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Enhancement of Power System Dynamics Using a Novel Series Compensation Scheme

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ABSTRACT: *Phase imbalanced capacitive compensation 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. 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/SIMULINK Software.*

Keywords: *Power system oscillation, POD Controller, STATCOM, TCSC, Phase imbalance capacitor*

I. INTRODUCTION

Many electric utilities world-wide are experiencing increased loadings on portions of their transmission systems, which can, and sometimes do, lead to poorly damped, low- frequency oscillations (0.5 – 2 Hz). These oscillations can severely restrict system operation by requiring the curtailment of electric power transfers as an operational measure. They can also lead to widespread system disturbances if cascading outages of transmission lines occur due to oscillatory power swings, like the blackout in Western North America on August 10, 1996 [6]. The damping energy is obtained by the modulation of load or generation for a period of time, typically in the range of five to ten seconds. The damping energy must have the correct phase shift relative to the accelerated/decelerated system as incorrect phase angles can excite the oscillations.

FACTS controllers are power electronic based controllers which can influence transmission system voltages, currents, impedances and/or phase angles rapidly [8], [9]. These controllers have the flexibility of controlling both real and reactive power, which could provide an excellent capability for improving power system dynamics. FACTS technology provides an unprecedented way for controlling transmission grids and increasing transmission capacity. FACTS controllers may be based on thyristor devices with no gate turn-off (only with gate turn-on), or with power devices with gate turn-off capability. In the studies conducted in this paper, a series FACTS controller based on thyristor switches as well as a shunt FACTS controller based on power devices with gate turn-off capability are considered. The series FACTS controller is called a Thyristor Controlled Series Capacitor (TCSC) whereas the shunt FACTS controller is called Static Synchronous Compensator (STATCOM) [8], [9].

II. THE HYBRID SINGLE-PHASE-TCSC COMPENSATION SCHEME

Figure 1 shows a phase imbalanced hybrid series capacitive compensation scheme using a TCSC. In such a scheme, 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 compensation at the power frequency combined with the fixed capacitor Cc 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. Mathematically, this can be explained as follows:

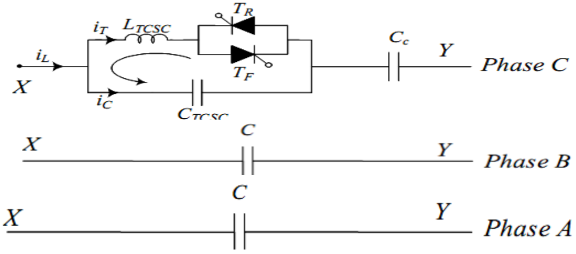


Figure 1: Hybrid single-phase TCSC compensation scheme

At the power frequency, the series reactance between buses X and Y in Figure1 in phases a, b and c are given by:

$$X_a = X_b = \frac{1}{j\omega_o C}$$

$$X_c = \frac{1}{j\omega_o C_c} - jX_{TCSCo}$$

Where $-j\,X_{TCSCo}$ is the effective capacitive reactance of the TCSC at the power frequency such that $X_a = X_b = X_c$.The control offered by the TCSC is an impedance type control, i.e. the inserted voltage is proportional to the line current. This type of control normally is best suited to applications in power flow corridors, where a well-defined phase angle difference exists between the ends of the transmission line to be compensated and controlled. In addition, the STATCOM can offer voltage regulation by functioning as a very fast variable reactive power generation source. As a result, transient stability improvement and the increase in the maximum real power transmitted can be achieved. TCSC and STATCOM can also be used, however, to provide additional damping to the electromechanical (0.5 - 2Hz) power oscillations as they provide fast speed of response and executes any switching patterns without such restrictions that might apply for mechanical switches.

