# Verification of TCSC Control Strategies Impact on Subsynchronous Oscillations

Ahad Kazemi and Majid Ahankhah

*Abstract* -- **This paper presents a detailed analysis of the impact of different TCSC control methodologies on subsynchronous oscillations problem of a series capacitive compensated transmission system. The study system was modified from the First IEEE SSR benchmark model by changing a part of the fixed series capacitor to TCSC. At first the SSR analysis of the system is simulated without TCSC. Then simulation is done with TCSC model. Three different methodologies are checked, namely: constant current, constant firing angle and constant impedance. The control models and their principles are also described. Then the system is evaluated for several different compensation levels. The SSR analysis is verified through eigenvalues analysis using simulation studies.**

*Index Terms*--**Control system, Power transmission, Subsynchronous resonance, Thyristor circuits, Time domain analysis , TCSC**

## I. INTRODUCTION

SERIES capacitor compensation is a commonly used technique to raise the power transfer capability of high voltage long transmission lines of a power system to economically acceptable levels. This also has the added advantage of keeping the line regulation within tolerable margins. However, this technique may inadvertently increase the risk of subsynchronouse resonance (SSR) problems. This occurs when the subsynchronous frequency of the electrical components(such as transmission lines, series capacitors, transformers and generators) are close to the one of the natural torsional frequencies of the mechanical components of the turbo generators. During any system disturbance, such as line switching or load chang[1]ing, transient currents of sub harmonic frequency are excited and this eventually leads to large electromechanical oscillations which often result in generator tripping, system separation and in some cases, mechanical failure of the machine shafts. Even in cases where there is no mechanical failure, the severe stresses induced by the excessively large torques of high frequency invariably reduces shaft life due to mechanical fatigue[1].

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Ever since the two shaft failures in the Mojave generating station in 1970 and 1971, the subsynchronous resonance problem is received much attention and the IEEE (SSR) working group has proposed countermeasures such as static and dynamic filters and especial excitation system dampers, to prevent over alleviate the problems caused by SSR[2-4].
Since the torsional oscillations are caused by the undesirable component of exchange of energy between the electromechanical turbogenerator system and the electrodynamic power system, energy storage devices are good candidates for the solution of this problem.

Thyristor controlled series capacitor (TCSC) is a power electronic-based device that provides a fast and controllable series compensation of transmission line reactance. It has great application potential in accurately regulating power flow on a transmission line by increasing transfer power capability, damping inter-area power oscillations, mitigation subsynchronous resonance (SSR) and improving transient stability. During the 1990s the thyristor controlled series compensator (TCSC) was being introduced. Several TCSCs are now installed on transmission networks around the world.

The BPA's Slatt TCSC, dedicated in September 1993, was installed at the Slatt 500 kV substation in Bonneville Power Administration (BPA) in Oregon [5].This TCSC was in series with the Slatt-Buckley 500 kV transmission line. The location for the installation was selected to expose the TCSC to severe operating conditions and to gain sufficient operating benefits and experience.

The maximum dynamic range of capacitive reactance was 24 Ω and the nominal three phase compensation was 202 MVar. The results of this project showed that TCSC is not only an effective means of impedance and current control, but also a powerful means for increasing power system stability. Furthermore, TCSC also provides powerful damping against SSR. This paper implies a detailed analysis of the influence of different TCSC control strategies on the SSR problem.

The analysis is conducted for different series compensation levels with the following control strategies:

- Constant current control;
- Constant firing angle control;
- Constant impedance control.

In this paper, the studied system is the first IEEE subsynchronous resonance benchmark model witch is shown in Fig .1.

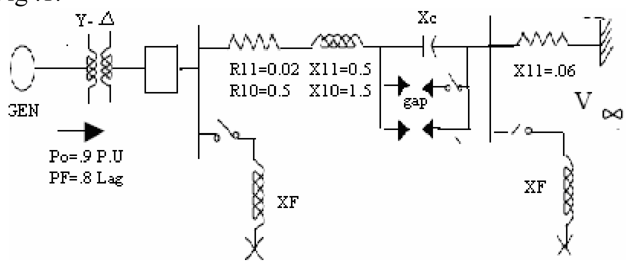



Fig.1. IEEE first benchmark system with a TCSC.

The study is performed using a detailed MATLAB/SIMULINK model for both the TCSC and the generator-shaft system. Several time-domain cases were evaluated, including both large and small disturbances. In this work the firing angle is individually applied to each phase. It is shown that, the mentioned approach is an effective technique in SSR mitigation for each oscillation mode.

## II. System Model Used In Subsynchronuse Damping Studies

### *A. Power system model*

Effect of TCSC on subsyncronous damping of an electrical power system is studied with modified first IEEE benchmark model for SSR studies [3], presented in Fig.2. All or part of the fixed series capacitor of the original model is replaced by controllable TCSC segment. Subsynchronous behaviour of TCSC is studied with no-load situation where active power transfer of the system is 0.9 p.u. A 892.4 MVA synchronous generator is connected to an infinite bus via a highly compensated 500 kV transmission line. The mechanical system consists of a four-stage steam turbine, the generator and a rotating exciter.

