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A Review on SSR Analysis of FACTS Compensated Power System Using Various Control Techniques

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***Abstract*—** Series Compensation of transmission networks employed with Flexible AC Transmission System device, for transfer of a bulk power, may have to deal with the phenomenon of Sub Synchronous Resonance. The Sub Synchronous Resonance is responsible for generator-turbine shaft damage due to self-excitation, especially in steam and wind turbine power plants, used in radial power systems. After referring about 92, standard research papers, this review paper is prepared, describing the history of Sub Synchronous Resonance problem and basic model developments. The paper demonstrates Induction Generation Effect and Torsional Interaction, both the types of self excitation problems related to Sub Synchronous Resonance. It also demonstrates how the problem of Sub Synchronous Resonance, is dealt in different types of power plants by using Flexible AC Transmission System devices in conjunction with various control techniques. Also some general methods or nonconventional techniques, for SSR mitigation are discussed. The paper is summarizing numerous, Sub Synchronous Resonance analysis techniques and performance of various Flexible AC Transmission System devices for mitigation of sub synchronous oscillations. The paper concludes with scope of research.

***Keywords*—** Sub Synchronous Resonance (SSR), Flexible AC Transmission System (FACTS), Single Machine Infinite Bus (SMIB), First Benchmark Model (FBM), Second Benchmark Model (SBM), Artificial Neural Network (ANN), Induction Generation Effect (IGE), Torsional Interaction (TI).

I. INTRODUCTION

Series capacitor compensation in AC transmission System is an economical mean to increase load carrying capability, control load sharing among parallel lines and enhance transient stability. But capacitors in series with transmission line may cause sub synchronous resonance, turbine-generator shaft failure, electrical instability and shaft damage from torsional stresses. SSR is a condition where the electric network exchanges significant energy with a turbine-generator at one or more frequencies below the synchronous frequency [8]. Two shaft failures occurred at the Mohave Generating Station in Southern Nevada in 1971 due to SSR [1, 27, and 29].

The interaction between the electrical network and the torsional system of the turbine-generator leads to self-excitation. The torsional oscillation modes generally have frequencies in the range of 10 to 50 Hz. Such torsional interactions were also discovered with Power System Stabilizer (PSS), HVDC controller and SVC voltage controllers. FACTS Controllers are used for regulation of power flows in prescribed transmission routes, secure loading of lines nearer their thermal limits, prevention of cascading outages by contributing to emergency control, damping of oscillations which can threaten security or limit the usable line capacity. While the SSR problem had discouraged system planners from introducing series compensation, the recent development of Thyristor Controlled Series Compensator (TCSC) and Gate Controlled Series Compensator (GCSC), has demonstrated that the SSR problem can be mitigated. New FACTS controllers based on Voltage Source Converters (VSC) such as Static Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC) for voltage and power flow control is expected to minimize the SSR problem.

The developments, in dealing with SSR are much more important to understand, if a researcher wants to contribute for improvement in mitigation of self excitation oscillations. So a comprehensive literature review on SSR is presented here. The literature review is divided in V sections. Section II talks about the problem Identification and basic findings related to SSR problem. In section III, various types of power plants, as a part of distributed system, suffering from SSR are discussed. In section IV the issues related with various FACTS and Solid state devices are described. In section V various control techniques used for damping SSR are demonstrated and in section VI general devices or methods for mitigating SSR, are mentioned.

II. BASIC FINDINGS RELATED TO SSR

The working on SSR phenomenon started in early 1970. The terms and definitions were proposed first and then on basic models the tests were performed to describe effects of various types of SSR problems.

In 1970 [1], authors have mentioned issues arising due to series compensation by realizing that it changes X/R ratio of the primary circuit and creates the tendency to hunt. They suggested typical values of rotor resistance R_r to damp the oscillations for machines with connected damper windings as: 0.01p.u. for copper dampers, 0.03 p.u. for brass and of 0.07p.u. for higher resistance dampers. In [2], various steam and hydro turbine models were suggested and eigen value sensitivity for a 4 generator hydro and 2 generator thermal system were checked for the parameters such as inertial time constants, washout filter gains and exciter gains. Considering eigen value analysis is more economical and practical for higher order system studies [3]. In 1977, the IEEE SSR Task force derived the First Bench Mark model (FBM) as shown in Figure 1; here real values were taken from the Navajo Project. The rotor spring mass model was prepared as shown in Figure 2 [4].

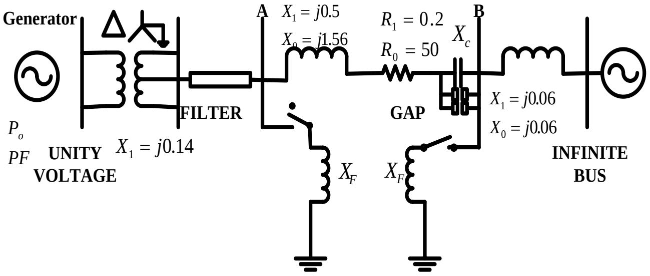


Figure 1. *Single line Diagram of IEEE FBM [4]*

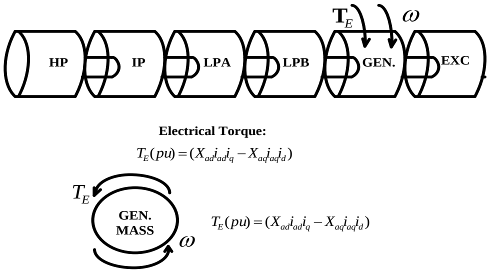


Figure 2. *Spring mass model [4]*

In 1982, authors suggested the modulated reactance by using dynamic stabilizer i.e. shunt reactor connected at generator terminals could dampen SSR, caused due to torsional interaction [5]. In [6], Canay gave a novel approach of damping torque analysis and showed that all questions concerning the torsional interaction phenomenon can be answered by comparing electrical and mechanical spring constants $K_e(j\omega)$ and $K_m(j\omega)$.

In 1985, the effects of namely high voltage direct current (HVDC), Superconducting Magnetic Energy Storage units (SMES), battery storage (a type of HDVC), and the Modulated Inductance Stabilizer (MIS) on series compensation were studied [7]. In 1985 only, IEEE SSR Working Group introduced terms, definitions and symbols for SSR oscillations [8]. Here it was shown that for an n mass system, n-1 modes were present and mode shapes displayed graphically were eigenvectors of rotational displacement or rotational velocity of the rotor inertial elements when the system was represented mathematically. In the same paper, the common base for combined electrical and mechanical system was derived. In [9], the IEEE Working Group found that the simple type of system employed in the FBM, with its single series resonance would rarely be encountered in actual operation of a power system. Therefore, a more common type of system was presented called Second Benchmark Model (SBM) which dealt with the "parallel resonance" and interaction between turbine-generators with a common mode. Two systems were tested; one as a single generator connected to two lines, one of which is series compensated and the other with two different generators, having a common torsional mode connected to a single series compensated transmission line. First the generator data and mechanical system data were prepared for the model. Then the eigen value and frequency analysis was carried out for self-excitation and torque amplification. The damping and torque results were quite demonstrating, the parallel resonance during SSR.

In 1989, a report of a panel discussion was presented by various companies for various test System at winter and summer power meetings [10]. General Electric Company, U.S.A. used, Finite Element Method for deriving the generator data and torsional mechanical data by considering no load mechanical damping. B. L. Agarwal and R.G. Farmer Co., U.S.A. prepaed, Palo Verde SSR test set up. They showed, the comparison of effective damping results using algorithm, EMTP simulation and eigen value methods. The mode shapes were determined by varying the spring constants and the ratio of generator velocities. Cesar Cruz, U.S.A. measured rotor oscillations for a Coronado generating station by injecting sinusoidal signal into exciter. Jerry Sims tested the Springville unit consisting of a Dynamic Stabilizer for primary protection and a subsynchronous oscillation (SSO) relay as backup protection. The results showed that the series compensation levels for marginal stability found by calculation and testing, be the same while for the more unstable levels of series compensation, there was considerable difference in the measured and calculated damping. In [11], IEEE committee report explained the basics involved with SSR as a reader's guide. Apart from IGE, TI and Torque Amplification, it talks about device dependent SSO. For small disturbances eigen value methods were used and for torque amplification problems, discrete time models were preferred. They found TI and IGE were slow i.e. they last for many seconds while torque amplification is of the order of 1 sec. In 1992, authors developed a computer program at the Bonneville Power Administration (BPA) and the Munich Institute of Technology, Germany. The analysis of transients in power system was carried by back substitution. The total current was calculated with any switched element by considering the non linear components that were present as per the flow chart in [13]. The built up matrix [Y] required, smaller computer storage.