In this paper, the effectiveness of the STATCOM and the hybrid single-phase-TCSC compensation scheme (Scheme I) supplemental controllers in damping power system oscillations is investigated. The test benchmark is shown in figure 2. The two load centers S1 and S2 are supplied by three large generating stations G1,G2 and G3 through five 500KV transmission lines. L1 and L2 are the two double circuit transmission lines and are series compensated with fixed capacitor banks located at the middle of the lines. The degree of compensation is 50%. The degree of compensation for fixed capacitor is $(X_C/X_L)*100$**%** and for hybrid compensated line is $(X_{Ce}+X_{TCSC})/X_L*100\%$. In order to maintain the voltages within 1±0.05 p.u. shunt capacitors are installed at buses 4and 5. Installed capacity is 4500MVA and peak load of the system is 3833MVA. The scheme is assumed to be installed in one or more circuits of lines L_1 and L_2 replacing the fixed series capacitor compensations as well as in the uncompensated line L3. The performance of the Scheme I and the STATCOM supplemental controllers is compared to the case with only fixed capacitor compensation in L1 and L2 (Fixed C) as well as to the case when the STATCOM supplemental controller is not activated (TCSC supplemental controller only).

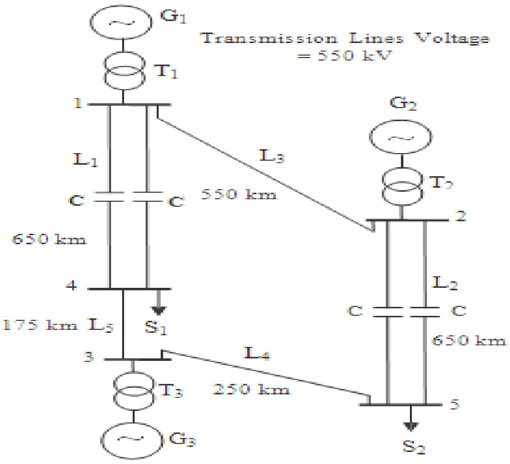


Figure 2: Test Benchmark.

III. TCSC AND STATCOM POWER OSCILLATION DAMPING CONTROLLERS

The TCSC can be made to vary the series-compensation level dynamically in response to the controller-input signal so that the resulting changes in the power flow enhance the system damping. The STATCOM controller consists of two loops which are: outer regulation loop and inner current loop. They work together to regulate the voltage at the connecting point with the system.

Voltage regulation improves the system damping. The traditional type of controller for Power Oscillations Damping (POD) uses cascade- connected washout filters and linear lead-lag compensators to generate the desired reactance modulation signal. The purpose of the wash-out filters is to eliminate the average and extract the oscillating part of the input signal. The lead-lag compensators provide the desired phase shift at the oscillating frequency. Such a controller is illustrated in Figure 2. In some situations, a simple controller consists of only the washout filters which can have a better performance than that of the lead-lag controller. Such a controller, shown in Figure 3 can be considered as a proportional type controller.

Figure 3: Structure of a lead-lag POD controller

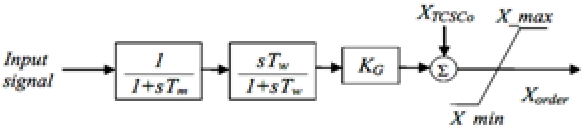


Figure 4 : Structure of a simple POD controller.

The selection of the appropriate input (stabilizing) signal is an important issue in the design of an effective and robust controller. The selected input signal must yield correct control action when a severe fault occurs in the system. As an example, it was reported that if the real power is used as input signal of a pure derivative controller, the output control signal may cause negative damping effects in the presence of disturbances involving large changes in the generator power angles.

The input 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. In the studies conducted in this thesis, the generator load angles and speeds, measured with respect to the load angle and speed of a reference generator are used as input signals.

It is worth noting here that due to the inherent imbalance nature of hybrid single-phase-TCSC compensation scheme during transients, the design of the TCSC supplemental controller using classical linear control techniques would be very difficult, if not, virtually impossible to achieve. However, nonlinear control theories for STATCOM and TCSC applications have been found to have a significant potential in recent years. Some of the examples are: Variable-Structure Controllers (VSCs), model reference adaptive controllers and self-tuning controllers. VSCs are capable of maintaining a desired response characteristic almost independently of the system structure. In the studies conducted in this paper, the supplemental controller parameters are determined by performing multiple time domain simulations with the aim of improving the transient responses of the system. In the case of multiple controllers, simultaneous tuning of the parameters of the controllers is performed to ensure that satisfactory dynamic and steady-state performances are met whilst minimizing or preventing undesirable interactions among controllers.