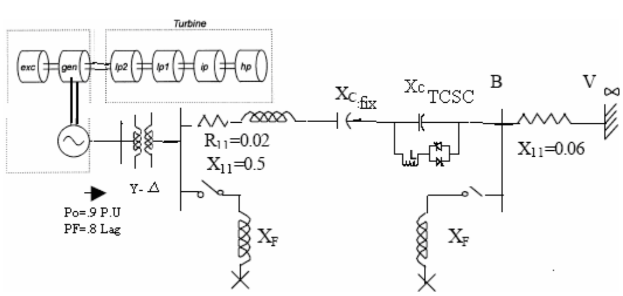



Fig.2. IEEE First Benchmark System with TCSC

The electrical and mechanical systems were modeled using a MATLAB/SIMULINK.

Two damper windings were provided in the q axis while in the d axis one damper and a field winding were considered. The turbine-generator mechanical system shown in Fig.3 consists of a high-pressure turbine (HP), an intermediate-pressure turbine (IP), two low-pressure turbines (LPA & LPB), the generator rotor (GEN) and the exciter (EXC). They together constitute a linear six-mass-spring system.

Mechanical damping is assumed to be zero in all the analyzed cases to represent the worst damping conditions.

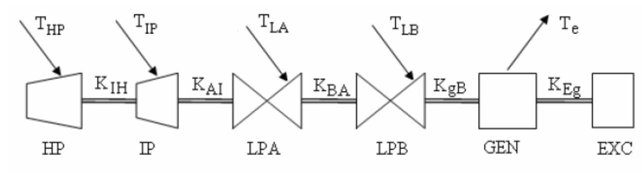



Fig.3. Structure of a typical six-mass shaft system model.

The complete electrical and mechanical data for the studied system are presented in [5].

### *B. TCSC model*

Impact of TCSC on subsynchronous damping is studied with general elements based TCSC simulation model.

The basic scheme of the Thyristor-Controlled Series Compensator (TCSC) is shown in Fig.4. It consists of a series compensating capacitor C shunted by a Thyristor-Controlled Reactor (TCR) L. Assume that the thyristor valve is initially open and that the line current $I_{line}$ produces a voltage $V_{cap}$ across the fixed series compensating capacitor C. Suppose that the thyristor-controlled reactor L is to be turned on at the instant of turn-on, the capacitor voltage $V_{cap}$ is negative, the line current $I_{line}$ is positive and thus charging the capacitor voltage in the positive direction [5]. Because of the negative voltage $V_{cap}$ over the capacitor C, the current $I_T$ becomes negative when the thyristor-controlled reactor is turned on. Here the reverse thyristor is conducting, see the upper thyristor in Fig.4. The reverse thyristor stops conducting when the current $I_T$ crosses zero in the time axis. When none of the thyristors are conducting, the currents $I_{line}$ and $I_{cap}$ are equal. One half period later the procedure described above repeats but now the voltage drop $V_{cap}$ over the capacitor is positive at the instant of turn- on, the line current $I_{line}$ is negative and thus charging the capacitor voltage in the negative direction. Because of the positive voltage $V_{cap}$ over the capacitor C, the current $I_T$ becomes positive when the thyristor controlled reactor is turned on. The forward thyristor stops conducting when the current $I_T$ crosses zero. By regulating the conducting time for the thyristors, the total fundamental capacitive reactance between node A and node B in Fig.4 can be varied. From a fundamental frequency point of view the inserted capacitive reactance of the TCSC is therefore controllable as $C_{TCSC}$ in Fig.4. With successfully varying the inserted capacitance $C_{TCSC}$, the power oscillation damping can be carried out in a transmission system.

However, to damp these and SSR phenomena, the TCSC model in this work must be completed with the mentioned strategies in following sections to provide varying reactance and current reference values.

The authors build up two linear models by analyzing the two different circuits that a phase circuit of the TCSC-compensated line can model: either that none of the thyristors are conducting or that one of them does.

$$\begin{bmatrix} \dot{I}_L \\ \dot{V}_C \\ \dot{I}_P \end{bmatrix} = \begin{bmatrix} -R/L & -1/L & 0 \\ 1/C & 0 & 0 \\ 0 & 0 & -K \end{bmatrix} \begin{bmatrix} I_L \\ V_C \\ I_P \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \\ 0 \end{bmatrix} V_D \quad (1)$$

or shorter as: $\dot{x} = A_1 x + BV_D$ (2)

where $K$ is a large positive number14, and $V_D$ is the forcing voltage of the whole TCSC-compensated line, see Fig.4.