III. SSR IN POWER PLANTS

This section demonstrates SSR observed in various types of power plants. The steam turbines are commonly found to be a part of power system. The Hydro units have mechanical parameters less prone to SSR than thermal units. In the era of distributed generation with existing steam turbine plants, distributed power is obtained through various types of wind turbines. Most wind turbines in Europe and North America use doubly fed induction generators (DFIGs) or full converter-based wind turbine generators [18] - [23].

A. Steam Turbine

Although Sub synchronous oscillations were first discussed in 1937, shaft torsional oscillations were neglected till 1971. Two shaft failures at the Mohave Generating Station in Southern Nevada, led to the understanding and development of the theory of interaction between series capacitor compensated lines and the torsional modes of steam turbine-generators. To model steam power plants, First Benchmark and Second Benchmark Model were used. In [14], a new NGH scheme was described for suppression of steady-state sub synchronous resonance of the series compensated transmission lines. The proposed scheme was also suitable for series capacitor protection and suppression of DC bias in the capacitors during transients. In [15], the proposed invention was designed to solve major SSR problems, transient torque and steady state electrical mechanical interaction. In [16], to model the steam turbine, nonlinearities in rotor parameters such as the terminal voltage, current or a combination of these quantities including various disturbances was considered. A variable blade section was investigated with a combined Finite Element Method (FEM), Artificial Neural Network (ANN) and Monte Carlo Simulation (MCS) for vibration reliability and fatigue analysis [17].

B. Doubly-fed induction generators (DFIG)

Among all the wind turbine technologies, doubly-fed induction generators (DFIGs) with variable speed operation are widely being used today for many reasons such as mechanical stress reduction, acoustic noise mitigation and the flexibility of active and reactive power control based on back-to-back converters between the grid and the induction machine rotor circuit [18]-[23].

The dynamics of the capacitor in the dc link between Grid Side Converter (GSC) and Rotor Side Converter (RSC) is modeled as a first-order differential equation. The GSC has a similar structure as SATACOM, which consists of a voltage source converter and a capacitor on the DC-link side which is shuntly connected to the terminal voltage through a coupling transformer represented by a leakage inductance. In [18], the control was realized through modulating the voltage command in the control loops of the GSC as shown in Figure 3. The impact of wind speed and compensation level was analyzed and it was found that resistance becomes more positive when wind speed increases. Also for compensation levels from 10% to 90%, the network model becomes unstable. In [19] authors clearly demonstrated that IGE instead of TI was the major reason for SSR in System, where impact of the inner current converter controller parameters and turbine parameters on SSR were addressed. The effect of the proportional gains in these control loops of P_e, T_e and ω_r showed that increasing gains have a detrimental impact on the damping. It was found unusual for the network resonant frequency to exceed 50 Hz, even at very high levels of compensation. In [20], Impedance models of RLC circuit, converters and a DFIG for a type 3 wind farm along with its RSC and GSC, were derived in terms of space vectors, as shown in Figure 4. Based on impedance model and Nyquist stability criterion it was stated that low wind speed was more problematic than high wind speed and RSC current control was detrimental to SSR stability.

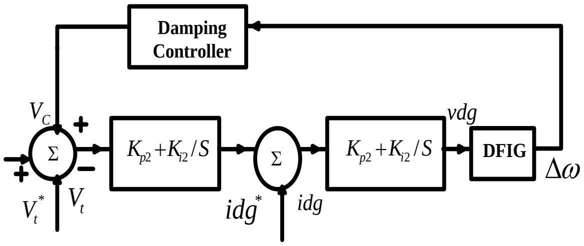


Figure 3. *Control loop for GSC [18]*

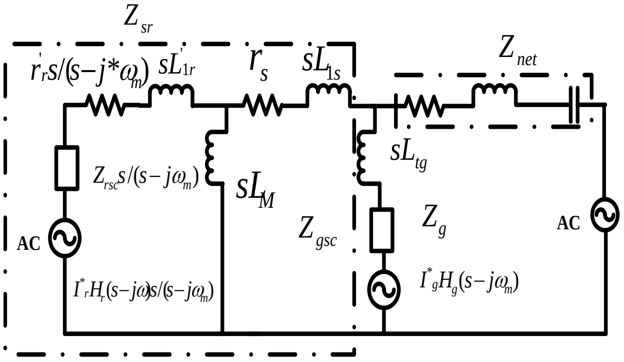
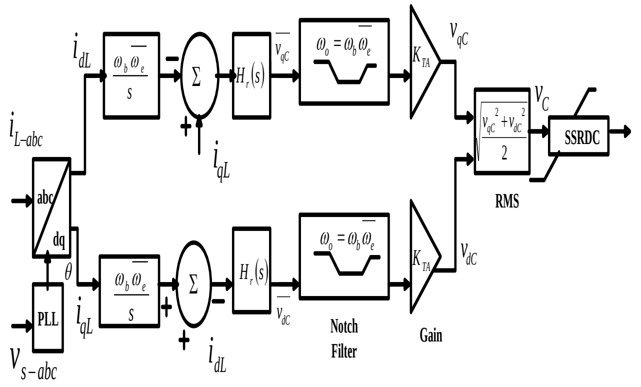


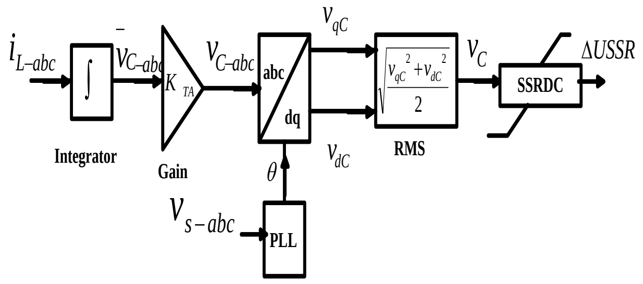
Figure 4. *DFIG Model [20]*

In [21], a change in sign of the phase and a dip in the impedance magnitude were considered as a sign of series network resonance seen by the wind farm under study. Also resistance and participation factors were analyzed. The states related to the series capacitor and the series compensated line participates heavily in the network mode. For a multi machine wind farm operated at unity power factor, by creating a 3 phase short circuit at 2 s and clearing after 100 ms, IGE was demonstrated where it was shown that the rotor voltage controllers can significantly influence the damping of network mode. In [22], a simple proportional SSR damping controller (SSRDC) was designed by properly choosing an optimum Input Control Signal (ICS) including rotor speed, line real power, and voltage across the series capacitor. Also optimum ICS was identified using residue-based analysis and root-locus method. The optimal ICS out of the three ICS ω_r, P_L and V_C, was the capacitor voltage V_C and the optimal controller insertion points were found lying on GSC. As V_c was not directly measurable so it was derived from line current as in (1) or by Method A or by Method B from block diagrams as shown in Fig 5.

$$\begin{bmatrix} \dfrac{v_q C}{v_d C} \end{bmatrix} = K_{TA} H(s) \begin{bmatrix} 1 & -\dfrac{\omega_b \omega_c}{s} \\ \dfrac{\omega_b \omega_c}{s} & 1 \end{bmatrix} \tag{1}$$



(a) Method A



(b) Method B

Figure 5. *Methods to derive Line Current [22]*

Hossein Ali et al., in [23], designed an SSR damping controller (SSRDC), for a 100-MW aggregated model of 50 wind turbine units each having a power rating of 2 MW DFIG-based offshore wind farm, connected to the infinite bus via a 161-kV series-compensated transmission line with GCSC. The eigen values were found from which the participation factor was obtained and various oscillation modes were identified. The three signals I_L, ω_r and V_{cg} were tested as ICS. It was found, V_{cg} as ICS, has better sub synchronous and super synchronous resonance damping.