IV. THE HYBRID SINGLE-PHASE-TCSC COMPENSATION SCHEME IS INSTALLED IN DIFFERENT FORMATS

A. CASE STUDY A: Load Profile I

The best system transient time responses of four different combinations of stabilizing signals are examined in this case.

The final results of the time domain controllers tuning are shown in Figure 5. The transfer functions for the four combinations of the TCSC supplemental controllers are given in Table II.

In Figure 5, it is seen that the power swing damping controller effectively damps the system oscillations. The responses of the fixed series capacitor compensation and the hybrid TCSC compensation are shown in figure 5. The positive contribution of the proposed hybrid scheme to the damping of the system oscillations is very clear. The best damping of the relative load angle responses are achieved with the δ_{21}-δ_{21} combination and the δ_{31}-δ_{21} combination is the second best damped response. With P_{L1}- δ_{21} combination the worst damped response is obtained and also results in the increase of the first swings.

TABLE I

The Four Examined Combinations of Stabilizing Signals for Case Study I

Combination	Each TCSC in L_1	Each TCSC in L_2
1	δ_{21}	δ_{21}
2	δ_{31}	δ_{21}
3	δ_{31}	P_{L2}
4	P_{L1}	δ_{21}

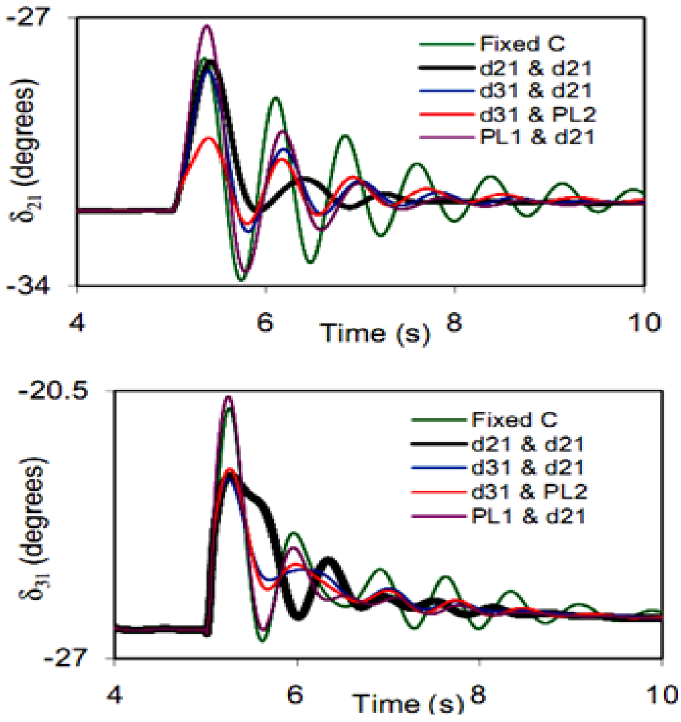


Figure 5: Generator load angles, measured with respect to generator 1 load angle, during and after clearing a three-phase fault at bus 4 (Load Profile I).

B. CASE STUDY B: Load Profile II

The stabilizing signal of the supplementary controllers is $\delta_{21.}$ In this case and the transfer functions are given in Table III. Compared to fixed capacitor compensation, the hybrid single phase TCSC scheme provides a better damping performance to the system oscillations, but there is a slight increase in the first swing of δ_{21} as shown in Figure 6.

TABLE II

Transfer Functions of the TCSC Supplemental Controllers for Case Study A

C	Each TCSC in L_1	Each TCSC in L_2
1	G(s)=0.25 (10/S+10)(3S/3S+1)	G(s)=-0.15 (10/S+10)(3S/3S+1)
2	G(s)=0.05 (10/S+10)(3S/3S+1)	G(s)=-0.15 (10/S+10)(3S/3S+1)
3	G(s)=0.1 (10/S+10)(3S/3S+1)	G(s)=-0.4 (10/S+10)(3S/3S+1)
4	G(s)=-0.25 (10/S+10)(3S/3S+1)	G(s)=-0.25 (10/S+10)(3S/3S+1)