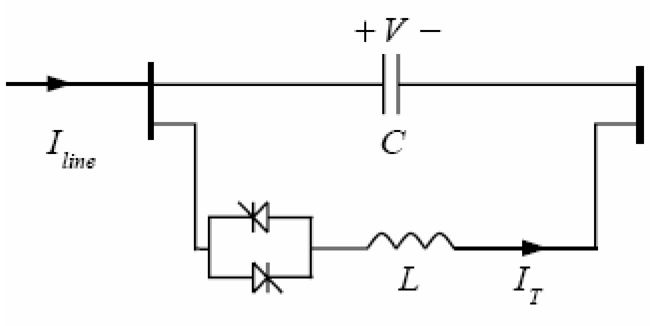



Fig.4. One-line diagram of one phase of a Thyristor-Controlled Series Compensator

When one of the thyristors is conducting, the following state space form represents the circuit.

$$\begin{bmatrix} \dot{I}_L \\ \dot{V}_C \\ \dot{I}_P \end{bmatrix} = \begin{bmatrix} -R/L & -1/L & 0 \\ 1/C & 0 & -1/C \\ 0 & 1/L_P & -R_P/L_P \end{bmatrix} \begin{bmatrix} I_L \\ V_C \\ I_P \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \\ 0 \end{bmatrix} V_D \quad (3)$$

or shorter as: $\dot{x} = A_2 x + BV_D$ (4)

The two above mentioned models can be changed to the equations by Park transformation.

$$\begin{bmatrix} \dot{V} \\ \dot{I}_T \end{bmatrix} = \begin{bmatrix} 0 & -1/C \\ 1/L & 0 \end{bmatrix} \begin{bmatrix} V \\ I_T \end{bmatrix} + \frac{1}{C} \begin{bmatrix} \cos\omega t & -\sin\omega t & 1 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} \quad (5)$$

And

$$\begin{bmatrix} \dot{V} \end{bmatrix} = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \cos\omega t/C & -\sin\omega t/C & 1/C \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} \quad (6)$$

## III. Eigenvalue Analysis

For dynamic characteristics assessment of the system, the eigenvalues are obtained from M-file in MATLAB. The decrement factor and frequency of oscillation are defined as a function of the real ($\sigma$) and imaginary ($\omega_{eig}$) components of the eigenvalue as:

Eigenvalue $\Rightarrow \lambda = \sigma + j\omega_{eig}$ (7)

Decrement Factor $\Rightarrow \sigma$

Frequency of Oscillation $f_{osc} = \omega_{osc}/2\pi$ (8)

Fig.5 depicts the real part of the SSR modes versus series compensation level. As seen the system has four unstable torsional modes [6].

When the subsynchronous electrical mod is to be close or coincides with one of the unstable mechanical modes, a torsional interaction between the electrical and mechanical system occurs. The results in table 1 shows a certain level of compensation that the system experiences an electrical self-excitation problem.

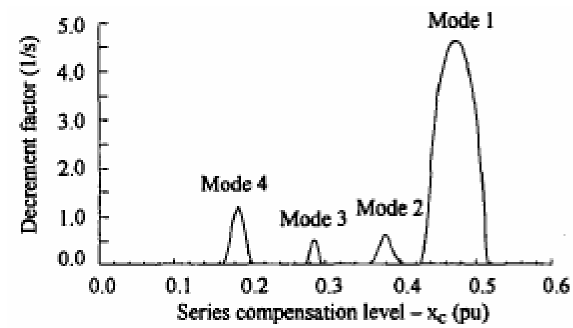



Fig.5. The real part of SSR mode eigenvalues as a function of the percentage compensation

This table also indicates the frequency and level of series compensation associated with the maximum torsional interaction depicted in Fig.2. The power system study model shown in Fig.1 is tuned to torsional mode 1 and the eigenvalues are computed with the generator giving with a 0.9 lagging power factor.

TABLE 1
FREQUENCY OF OSCILATION AND CPACITIVE REACTANCE FOR THE MAXIMUM TORSIONAL INTRACTION

| Mode | $X_C$ (PU) | Frequency (Hz) |
|---|---|---|
| Torsional 4 | .184 | 32.285 |
| Torsional 3 | .285 | 25.547 |
| Torsional 2 | .378 | 20.211 |
| Torsional 1 | .472 | 15.712 |

Table 2 presents the system eigenvalues. This table indicates that the eigenvalues # 9, 10 concerning with torsional mode1 present a negative damping factor.

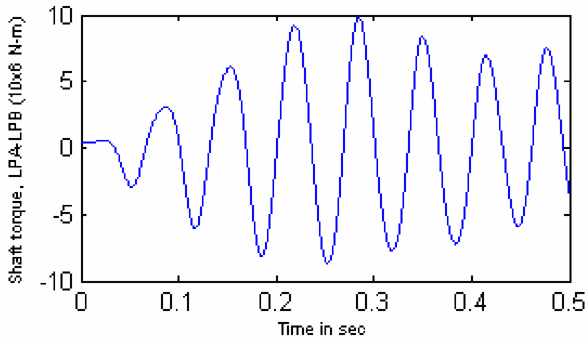
In this case the system experiences growing 15.7 Hz oscillations. In this case all other torsional modes are stable although their damping factor is very low.