C. Double-Cage Induction Generator (DCIG)

For IG-based wind farms, the double-cage IG is preferred above 5kW, due to its mechanical simplicity, high efficiency and low maintenance requirements [24-25]. The output of each generator depends upon the wind speed and the pitch angle. A high value of first rotor cage resistance may lead to negative damping [24]. The eigenvalues were influenced by the size (rating), power output of the wind farm, and the level of series compensation. The SSRDC was added to Power Scheduling Controller (PSC) of GCSC to damp SSR in Fixed Speed Wind Turbine Generators (FSWTGS). The performance of SSRDC of GCSC was compared with TCSC and Time Frequency Analysis (TFA) from Cohen's class expression in (2). SSR being non stationary signal, time frequency distribution TFD was obtained from Cohen's class equation. Also Instantaneous Distortion Energy (IDE) and maximum energy E_{max} were derived as per (6). A higher E_{max} indicated longer existence of the SSR frequencies in the line current disturbance.

$$TFD_{x(t,\omega;\phi)} = \frac{1}{4\Pi^2} \iiint x^*\left(u - \frac{\tau}{2}\right) x\left(u + \frac{\tau}{2}\right)$$
$$X\phi(\theta,\tau) e^{-j\theta t - j\tau\omega + j\theta u} \, d\theta \, d\tau \, du \tag{2}$$

The kernel reduced interference distribution was used to analyze and quantify the time-varying frequency; the equations (2) - (6) were used.

$$\int TFD_x(t,\omega;\phi) dw = |x(t)|^2 ; if \phi(\theta, \tau = 0) = 1 \tag{3}$$

$$\int TFD_x(t,\omega;\phi) dw = |x(\omega)|^2 ; if \phi(\theta, \tau = 0) = 1 \tag{4}$$

$$IDE(t) = \sqrt{\frac{\int TFD_D(t,\omega;\phi) dw}{\int TFD_F(t,\omega;\phi) dw}} * 100 \tag{5}$$

$$E_{\max} = \max\left\{\int TFD_s(t,\omega;\phi) dt\right\} = \max\left\{|x(\omega)|^2\right\} \tag{6}$$

In [25], For a 2.3 MW DCIG, eigenvalues and sensitivities with respect to stator resistance R_s, stator leakage reactance $X_{s\sigma}$ and first rotor cage resistance R_{r1} were determined, for a wide range of series compensation levels for various sizes from 100 MW to 500 MW wind farms. The study of IGE and impact of three-phase fault on electromagnetic torque during rated power output conditions were discussed. If the clusters were connected through collector cables, it was found, as the cable length decreases, the impact of the series compensation on the wind turbine becomes larger. The eigen value frequencies were matching with the frequencies found by FFT.

IV. SSR IN FACTS DEVICES

There are various types of FACTS devices classified according to their connection such as series connected controller, shunt connected controller and combination of shunt series connected controllers. The biggest advantage of FACTS Controllers is their speed compared to mechanical controllers. The main types of FACTS devices used for SSR damping are described below:

A. Voltage Source Converter (VSC)

Voltage Source Converters are used for interfacing the HVDC transmission systems or wind farms. A VSC-based system may interact with an electrically nearby synchronous machine, through its incremental output impedance. VSC may reduce the damping because in low frequency range, VSC impedance has capacitive properties and at high frequency range it has inductive properties. In [30], a current-controlled VSC was installed with IEEE SBM, using the grid voltage in a second feed-forward controller, creating active output impedance in parallel to the original one so that the resultant total impedance became positive. The modified transfer functions yielded a zero-dc-gain and facilitated the shaping of the output impedance around a center frequency.

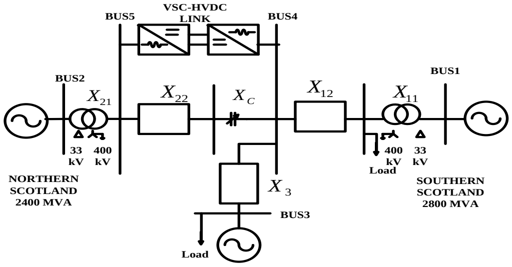


Figure 6. *Mainland Great Britain System [31]*

In [31], a three-machine model, resembling the operating conditions of the mainland GB system, having onshore fixed capacitor and offshore VSC-HVDC link as shown in Figure 6, was implemented on Real Time Digital Simulator (RTDS). A damping controller involving Band Pass Filter (BPF), Phase Lock Loop (PLL), gain block and lag-lead compensator, was used to inject an anti-phase signal into the AC system at a target subsynchronous frequency.

In [32], a technique was suggested using the grid voltage in a second feed forward controller as shown in Figure7, with an additional modification using the cascaded transfer functions, which magnified the overall positive admittance given by (10), a positive damping at the assigned torsional mode was ensured. For the adopted control topology, dc-link voltage control at unity power factor, the off-diagonal elements were zeros; and the diagonal elements *Y*11(*s*) and *Y*22(*s*) were given by (7). During grid-voltage transients, the compensator dynamics yielded a transient component that was added to the reference current to shape the VSC output admittance; the transient component was directly reflected to the current response. The VSC-HVDC link was compared with the proposed SSRD which was found more effective. Also the results were verified using the hardware. In [92], The ground fault was sensed by using VSC with extra voltage balancing half-bridge and front end converter, which was isolated on occurrence of fault.

B. Static synchronous compensator (STATCOM)

Series passive compensation and shunt active compensation provided by static synchronous compensator (STATCOM) are connected at the electrical center of the transmission line to support systems that have a poor power factor and often-poor voltage regulation [33-37]. In 2006, authors designed a Subsynchronous Damping Controller (SSDC) using the Thevenin voltage signal to modulate the reactive current reference of STATCOM having 12 pulse, two- and three-level voltage source converter with Type-2 and Type-1control [33]. Here for damping of power swings, the SSDC (represented by a transfer function) taking the Thevenin voltage signal V_{th}=V_s+ $X_{th}I_s$, derived from the locally available STATCOM bus voltage (Vs) and the reactive current (Is), was used. It modulated the reactive current reference to improve the damping of the unstable torsional mode. For the design of SSDC transfer function $T_2(s)$ based on parameter optimization, was assumed as in (8) and the objective function was as in (9).

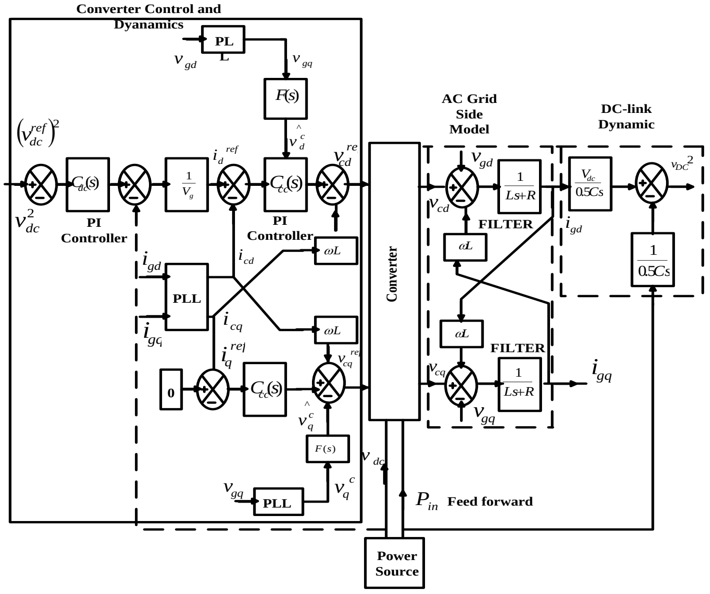


Figure 7. *Dynamic and Control Model of the VSC [32]*

$$Y_{VSC}=\frac{\Delta iv_{vsc(s)}}{\Delta v_{gvsc(s)}}=\begin{bmatrix}Y_{11}(s) & Y_{12}(s)\\ Y_{21}(s) & Y_{22}(s)\end{bmatrix} \tag{7}$$

$$Y_{11}(s)=$$

$$C_{cc}(s)RL(s)\left(\begin{array}{l}\left\langle\dfrac{-P^0}{[1+C_{cc}(s)RL(s)]V_g{}^{02}}\right\rangle+\\ \dfrac{C_{dc}(s)}{sC[1+C_{cc}(s)RL(s)]+C_{cc}(s)C_{dc}(s)RL(s)}*\\ \left(\dfrac{P^0}{v_g{}^2}+\dfrac{FF(s)-1}{[C_{cc}(s)RL(s)]}-\dfrac{P^0C_{cc}(s)RL(s)}{v_g{}^{o2}[1+C_{cc}(s)RL(s)]}\right)\end{array}\right)$$

$$-\frac{FF(s)-1}{[C_{cc}(s)+RL(s)]}$$

$$T_2(s) = \frac{as + b}{s^2 + cs + d} \tag{8}$$

$$Minimize f(r) = \sum_{\omega_{\min}}^{\omega_{\max}} (T_{de(des)}(\omega) - T_{de}(\omega))^2$$

$$subjected \begin{cases} c > 0, c^2 - 4d < 0 \\ \omega_{\min} \le \omega \le \omega_{\max} \end{cases} \tag{9}$$

The constraints ensure that the poles of the transfer function are complex and have negative real parts.