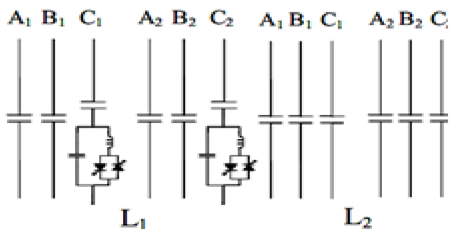


TABLE III

Transfer Functions of the TCSC Supplemental Controllers for Case Study II

Each TCSC in L_1	G(s)=0.3 (10/S+10)(3S/3S+1)
Each TCSC in L_2	G(s)=-0.15 (10/S+10)(3S/3S+1)

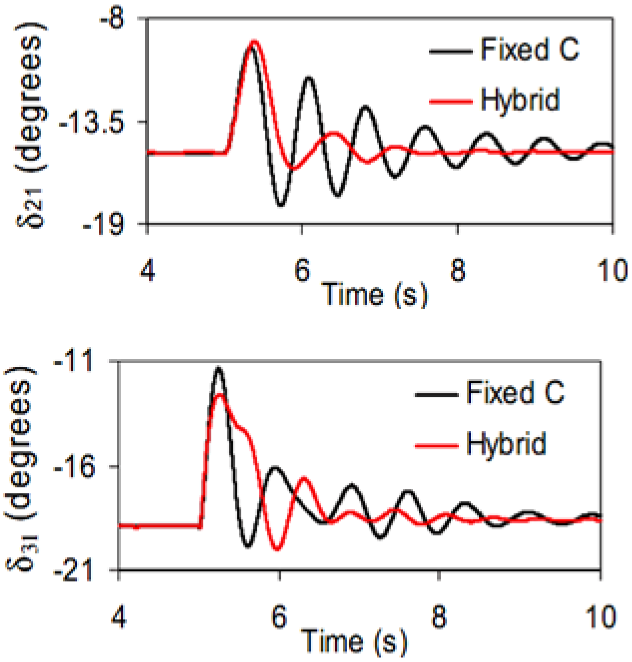


Figure 6: Generator load angles, measured with respect to generator 1 load angle, during and after clearing a three-phase fault at bus 4 (Load Profile II).

C. CASE STUDY C: A Dual-Channel Controller

Two natural modes of oscillations can be observed in any of the four signals δ_{21}, δ_{31}, PL1 and PL2 and these are used to add damping as in case study A. More effective damping will be resulted when two properly selected signals are added. The two natural modes of oscillations are not in phase in general. A dual-channel controller would adjust separately the gain and phase of each mode of oscillations and thus provides a better damping.

TABLE IV

The Six Examined Combinations of Stabilizing Signals for Case Study III

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

The dual channel TCSC supplemental damping power system oscillations using six pairs of signals is shown in figure 7.and are given in Table IV. The best and the second best damped responses are obtained with pairs 2 and 5, and the transfer functions of the TCSC supplemental controllers for the six pairs of signals are given in table V.

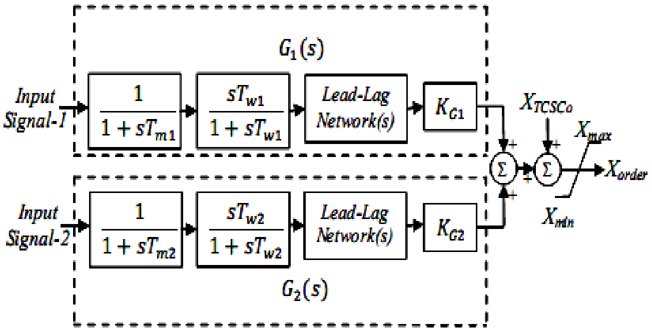


Figure 7: Structure of a dual-channel power oscillations damping controller.