TABLE 2
SYSTEM EIGENVALUES

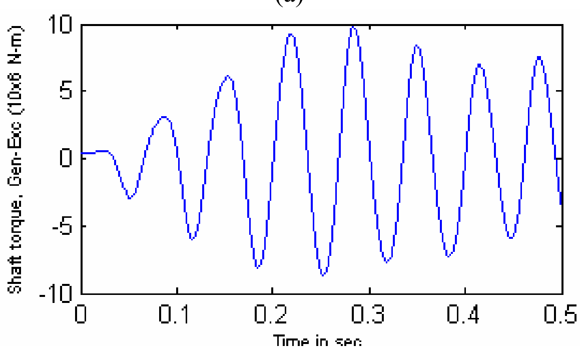
| EIGENVALUES | | | | Damping factor | Oscillating Frequency (Hz) |
|---|---|---|---|---|---|
| # | Mode | Real | Imaginary | | |
| 1,2 | Torsional 5 | -0.0000 | ± 298.18 | 0.0000 | 47.456 |
| 3,4 | Torsional 4 | -0.0304 | ± 202.85 | 0.0000 | 32.285 |
| 5,6 | Torsional 3 | -0.0280 | ± 160.52 | 0.0000 | 25.547 |
| 7,8 | Torsional 2 | -0.0105 | ± 126.99 | 0.0000 | 20.211 |
| 9,10 | Torsional 1 | +4.7752 | ± 98.723 | -0.0508 | 15.712 |

## IV. TIME-DOMAIN SIMULATIONS

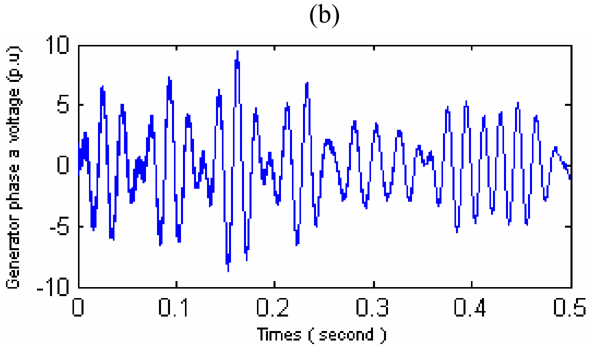
The described case is simulated using MATLAB /SIMULINK and the obtained results are given in Fig.6.



(a)



(b)



(c)

Fig.6. Mode 1 dynamic performance analysis with fixed series compe-nsation : (a) Shaft torque LPA-LPB ; (b) Shaft torque GEN-EXC ; (c) Generator phase a voltage

A three-phase fault is applied at point B in the system to excite the torsional modes.

As seen in the electrical torque response in Fig.6, the subsynchronous oscillations are rapidly increasing, whereas the subsynchronous component is unstable. By growing rotor oscillations, induced voltages and currents are increased. As shown in Fig.7 this problem causes mechanical shaft torques to goe high excessively.

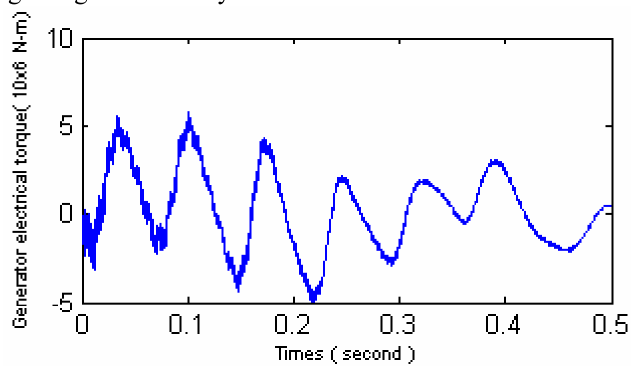



Fig.7. Variation of electrical torque at mode 1.

Since the results in eigenvalues analysis show oscillations in the system, the simulation results present these oscillations too.

## V. TCSC CONTROL STRUCTURE

General structure of TCSC controller is represented in Fig.8. The controller is implemented in MATLAB using simpower control blocks. The TCSC controller is based on proportional-integral (PI) regulator. The derivative component controller feedback is compared with reference value and applied to the controller to increase the damping of SSR modes. For protecting the TCSC during faults, an operation mode selector block is used. In the severe faults situations the thyristor switch reactor (TSR) mode is selected. In this case if the energy of Metal-Oxide Varistor (MOV) exceeds a certain limit, the TSR mode is activated. In this mode the thyristors are conducting at 90 and 270 degrees respectively and therefore sets the thyristors in full conduction. This mode contributes the MOV energy requirements decreasing and makes it possible to have fewer MOV columns installed in parallel with the TCSC equipment. The waiting mode operates during fault clearance time and makes it possible the dc offset voltage to be discharged. Different disturbances are simulated and correctness of results are presented.