For transient simulation, a step decrease of 10% mechanical input torque was applied at 0.5 sec and removed at 1 second. Though STATCOM voltage control marginally reduced the peak negative damping but the SSCI was effective in damping SSR in the entire range of compensation level proving its robustness [34]. In [35], a Self Excited Induction Generator (SEIG) based wind park rated at l00 MW, was connected to the electric grid through a fixed series compensated transmission system comprising the SSSC and STATCOM for SSR damping controller. In SSSC the damping power control loop signal as shown in Figure 9 was included in phase with the rotor speed deviation $\Delta\omega_r$ and added to (10) and (11).

$$P_{e1} = \frac{V_s V_r}{X_T - X_s} \sin\delta_s \tag{10}$$

$$P_{e2} = \frac{V_s V_r}{X_T} \sin\delta_s + \frac{V_s V_q}{X_T} \cos\left(\frac{\delta_s}{2}\right) \tag{11}$$

Also different control algorithms were synthesized depending on the desired type of friction i.e. coulomb or linear or combination of two. The STATCOM was controlling the bus terminal voltage V_t, by control law $\Delta V_t = K_d * \Delta\omega_r$ and linearized transmitted power as expressed by (12.1) and (12.2).

$$\Delta P_{e2} = \left(\frac{1}{2} - \frac{V_s V_t}{X_T/2}\cos\frac{\delta_s}{2}\right)\Delta\delta_s + \left(\frac{V_s K_d}{X_T/2}\sin\left(\frac{\delta_s}{2}\right)\right)\Delta\omega_r \tag{12.1}$$

$$\Delta P_{e2} = K_{sT1} * \Delta\delta_s + K_{ds} * \Delta\omega_r \tag{12.2}$$

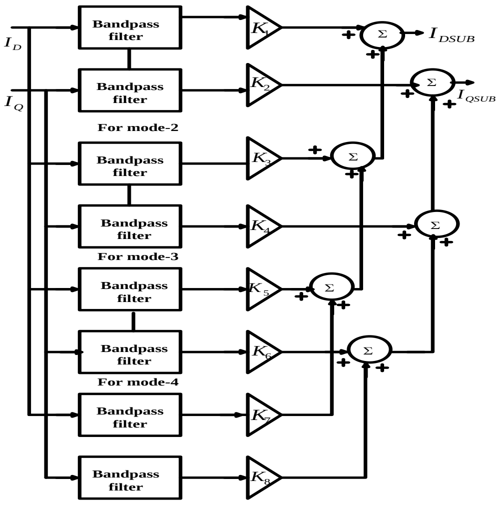


Figure 8 (a*) Block Dia. Of SSCI [37]*

In 2009, authors designed a Subsynchronous Current Injector (SSCI) with STATCOM with narrow bandwidth of 2-5 Hz band pass filters as in Figure 8 (a) whose gains were adjusted by application of damping torque analysis [37]. The sub synchronous frequency signals I_{Dsub} and I_{Qsub} were converted to in-phase and quadrature components I_{Psub} and I_{Qsub}, used to inject the anti phase subsynchronous currents by the STATCOM as in Figure 8 (b).

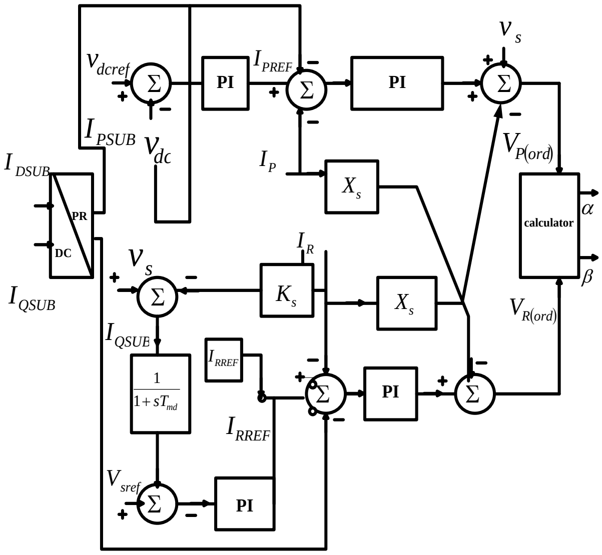


Figure 8. *(b) Type-I Controller for STATCOM [37]*

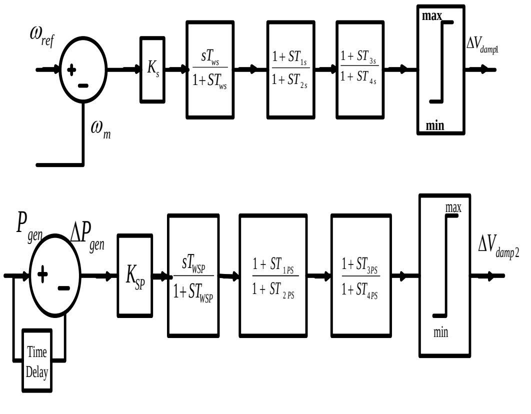


Figure 9. *Damping control loops of ω_r and ΔP_{gen} [35]*

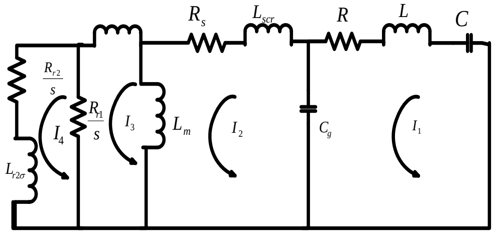


Figure 10. *Equivalent circuit of wind farm [36]*

In 2014, authors tested a STATCOM based controller applied to the modified IEEE FBM where the synchronous generator was replaced with a 500-MW wind farm employing 217 numbers of identical 2.3-MW double-cage IGs [36]. The STATCOM controller receiving the Point of Common Coupling (PCC) voltage and STATCOM reactive current signal were used to produce the modulation index and phase angle difference signals. For the equivalent circuit of a wind farm connected to a series compensated transmission line as in Figure10, the characteristic equation was as in (13).

$$\left|Z\right| = a_6 p^6 + a_5 p^5 + a_4 p^4 + a_3 p^3 + a_2 p^2 + a_1 p + a_0 \tag{13}$$

Out of the six roots, one complex conjugate pair was found to be sensitive to the slip of the machine. As the slip was increasing, the roots moved to the right, crossed the imaginary axis. The points where the roots crossed the imaginary axis were termed resonant points.

For a Short Circuit Ratio=2, both SSSC and STATCOM controllers were tested in response to a mechanical torque reduction of 0.5 p.u. for a period of 1 sec. and subjected to a 3φ fault at the terminal of the wind park at instant t = 20 sec., for a duration of 150 ms. Here it was found that STATCOM had less negative damping and lesser stability margin compared to SSSC.

C. Static Synchronous Series Capacitor(SSSC)

SSSC is a new generation series FACTS controller based on VSC [38-41]. In [38], authors tested for SSR mitigation with a combination of SSSC and dielectric capacitors in HYPERSIM software, where along with generators, exciters and PSS, thermal turbines and governors were modeled. The equivalent voltage in Figure11 is representing, 3-phase AC voltage produced by a 3-level VSC, which was inserted in series with the transmission line through a transformer. The eigen value analysis and time domain simulation showed that, the size of SSSC, equal to 1/3rd of total compensation could damp the torsional oscillations. In [39], authors provided active series compensation by 3-Level,12 pulse VSC based SSSC where in MATLAB SIMULINK, damping torque analysis was carried out on classical 2.2 model of synchronous generator and it was observed that the SSSC with constant reactive voltage injection mode was SSR neutral. By controlling the ON and OFF switching instants of the GTOs, the widths of the pulses were varied and consequently the magnitude was controlled. Phase angle control was obtained by shifting the voltage pulses of chosen width forward or backward in time. Later in 2009, authors, suggested a SSCS (Sub synchronous Current Suppressor), designed based on damping torque analysis, where the subsynchronous frequency component of line current extracted by frequency of 2-5 Hz, was used to modulate the SSSC injected voltage which damped sub synchronous current in the network [40].