TABLE V

Transfer Functions of the TCSC Supplemental Controllers

Pair 2 Each TCSC in L_1	G_1(s)=0.25 10/S+10)(0.5S/0.5S+1) G_2(s)=-0.5 /S+60)(0.01S/0.01S+1)
Pair 2 Each TCSC in L_1	G_1(s)=0.25 (10/S+10)(0.5S/0.5S+1) G_2(s)=-0.5 0/S+60)(0.01S/0.01S+1)
Pair 5 Each TCSC in L_1	G_1(s)=0.28 (10/S+10)(3S/3S+1) G_2(s)=-(60/S+60)(0.01S/0.01S+1)* ((S+0.1)/(S+0.2))((S+0.5)/(S+3))
Pair 5 Each TCSC in L_2	G_1(s)=0.26 (10/S+10)(S/S+1) G_2(s)=2.5(60/S+60)(0.01S/0.01S+1)* ((S+0.1)/(S+0.2))((S+0.5)/(S+3))

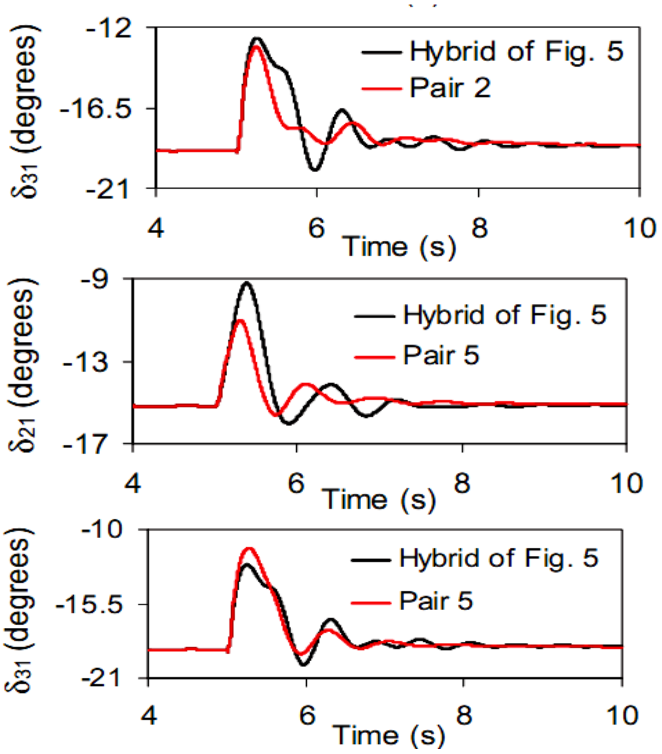
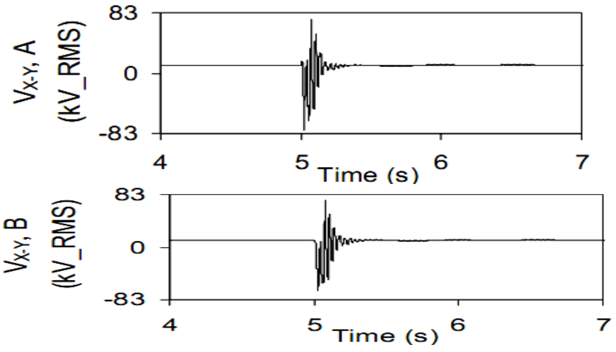


Figure 8: Generator load angles, measured with respect to generator 1 load angle, during and after clearing a three phase fault at bus 4 (Load Profile B, dual-channel controller).

Figure 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.



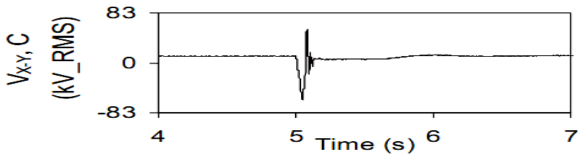


Figure 9: Phase voltages, V_{X-Y} across the hybrid single-phase- TCSC scheme on L1 during and after clearing a three-phase fault at bus 4 (Load Profile B, dual-channel supplemental controllers, Pair 2).

V. CONCLUSION

Increasing the proportion of the single-phase-TCSC to the fixed capacitor of its phase results in improving the damping of system oscillations. Increasing the proportion of the hybrid single-phase-TCSC compensation scheme to the total fixed capacitor compensation (i.e. Installing the scheme in more transmission line circuits replacing fixed capacitor compensation) enhances significantly the damping of system oscillations. Choosing the values of such two proportion options can be considered as an optimization task between dynamic stability improvements and economical and reliability advantages of fixed series capacitors. In all case studies adequate power system oscillation damping is obtained with proportional type TCSC and STATCOM supplemental controllers. Overall the best damping of the relative load angle responses are achieved when the hybrid single-phase TCSC is installed in line L3 as well as in the two circuits of line L1.

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