|---|
| Pair 2<br>Each TCSC in $L_1$ | $G_1(s)=0.25\frac{10}{(s+10)}\frac{0.5s}{(0.5s+1)}$<br>$G_2(s)=-0.5\frac{60}{(s+60)}\frac{0.01s}{(0.01s+1)}$ |
| Pair 2<br>Each TCSC in $L_2$ | $G_1(s)=0.25\frac{10}{(s+10)}\frac{0.5s}{(0.5s+1)}$<br>$G_2(s)=-0.5\frac{60}{(s+60)}\frac{0.01s}{(0.01s+1)}$ |
| Pair 5<br>Each TCSC in $L_1$ | $G_1(s)=0.28\frac{10}{(s+10)}\frac{3s}{(3s+1)}$<br>$G_2(s)=-2.5\frac{60}{(s+60)}\frac{0.01s}{(0.01s+1)}$<br>$*\frac{(s+0.1)}{(s+0.2)}\frac{(s+0.5)}{(s+3)}$ |
| Pair 5<br>Each TCSC in $L_2$ | $G_1(s)=0.26\frac{10}{(s+10)}\frac{s}{(s+1)}$<br>$G_2(s)=2\frac{60}{(s+60)}\frac{0.01s}{(0.01s+1)}$<br>$*\frac{(s+0.1)}{(s+0.2)}\frac{(s+0.5)}{(s+3)}$ |

Fig. 9 illustrates the three-phase voltages, VX-Y, across the hybrid single-phase-TCSC compensation scheme (installed in L1 and the controllers are Pair 2) during and after clearing the fault. The system phase imbalance during the disturbance is clearly noticeable especially in phase C.

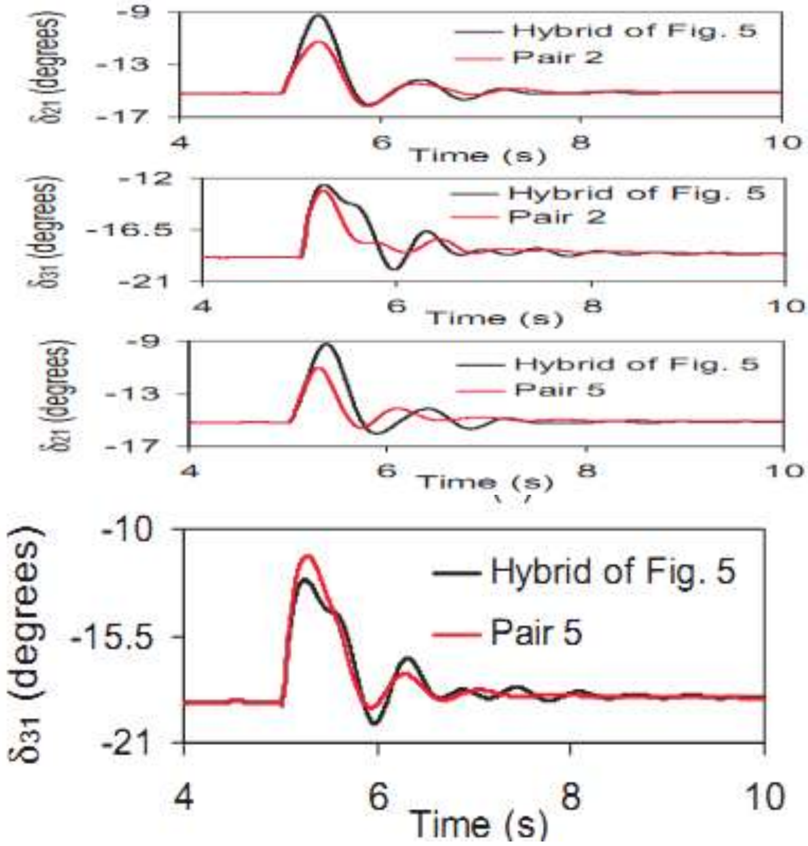



**Fig. 8.** Generator load angles, measured with respect to generator 1 load angle, during and after clearing a three-phase fault at bus 4 (Load Profile B, dual-channel controller).

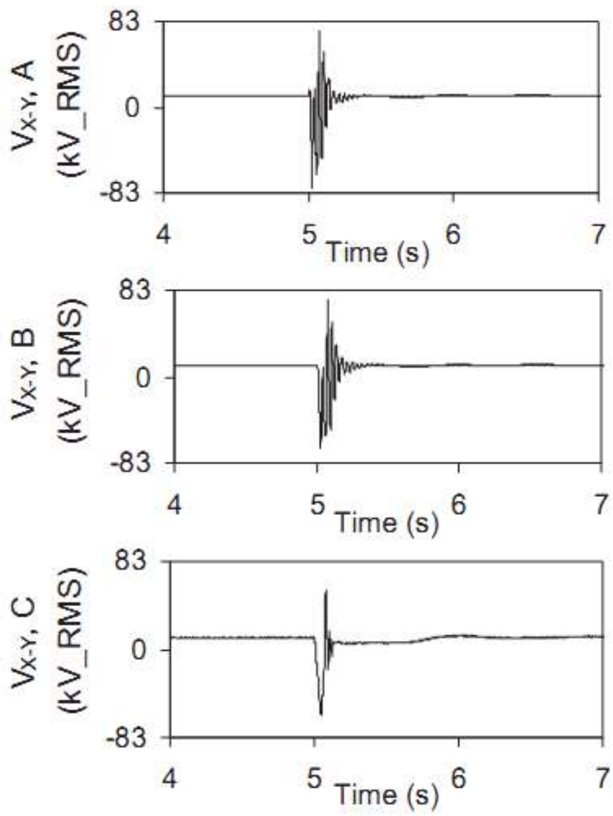



**Fig. 9.** Phase voltages, VX-Y across the hybrid single-phase-TCSC scheme on L1 during and after clearing a three-phase fault at bus 4 (Load Profile B, dual-channel supplemental controllers, Pair 2).

## V. CONCLUSION

The paper presents the application of a new hybrid series capacitive compensation scheme in damping power system oscillations. The effectiveness of the presented scheme in damping these oscillations is demonstrated through several digital computer simulations of case studies on a test benchmark. The presented hybrid series capacitive compensation scheme is feasible, technically sound, and has an industrial application potential. The project presents the application of a new hybrid series capacitive compensation scheme in damping power system oscillations. The effectiveness of the presented scheme in damping these oscillations is demonstrated through several digital computer simulations of case studies on a test benchmark.

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