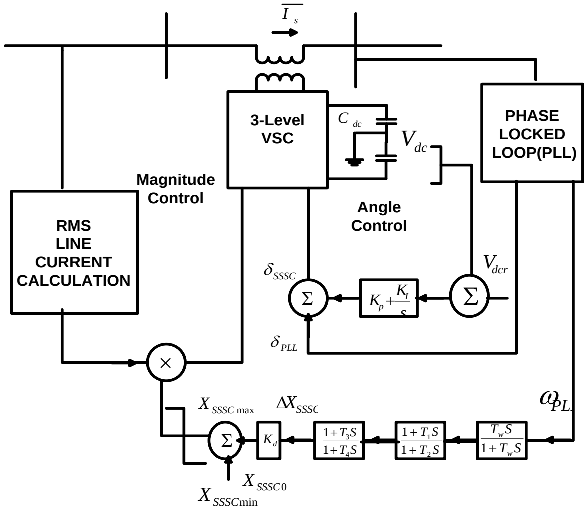


Figure 11. *Control of SSSC* [38]

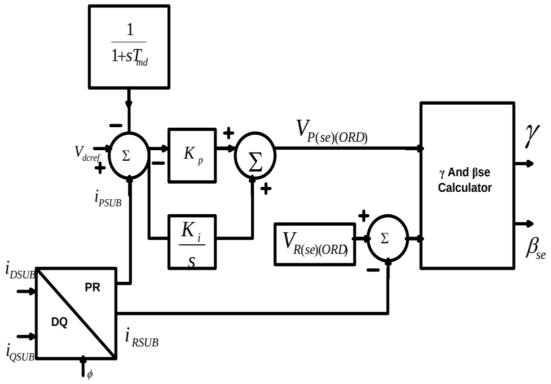


Figure 12. *Type-I Controller for SSSC* [40]

As shown in Figure 12, the Sub synchronous frequency line current i_{Dsub} and i_{Qsub} were transformed to in-phase and quadrature components i_{Psub} used to modulate, the in phase and quadrature voltages $V_{Pse\ (ORD)}$ and $V_{Rse\ (ORD)}$ of SSSC. The SSCS parameters were tuned based on damping torque to get optimum performance for improving the damping of all torsional frequencies and facilitating the compensation upto 90%. Later in [41], by using SSSC bus voltages and currents based on phase imbalance, unbalanced series voltages were injected in quadrature with the line currents. The degree of phase imbalance was defined by the factor ratio of the injected voltage to the pre-fault steady-state voltage across the series capacitor. In capacitive mode of SSSC, the Line Voltage Unbalance Rate (LVUR) defined by the given (14) was calculated for single phase.

$$\begin{aligned} LVUR\% &= \frac{MaximumDeviationfromAverage}{Averageofthreelineto\ linevoltages} * 100 \\ &= \frac{Max[(v_{ab}-v_{av}),(v_{bc}-v_{av}),(v_{ca}-v_{av})]}{v_{av}} * 100 \\ wherev_{av} &= \frac{v_{ab}+v_{bc}+v_{ca}}{3} \end{aligned} \tag{14}$$

In [91], The paper presents a novel full 48-pulse GTO voltage source converter of STATCOM a FACTS device using the decoupled current control based on a pulse width modulation switching technique ensured fast controllability, minimum oscillatory behavior and minimum inherent phase locked loop time delay as well as system instability reduced, impact due to a weak interconnected ac system.

D. *Unified Power Flow Controller(UPFC)*

It is a combination of static synchronous compensator (STATCOM) and a static series compensator (SSSC) coupled via a common dc link allowing, bidirectional flow of real power between the series output terminals of the SSSC and the shunt output terminals of the STATCOM. It is the most versatile of FACTS controllers which yields simultaneous control of all basic power system parameters including voltage amplitude and angle, line impedance and power flows [42-45]. It controls its bus voltage by generating or absorbing reactive power through the shunt inverter as well as controlling the power flow on the transmission line by adjusting the magnitude and phase shift of the series inverter injected voltage as shown in Figure13. It can take care of IGE as well TI in local and inter area oscillations.

In 1998, K.R. Padiyar showed [42], UPFC allows three degree of freedom by controlling: 1. Magnitude and angle of series voltage. 2. Shunt reactive current.

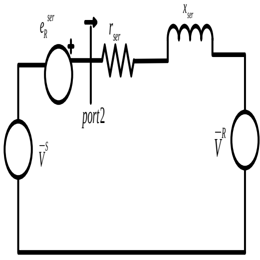


Figure13. *Series Injected Voltage [42]*

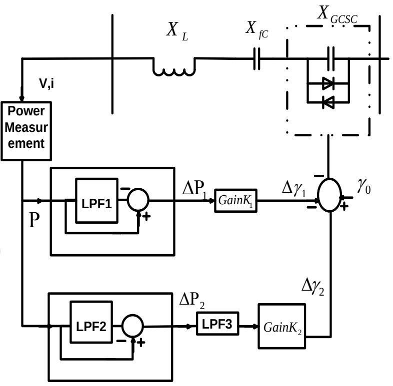


Figure14. *SSDC for GCSC[65]*

From bode plot of transfer function $\Delta P^{u2}(s)/\Delta u(s)$ showed larger gains to be used in the output feedback controller for consequent speeding up of the response. In voltage control real voltage e_P^{ser} was calculated shown in Figure 24(a) Shunt current controller was as in Figure 24(b). In [43], UPFC was connected to the compensated line and wide-area data was used for inter-area oscillation damping. The oscillation signals were obtained via Phasor Measurement Unit (PMU) installations such that for increased compensation, the torques and speed showed stable response.

E. *Static VAR Compensator (SVC)*

A static VAR compensator is an electrical device for providing fast-acting reactive power on high-voltage electricity transmission network [12, 46, 47]. In 1996, a laboratory model of a three phase, three level SVC has been successfully implemented and tested. The experimental study carried out on the system has demonstrated the ability of the SVC to both absorb and generate reactive power [12]. The voltage source and current source type VAR generators were used for improved response time and lesser harmonic distortion. The naturally commuted thyristor circuits generate lagging VARs and forced commutated circuits generate lagging and leading VARs. An SVC for a DFIG based wind farm had the controller gain adaptive to wind generation level as the risk of SSR at higher generation was lower in wind farms. Here SVC was operated in voltage control mode using Thyristor Controlled Reactor (TCR) and in damping control mode using High Pass Filter (HPF) where loop gain adoption was checked by frequency response [47]. Authors derived that the use of combination of deviation in speed and electrical power output of the generator as input signals to PSS operated along with SVC improved even the large disturbance stability [48]. As in [49], frequency changer designed with the power doubling scheme needed, SVC of 0.5pu VA rating to supply 1pu reactive VA of AC system. The model of SVC, would control SSR by the use of thyristor controlled VAR compensator. The optimum value of speed sensitivity factor of 0.125 at high compensation level, could eliminate SSR due to IGE and TI both [50].

F. *Thyristor Controlled Switched Capacitor(TCSC)*

In TCSC, the power circuit comprises a capacitor bank in parallel with a thyristor controlled reactor and a Metal Oxide Varistor (MOV) arrester to protect the capacitor. The thyristor valve includes a snubber circuit. By selecting proper conduction angle SSR can be eliminated. The TCSC prototype istalled at Buckley- Slatt 500kV plant was tested by modulating its reactance, for damping power swings, transient stability, power flow control and SSR control [51]. The discrete time model of a TCSC was obtained by Poincare map and the eigenvalues of the Jacobian could give the idea about modal damping of the system [52]. In 1996, Tests performed at Slatt 500kV substation verified that vernier firing angle control of TCSC, reduces negative damping effect of SSR condition [53]. Improvement in design of TCSC was brought by use of TCSC-Thyristor Controlled Capacitor, by replacing the SCRs with GTOs; this helped operating TCSC at higher loads [54]. To reduce SSR, a method of constant angle ignition control was suggested by authors where though ignition angle was maintained constant thyristor current was varying with period of SSR. But with a proper choice of conduction angle, SSR was damped [55]. In 1999, the Power Oscillation Damper (POD) installed in Brazil using PLL served the purpose of detuning SSR as well limiting fault current [56]. In 2010, authors suggested a method to calculate the equivalent fundamental frequency resistance of TCSC where it was found that inductive behaviour of TCSC impedance neutralized SSR and resistive part converted subsynchronous energy that could weaken the SSR [57]. To choose proper conduction angle the TI mode reactance was compared with frequency equivalent reactance. Also a dynamic model of TCSC by Point Care mapping was prepared to verify resistive characteristics of TCSC [58]. The scheme applied to Mohave station suggested by N.G. Hingorani was tested wherein a resistor connected to a back to back connection of thyristors was used to waste extra voltage of SSR by firing of thyristors [59]. In a hybrid system having TCSC and fixed capacitor, having $X_{effective}= X_{TCSC\ /}\ X_C$ as a function of firing were confined to avoid parallel resonance. Also with wide bandwidth phase compensation, positive damping to all torsional modes was observed [60].