### *A. TCSC Constant Current Control Strategy*

The typical TCSC constant current control (CC) controller model is shown in Fig.9. The desired line-current magnitude is fed as a reference signal to the TCSC controller, which strives to maintain the actual line current at this value. The three-phase current is measured and rectified in the measurement unit. The rectified signal is passed through a filter block and normalized to ensure per-unit consistency with the reference-current signal. The controller is typically of the PI type that outputs the desired susceptance signal within the preset limit. A linearizer block converts the susceptance signal in to a firing angle signal. Firing angle is applied to firing pulse generator block for producing firing pulses which have been synchronized by the line current. Firing pulses are applied to the thyristors valve for maintaining the line current on a desirable value. Parametric analysis is carried out to compute the influence of the rating of the TCSC device on the SSR problem. It is observed that for the same operating point or degree of compensation the higher the rating of the TCSC, the higher the sensitivity of the controllers. It will be shown that the small TCSC device, with a rating of 35% of the total capacitive compensation, can effectively damp the SSR phenomenon. This means that for mode 1, out of a total of 0.472 p.u of capacitive reactance, 0.165 p.u will be provided by the TCSC and 0.307 p.u by the fixed capacitor.The TCSC parameters affect not only the fundamental frequency resonances, but also the shape of the reactance curve versus firing angle and harmonic content of the TCSC voltage. The following formula, gives an equivalent of the TCSC as a function of the conducting angle ( $\gamma$ ) [7] , [8].

$$X_{TCSC}=\frac{1}{\omega C}-\frac{A}{\pi\omega C}[\gamma+\sin\gamma]+\frac{4A\cos^2\gamma/2}{\pi\omega c(k^2-1)}[k\tan\frac{k\gamma}{2}-\tan\frac{\gamma}{2}] \qquad (9)$$

where

$$A=\frac{\omega_o^2}{\omega_o^2-\omega^2}\quad,\ \omega_o^2=\frac{1}{LC}\quad,\ k=\frac{\omega_\circ}{\omega} \qquad (10)$$

Where C is the capacitance of the TCSC capacitive branch and L is the inductance of the Thyristor -Controlled Reactor branch. The variation of $X_{TCSC}$ as a function of $\alpha$ is show n in Fig.10. The above equation shows that there is parallel resonance of capacitor and TCR at fundamental frequency, corresponding to values of $\alpha = 150^\circ$.

By appropriately choosing the value of $k = \frac{\omega_\circ}{\omega}$ it is possible to ensure that there is only one resonance point

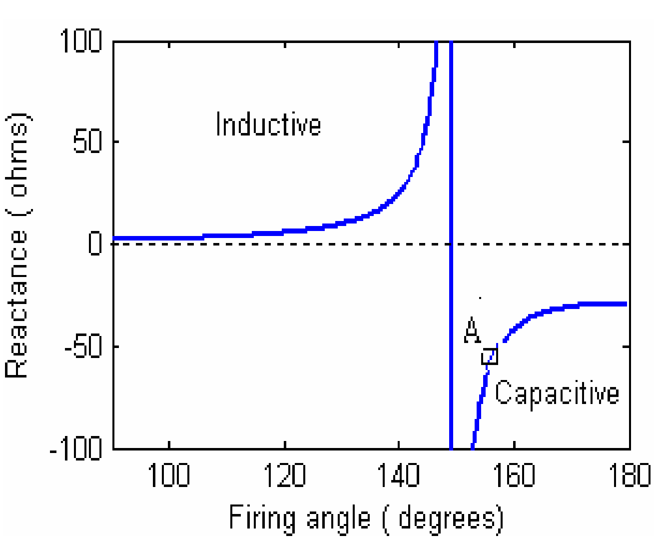



Fig.10. TCSC steady-state impedance characteristic.

for the range $0<\alpha<180^\circ$. Near the resonance, TCSC has very high impedance and this will result in a very large voltage drop. Hence, it is necessary to operate the TCSC such that $X_{TCSC}$ is not more than a limit. The steady state control characteristics of the constant current control is shown in Fig.11.

Assuming $V_{TCSC}$ to be positive in the capacitive region, the characteristics have three segments OA, AB and BC. The control range is AB, OA and BC corresponding to the limits on $X_{TCSC}$ .

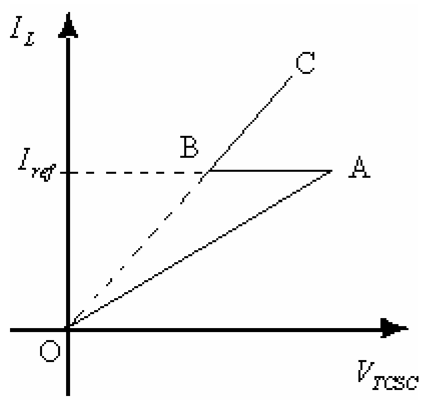
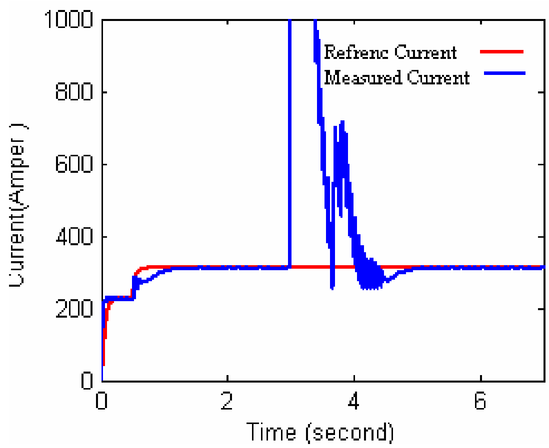