G. Gate Controlled Series Capacitor(GCSC)

It consists of a capacitor and two reverse blocking semiconductor switches (e.g., Gate Turn Off, Integrated Gate Commutated Transistor) connected in anti-parallel [61, 62, and 63]. Controlling the turn-off angle the voltage on the capacitor was controlled, consequently controlling the series compensation level of the transmission line. GCSC used at South-Southeast Brazilian Network increased power flow from 43% to 80% through line 2 by increasing its compensation [61]. As shown in Figure14, the SSDC consisting of a filter and a gain block proposed by authors, the power variation ΔP was obtained by subtracting the "average power" from the actual transmitted power. The choice of the gain k was done by trial and error method. When, the gain k =0, the GCSC operate without SSR damping control (fixed turn-off angle control). The output signal of this controller $\Delta\Upsilon$ was proportional to the power oscillation in the system. The sum of $\Delta\Upsilon$ with a fixed (steady state) turn-off angle (Υ_o) was the resulting turn-off angle (Υ) of the GCSC. With the SSR damping controller having cut-off frequency fc= 3 Hz and k= 5 [°/MW], the oscillation damped in less than 5s [63]. Two multi module MMGCSCs (multiple GCSCs connected in parallel) inserted between buses 26-29 and buses 21-22 in an IEEE 39 bus system were tested for 3-φ fault and line outages. The GCSC turn off angle was estimated by a nonlinear modified PI controller (NMPI) that could force the MMGCSCs to operate near their extreme limits to damp SSR and rotor angle oscillations [64]. Authors verified the effect of size of GCSC on damping SSR. By simulating a modified SSDC having 3 combinations of GCSC reactance and fixed capacitor reactance equal to 1:2, 1:1 and 2:1, they verified the controller as in Figure15 where by adding and removing resistor on bus B in IEEE FBM, the turn-off angle modulated X_c such that the power flow could decrease when it was increased [65]. In 2010[66], GCSC was used for reducing stress due to SSR on IEEE FBM 2.1 model and developed a state coefficient matrix [65]. In [12,67] Recently it is shown residue based analysis can be used to select Input Control Signal (ICS) for SSRDC. The Root Locus could be used to find the gain required for damping SSR. For the, IEEE FBM of DFIG based offshore wind farm, when voltage across GCSC V_{cg} was selected as ICS, the larger were the residues i.e. lesser was the gain required. From the results of Root Locus method, it was found that ICS had more compensation limit and assurance of SSR damping without sacrificing stability of super synchronous resonance mode's stability.

V. CONTROL TECHNIQUES

In 1995 authors, applied a discrete method on SMIB and New England 10 bus systems based on phase plane trajectories for controlling the switching of TCSC. In SMIB, the capacitor was switched off only when potential energy become maximum and kinetic energy had become zero. In multi machine system the machine was tested for a fault with and without line outage with same switching strategy and it was found, the energy of system decrease slowly with switching of TCSC and the damping improved for controllers within cut sets [68]. A robust Artificial Neuro Fuzzy Inference System (ANFIS) controller was designed for a 160 MW nonlinear Multiple Input Multiple Output (MIMO) steam boiler-turbine unit. ANFIS was trained by Linear Quardratic Regulator (LQR), state feedback optimal controller for contolling the deviation in fuel, steam and water valves with reference to deviation in pressure output, power output and water level deviation [69]. A PSO based algorithm was developed to maximize wind share in the grid tested on Kerala (India) grid 220kV, 25-bus system. Objective function was defined such that optimal loading and maximum safe instantaneous penetration got ensured. Using three types of algorithms namely, 1load increase, 2generation displacement and 3combined generation displacement, algorithm 2 ensured 17.74 p.u. active power output and 48.14% penetration, while algorithm 3 ensured 20.66 p.u. active power output and 36.126% penetration [70]. Although the TEX torsional motion relay and armature current relay are exhibiting a nonguaranteed performance, an algorithm for SSR detection was developed, using Wavelet Transform (WT) and Artificial Neural Network (ANN). Here, on SBM, a disturbance detector sending a 30Hz, 60Hz and combined signal to ANN through WT, verified 97% detection rate. It was found very fast and accurate [71]. Shangdu Power Project, Inner Mongolia China was tested for Genetic Algorithm Simulated Annealing technique where the stator and rotor controller parameters of Supplementary Excitation Damping Control (SEDC) and Generator Terminal Subsynchronous Damping Control (GTSDC) were optimized by the objective function [72]. A multi machine system with 4 SVCs in China was simulated in PSCAD, by considering all 4 SVCs and any two SVCs in service. From the model, the Complex Torque Coefficient Matrices (CTCM), were obtained by comparing torque equation with scanned frequency in SSR range without ignoring system dynamics. The curves showing intersection of electrical spring constant K_e and mechanical spring constant K_m as well electrical damping constant D_e and mechanical damping constant $-D_m$, were traced to check the unstable modes. Torsional oscillation modes were the roots of $K_m(j\omega)+K_e(j\omega)=0$. Torsional mode at ω was unstable if $D_m(j\omega)+D_e(j\omega)<0$. In [74], authors verified the method of delayed feedback control using direct method based on Cluster Treatment of Characteristic Roots (CTCR) on IEEE SBM model using time domain simulation. CTCR method could give stability intervals in time delayed LTI System by determining all possible pure imaginary roots for that the DFC controller used rotor angular speed ω_r from its value τ time in past as shown below Figure 15. From system Jacobean matrix, Root Tendency RT and no. of unstable roots NU were determined from (15), (16) and results were verified in MATLAB-SIMULINK showing time delay intervals in which system was stable. The output of controller was added to AVR as stabilizing input.

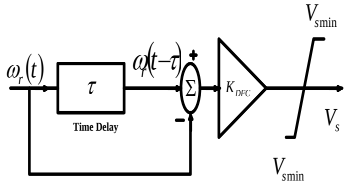


Figure15. *DFC Control of DFIG [74]*

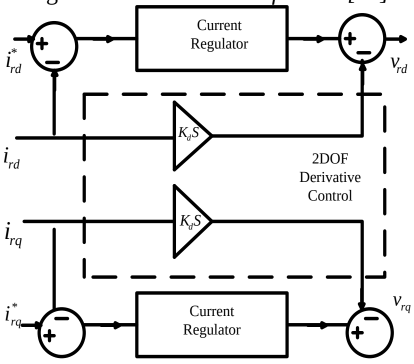


Figure16. *RSC Controller Loop [76]*

$$RT\Big|_{\omega=\omega_{ck}\tau=\tau_{ck}}=\operatorname{sgn}\left[\operatorname{Re}\left(\frac{\sum_{j=0}^{n}a_{jje^{-j\omega t}}}{\sum_{j=0}^{n}\left[\frac{da_j}{dt}-ja_j\tau\right]e^{-j\omega t}}\Big|s=_{\omega=\omega_{ck}\tau=\tau_{ck}}\right)\right] \tag{15}$$

$$NU(\tau)=NU(0)+\sum_{k=1}^{m}\prod\left(\frac{\tau-\tau_{ko}}{\Delta\tau}\right)U(\tau,\tau_{ko})RT_k \tag{16}$$

In [75], A 16 machine, 68 bus network, equivalent model of New York Power System (NYPS) and the New England Test System (NETS) was simulated in Dig SILENT Power Factory for evaluating Risk of SSR given by (17), that takes the severity and probability of SSR into account. The risk matrix was selected through state enumeration method. The TCSC reactance X_{TCSC} was found by synchronous reversal method and practically the ratio X_{TCSC} / X_{FC} was maintained between 2 and 3.

$$Risk=\sum_{i=1}^{n}\left(probability\times consequences_{SSR}\right) \tag{17}$$

In [76], time-domain simulation on DFIG wind farm was carried out to show that the control loop of the RSC based on improved capacitor voltage estimation method could reduce, IGE. Even at higher compensation and low wind speeds, the dynamics of controller with derivative action as shown in Figure16, were not affected.