Fig.11. Constant current control

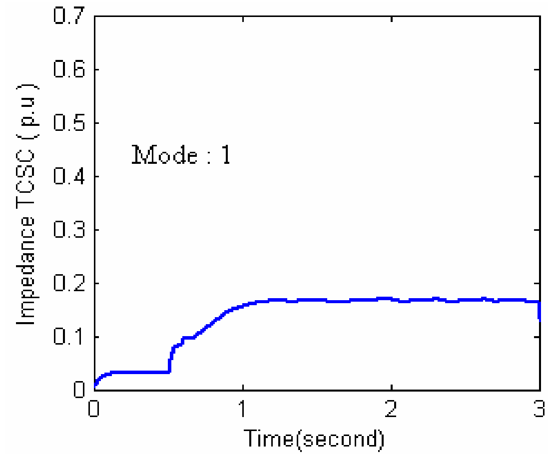
Fig.10 shows the reactance characteristic of the implemented TCSC as a function of the firing angle. Point A is chosen as the operating point since it is the best compromise between a fast control and a safe operating condition, because the steady state operating point should be close enough to the parallel resonance region to permit fast modification of the system impedance for small variation of the firing angle.

The transient simulation of the system is carried out using MATLAB/SIMULINK package. Fig.12 also shows the dynamic behavior of the system when it is tuned to mode 1 and operating with a TCSC is local current control. Here the TCSC in initially blocked on this condition. There is no different between fixed and thyristor controlled series capacitor. The TCSC starts working At t=.5 s. The three phase fault is implemented at point B at the time that the TCSC reaches to steady state operation point (t=3 s). As shown in Fig.12 the TCSC by constant current control has capability to damp SSR phenomenon.The controller has succeeded in damping all the SSR modes at different compensation levels.

Robustness of the controller is clearly shown in Fig.13 where the measured ac current is dynamically stable at all torsional modes.




( a )

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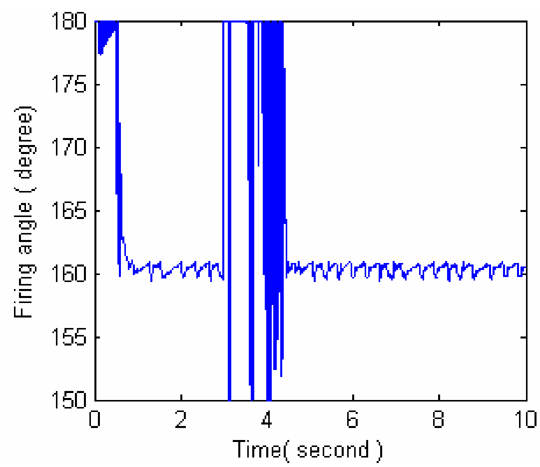


( c )

Fig.12. Mode 1 dynamic performance analysis – TCSC with constant current control: (a) Reference and measured current ; (b) Impedance of TCSC ; (c) Firing angle

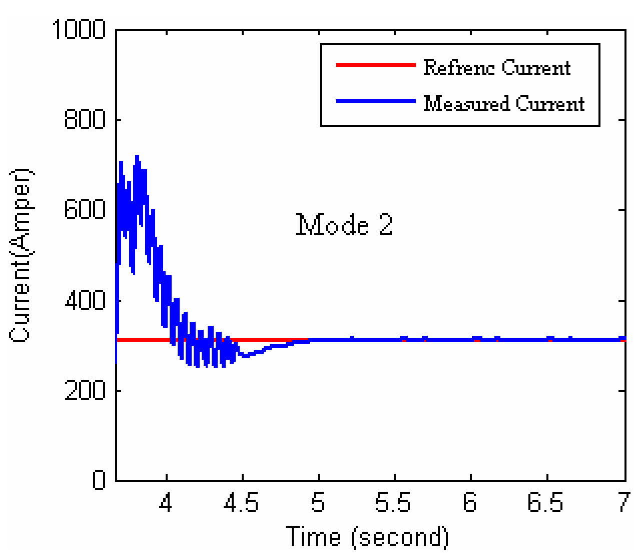


Fig.13. Mode 2 dynamic performance analysis – TCSC with constant current control.

*B. TCSC Constant Firing Angle Control Strategy*

Constant firing angle control is based on the reactance versus firing angle characteristic of the device, like the one presented in Fig.11. This is essentially an open-loop structure that associates an output impedance to each firing angle of the valves [9]-[10].

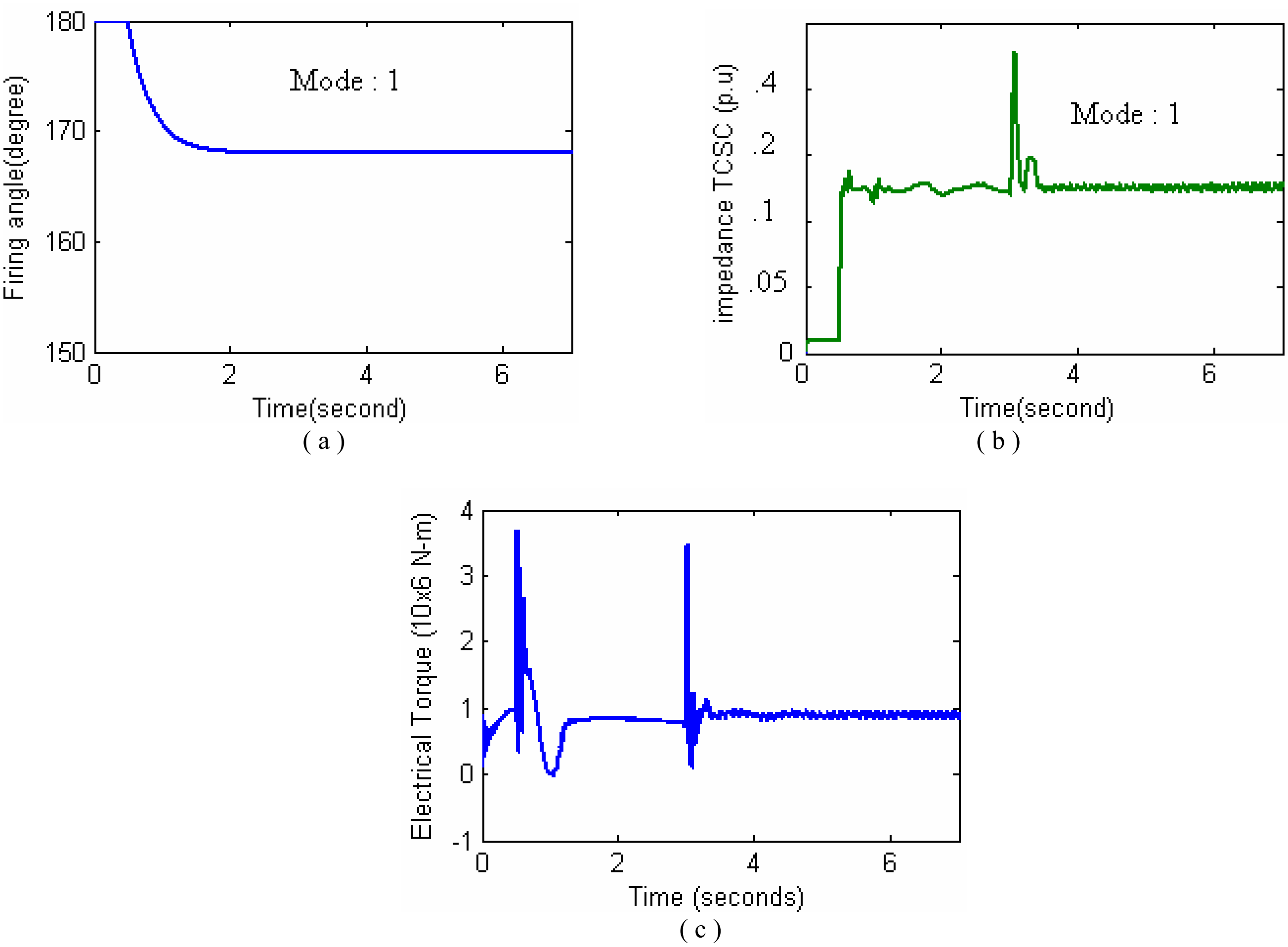


Fig.14. Mode 1 dynamic performance analysis – TCSC with constant firing angle control: (a) Firing angle ; (b) Impedance of TCSC ; (c) Electrical torque

For the steady state operating point it is necessary that the firing angle to be 156.6 degrees. This is associated to an output capacitive reactance of 0.165 p.u.

A three-phase fault is applied at point B to excite torsional modes. The constant firing angle controller successfully ensured stable mode 1 operation mode (Fig .14).

*C. TCSC Constant Impedance Control Strategy*

This technique is the same as constant current control approach, but measured and reference impedances, instead of measured and reference currents, are applied to PI regulator for controlling TCSC. If reference impedance is considered 0.165 p.u, system is tuned on mode 1. It means that after any perturbation the system oscillation on mode 1 is going to damp. The damping rate clearly is shown in Fig.15.

The TCSC impedance controller that is designed to ensure a stable mode 1 operation is further tested for all other modes. The controller has succeeded in mitigating all the SSR modes at different compensation levels. The robustness of the controller is clearly, where the measured impedance is stable at all torsional modes. It means the measured ac current is dynamically stable at all torsional modes. It means the measured ac current is dynamically stable at all torsional modes.