VI. GENERAL METHODS FOR SSR MITIGATION

In [77], using field voltage and terminal voltage measurements at various excitation and loading conditions utilized to train the ANN and Output Error Method (OEM) was employed for estimation of d-q axis rotor parameters. The method used could predict internal parameters at large disturbances. Using the same method, the saturable mutual Inductances L_{ads} and L_{aqs} were estimated as a function of power angle, field current, active and reactive power at rated terminal voltage. Also the field and damper winding parameters were estimated [78]. For a steam turbine, the trained neural networks were used to verify local faults of fuel tube leakage, high pressure transmission system and low pressure transmission system [79]. Using a CMAC (Cerebellar Model Articulation Controller) neural network various faults like membrane oscillation, unbalance, and no orderliness along with six vibration frequencies were detected [80]. Authors proposed a self organizing fuzzy logic controller of boiler turbine fossil fuel plant to control valve, actuators that control mass flow rates of fuel, steam to the turbine and feed water to drum with very good time response, without requiring plant model [81]. The H^{∞} Technique can be applied to identify signatures of SSR. It was applied to image processing example of finding heart deformation for object kinematics estimation from images, used a similar structure to Kalman filter but with different optimization criteria such that the worst case energy gain was below a prescribed value, without requiring any a priory data [82]. The data mining concept using Neural Network and Genetic Algorithm, was used for identifying fault of steam turbine that extracts the fault from historic data [83]. In 2013, authors proposed a method of Nonlinear Model Predictive Control(NMPC) to a 166 MW Gas Turbine, for frequency and temperature control by applying orthogonal collocation on finite elements that convert a dynamic problem into algebraic equations [84].

The Magnetic Energy Recovery Switch (MERS), offering reduced capacitive reactance and a long resistive characteristic in the sub harmonic frequency domain, indicated good sub harmonic characteristics and a low chance for initiating SSR [85]. In early 80s the SSR problem was tackled by NGH-Damping scheme as in Figure17. The hypothesis behind the scheme was that the unbalance charge in series compensated capacitor is interchanged with system inductance to produce oscillations [86]. As shown in Figure18, the scheme involved a linear resistor and an anti parallel thyristor combination across a series capacitor segment with measuring equipment and appropriate control. When a zero voltage crossing point of the capacitor voltage was detected, the succeeding half cycle period was timed. If and when the half cycle exceeded the set time (8.33ms), the corresponding thyristor was fired to discharge the capacitor through the resistor and brought about its current zero sooner than it would be otherwise. After, the torsional oscillations excited due to the disturbance in the power system were suppressed thoroughly, the prefiring would last for some period of time and it would return to the normal half cycle firing again. Therefore, the prefiring function works only in the case that sub synchronous resonance gos detected [87]. A method of two-point load flow was applied on China Southern Power Grid which took resistance into account with frequency scanning method that could rapidly detect SSR problem [88].

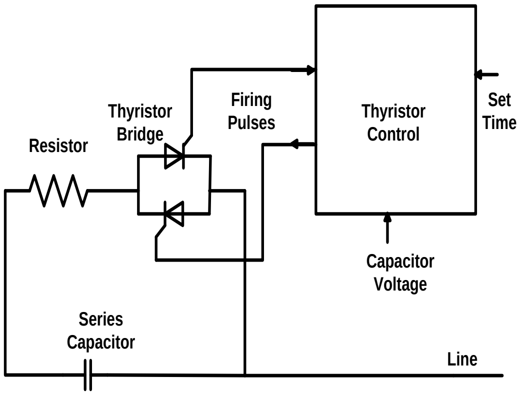


Figure 17. *NGH damping scheme [86]*

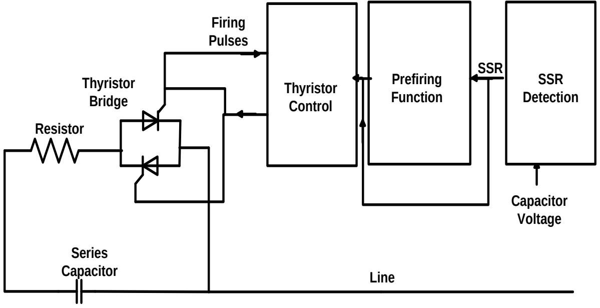


Figure18. *Improved NGH damping scheme [87]*

In [89], the double fed motor with rated capacity of 1 MVA, 0.69 kV was installed on the generator side at the end of the shaft, whose stator windings were directly connected to the generator bus, and rotor was excited by two VSCs, when the generator shaft speed exceeded the synchronous speed, the doubly fed motor could drive the shaft speed back to the synchronous speed through the control system. In [90], For a Single Cage Induction Generator based wind farm, the eigenvalue analysis was carried out at various compensation levels and it was found that as the number of machines aggregated increase, the amplitude of torque response at higher compensation levels increase drastically.

VII. CONCLUSION AND FUTURE SCOPE

A. CONCLUSION

Series Compensation is preferred over shunt compensation, as it is less sensitive to system load characteristics and equipment location along a transmission line. The interactions between wide-bandwidth power controlling devices, such as HVDC converters, SVC, PSS turbine-generators with large pulsating loads like arc furnaces, may lead to torsional interactions. The main advantage of time domain analysis is that the thyristors, firing circuits, controls as well nonlinearities can be modeled and the main drawback is that excessive computation times are required. VSCs interacting with long series compensated transmission line affect damping of the system. The added VSC-based system has a small effect on the damping profile, when the VSC is fully loaded, due to the increase in the negative conductance of the VSC. The TCSC has the disadvantage of presenting a parallel resonance between the capacitor and the thyristor controlled reactor at the fundamental frequency. Range of TCSC is somewhat narrow. TCSC is pricewise more competitive than SSSC. SSSC has high flexibility level but has a much higher cost involved due to the complexity of the converters. GCSC utilizes a smaller capacitor. One potentially interesting application of the GCSC is in the retrofitting of existing fixed series capacitors, making them one of a useful, FACTS device.

B. FUTURE SCOPE

Use of a simple lead/lag circuit adequately compensate for the thyristor firing transport delay, resulting in positive damping for all SSR modes in practical systems. The FACTS devices such as TCSC or GCSC for damping of SSR in radial system can be modified through design a SSR damping controller with optimized gain parameters. A comparison of FACTS devices for their performance on SSR mitigation can also be studied.

REFERENCES

[1] L.A. Kilgore, L.C. Eiliott, E.R. Taylor, *"The prediction and control of self excited oscillations due to series capacitors in power system"*, IEEE Transaction,Vol.**90**,Issue.**3**,pp.**1305-1311**, **1971**.

[2] IEEE Committee Report, *"Dynamic models for steam and hydro turbines in power system studies"*, In the Proceedings of IEEE Power & Energy Society Winter Meeting (PES Win. Meeting 1972), pp.**1904-915**, **1972**.

[3] Paul J. Nolan, Naresh K. Sinha, Robert T.H. Alden, *“Eigenvalue sensitivities of power system including network and shaft dynamics”,* IEEE Transaction,Vol.**95**, pp. **1318-1323**, **1976**.

[4] “*First Benchmark Model For Computer Simulation Of Subsynchronous Resonance*”, IEEE Transaction,IEEE Committee Report,Vol.**96**, Issue.**5**, pp.**1565-1572**, **1977**.

[5] T.H. Putman, D.G. Ramey, “*Theory of the modulated reactance solution for subsynchronous resonance*”, IEEE Transaction,Vol.**101**, Issue.**6**, pp.**1527-1535**, **1982**,.

[6] I. M. Canay, “*A novel approach to the torsional interaction and electrical damping of the synchronous machine*”, IEEE Transaction,Vol.**101**, Issue.**10**, pp.**3630-3638**, **1982**.

[7] N.C. Abi-Samra , R.F. Smith, T.E. Mc Dermott, M.B. Chidester , “*Analysis of thyristor- controlled shunt SSR countermeasures*”, IEEE Transaction,Vol.**104**, Issue.**3**, pp.**584-597**, **1985**.