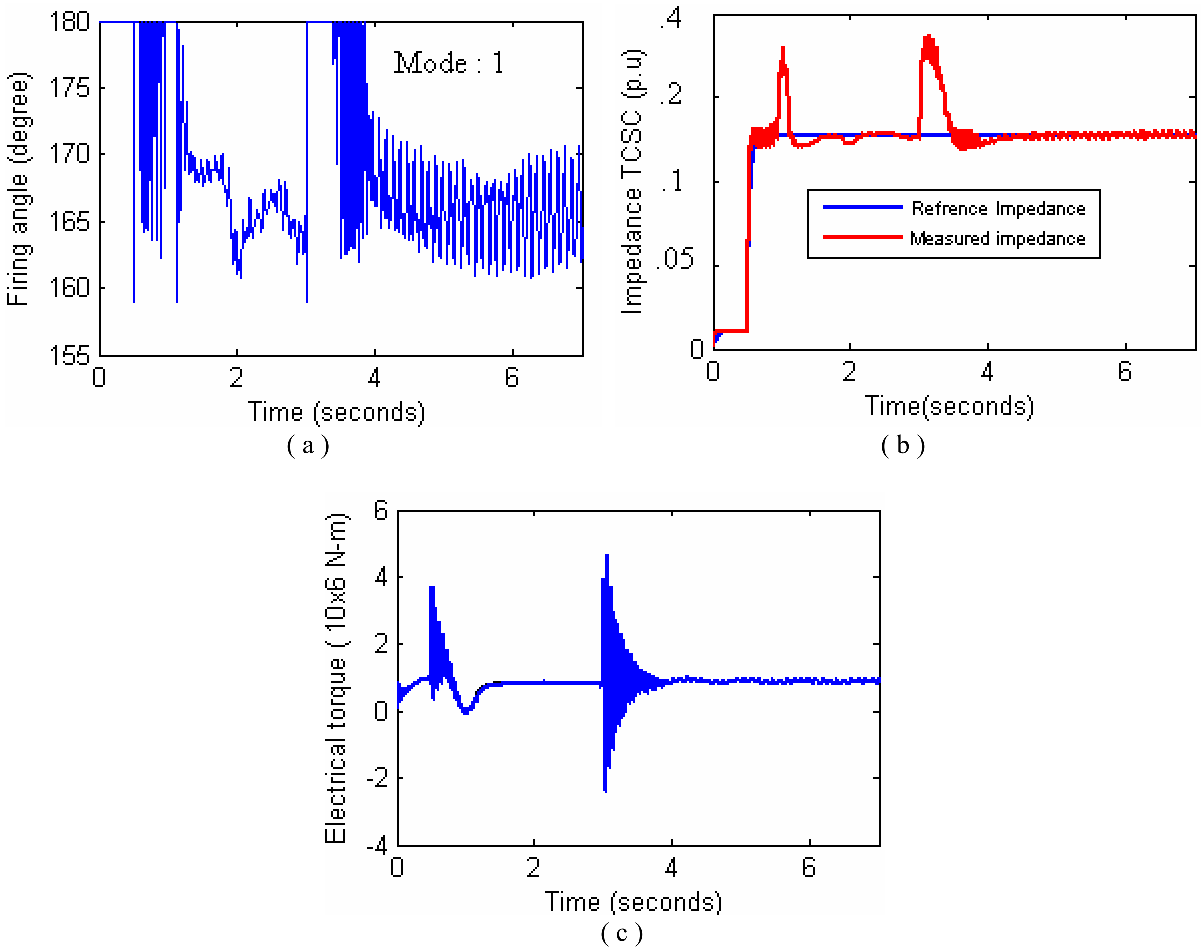


Fig.15. Mode 1 dynamic performance analysis – TCSC with constant impedance control: (a) Firing angle; (b) Impedance of TCSC ; (c) Electrical torque

## VI. Conclusion

In this paper the SSR characteristics of a series compensated transmission line with TCSC have been studied. The IEEE benchmark system for evaluation of the SSR phenomenon was modeled using the MATLAB/SIMULING program. The system instabilities were computed by an eigenvalue M file program in MATLAB software. This analysis indicated that the system has four unstable torsional modes distributed over wide frequency range. Time-domain simulations using MATLAB/SIMULINK program confirms the linear analysis and shows that the system experiences torsional interaction problems when operating with fixed series compensation. The part of fixed capacitance was replaced with thyristor controlled series compensator. The dynamic performance results have shown that the TCSC, operating in local current control, constant firing control and constant impedance control can efficiently solve the phenomenon of subsynchronous oscillations. The offered controller is based on local measurements. In the constant current controller and constant impedance controller, measured and reference currents and impedances have been applied to PI regulator for controlling damping of SSR problem respectively. There is no need to feed back any remote variables, such as the synchronous machine velocities. But the constant firing angle controller is an open-loop controller. It means that any feedback is not used to controller. Any firing angle results to related reactance. The TCSC controllers designed to guarantee a stable torsional mode 1 operation were checked for all possible SSR modes. It was shown that the design controllers are robust and solve the SSR phenomenon for all levels of line compensations.

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## VIII. Biographies

**Ahad Kazemi**, was born in Tehran, Iran, in 1952. He recived his MSc degree in electrical engineering from Oklahama Statasze University, U.S.A in 1979. He is currently an associate professor in electrical engineering department of Iran University of science and technology, Tehran, Iran. His research interests are reactive power control, power system dynamics, stability and control and FACTS devices.

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