[8] “*Terms, Definitions and Symbols For Subsynchronous Oscillations*”, IEEE Transaction,Vol.**104**,Issue.**6**,pp.**1326-1334**, **1985**.

[9] “*Second Benchmark Model For Computer Simulation Of Subsynchronous Resonance*”, IEEE Transaction,Vol.**104**,Issue.**5**, pp.**1057-1066**, **1985**.

[10] Eli Katz, Jim Tang, “*Comparison of SSR Calculations and Test Results*” IEEE Committee Report, IEEE Transaction,Vol.**4**,Issue.**1**, pp.**336-344**, **1989**.

[11] “*READER’S GUIDE TO SUBSYNCHRONOUS RESONANCE*”, IEEE Committee Report, IEEE Transaction,Vol.**7**,Issue.**1**, pp.**150-157**, **1992**.

[12] J.B.Ekanayake, N. Jenkins, “A three-level Advanced Static VAr Compensator”,IEEE Transaction,Vol.**11**,Issue.1,pp.**540-545**, **1996**.

[13] Hermann W. Dommel, “*Digital computer solution of electromagnetic transients in single and multiphase networks*”, IEEE Transaction,Vol.**104**, Issue.**5**,pp.**388-399**, **1969**.

[14] Narain G. Hingorani, “*A new scheme for sub synchronous resonance damping of torsional oscillations and transient torque -part-I*”, PER, pp.**1852-1855**, **1981**.

[15] Narain G. Hingorani”,*A New Scheme for Subsynchronous Resonance Damping of Torsional Oscillations and Transient Torque-Part-II*”, PER, pp.**1856-1857**, **1981**.

[16] Pouyan Pourbeik, Donald G Ramey, Nicholas Abi-Samra, Deniel Brooks, Anish Gaikwad, “*Vulnerability of large steam turbine generators to toorsional interactions during electrical grid disturbances*”, IEEE Transaction,Vol.**22**,Issue.**3**,pp.**1250-1258**, **2007**.

[17] Wei Duan, Zhangqi Wang, “V*ibration reliability analysis of turbine blade based on ann and monte carlo simulation*”, In the Proceedings of IEEE (ICNC 2010**)**, Valencia,**Spain**,pp.**1934-1939**, **2010**.

[18] Chanxia Zhu, Lingling Fan, Minqiang Hu, “*Control and analysis of DFIG-based wind turbines in a series comensated network for ssr damping*”, In the Proceedings of IEEE Power & Energy Society General Meeting (PES 2010), Detroit, Michigan, **USA**,pp**.1-6**, **2010**.

[19] Lingling Fan, Rajesh Kavasseri, Zhixin Lee Miao, Chanxia Zhu, “ *Modelling Of DFIG- Based Wind Farms for SSR Analysis*”, IEEE Transaction,Vol.**25**, Issue.**4**, pp.**2073-2082**, **2010**.

[20] Zhixin Miao, “*Impedance Model Based SSR Analysis for Type 3 Wind Generator and Series Compensated Network*”,Vol. **27**, **Issue. 4**, pp.**984-991**, **2012**.

[21] D.H.R. Suriyaarachchi, U.D. Annakage, C. Karawita, D.A. Jacobson, “ *A procedure to study sub-synchronous interactions in wind integrated power system*”, IEEE Transaction,Vol.**28**,Issue.**1**, pp. **377-384**, **2013**.

[22] Rajiv K. Verma, Akshaya Moharana, “*SSR in double-cage induction generator based wind farm connected to series- compensated transmission line*”, IEEE Transaction,Vol.**28**, Issue.**3**,pp.**2573-2583**, **2013**.

[23] Hossein Ali Mohammadpour, Enrico Santi, “*Modelling and control of gate- controlled series capacitor interfaced with a dfig-based wind farm”,* IEEE Transaction,Vol.**62**,Issue.**2**,pp.**1022-:1033**, **2015**.

[24] Hossein Ali Mohammadpour, M Moinul Islam, Enrico Santi, Yong-June Shin, “*SSR damping in fixed speed wind farms using series FACTS controllers*”, IEEE Transaction,Vol.**31**,Issue.**1**, pp.**76-86**, **2016**.

[25] Hossein Ali Mohammadpour, Enrico Santi , “*SSR damping controller design and optimal placement in rotor-side and grid-side converters of series- compensated DFIG-based wind farm*”, IEEE Transaction,Vol.**6**,Issue.**2**, **2015**.

[26] K.R. Padiyar, “*Analysis of Subsynchronous Resonance in Power System*”, Boston, MA, **USA**: Kluwer Academic,1999.

[27] K.R. Padiyar, “*Power System Dynamics, Stability & Control, Hyderabad*”, **India**: B S Publications, 2008.

[28] P. Kundur, “*Power System Dynamics, Stability & Control*”, New York, NY, **USA**: McGraw-Hill, 1994.

[29] P. M. Anderson, “*Subynchronous Resonance in Power System*”, New York, NY, **USA**: IEEE Press, 1990.

[30] Khaled Mohammad Alawasa, Wilsun Xu, Fellow, “ *New approach to damp subsynchronous resonance by reshaping the output impedance of voltage-sourced converters*”, In Proceedings of IEEE Power & Energy Society General Meeting (PES Gen. Meeting 2013),pp.**1-5**, **2013**.

[31] Luke Livermore, Carlos E Ugalde-Loo, Qing Mu, Jun Liang1, Janaka B Ekanayake1,Nick Jenkins1, “*Damping of subsynchronous resonance using avoltage source converter-based high-voltage directcurrent link in a series-compensated Great Britain transmission network*”, IET Gen., Transm. Distrib.,Vol.**8**, Issue.**3**, pp.**542‑551**, **2014**.

[32] Khaled Mohammad Alawasa, Wilsun Xu, Fellow, “ *A simple approach to damp ssr in series compensated system via reshaping the output admittance of a nearby VSC-based system*”, IEEE Transaction,Vol.**62**, Issue.**5**, pp.**2673-2682**, **2015**.

[33] K.R. Padiyar, Senior Member, IEEE, and Nagesh Prabhu, “*Design and performance evaluation of subsynchronous damping controller with STATCOM*”, IEEE Transaction,Vol.**21**,Issue. **3**,pp.**1398-1405**, **2006**.

[34] Nagesh Prabhu; M. Janaki; R. Thirumalaivasan, “*Damping of subsynchronous resonance by subsynchronous current injector with STATCOM*”, In the Proceedings of IEEE Conference on Convergent Technologies(TENCON 2009),**Singapore**,pp.**1-6**, **2009**.

[35] MSEI Moursi, Vinod Khadkikar, “*Novel control strategies for ssr mitigation and damping power system oscillations in a series compensated wind park*”, In the Proceedings of Annual Conference of the IEEE Industrial Electronics Society (IECON 2012), Montreal, Quebec, **Canada**,pp.**5335-5342**, **2012**.

[36] Akshaya Moharana, Rajiv K. Verma, Ravi Seethapathy, “*SSR alleviation by STATCOM in induction- generator based wind farm connected to series compensated line*”, IEEE Transaction,Vol.**5**, Issue.**3**, pp.**947-957**, **2014**.

[37] Nagesh Prabhu; M. Janaki; R. Thirumalaivasan, “*Damping of subsynchronous resonance by subsynchronous current injector with STATCOM*” , In the Proceedings of IEEE Conference on Convergent Technologies(TENCON 2003),Bangalore,**India**, pp.**1-6**, **2009**.

[38] Fawzi A. Rahman AI Jowder, Boon-Teck Ooi “*Series compensation of radial power system by a combination of SSSC and dielectric capacitors*”, IEEE Transaction,Vol.**20**,Issue.**1**,pp. **458-465**, **2005**.

[39] K.R. Padiyar ,Nagesh Prabhu “,*Analysis of subsynchronous resonance with three level twelve-pulse VSC based SSSC*”, In the Proceedings of IEEE Conference on. Convergent Technologies (TENCON 2003),Bangalore,**India**,pp.**76 – 80**, **2003**.

[40] Nagesh Prabhu, R Thirumalaivasan ,M Janaki, “*Design and performance evaluation of subsynchronous current suppressor with SSSC*” In the Proceedings of IEEE (TENCON 2009), Suntec City, **Singapore**,pp.**1-6**, **2009**.

[41] D. Rai, , S.O. Faried, G. Ramakrishna and A. Edris, “Impact *of imbalanced phase operation of SSSC on damping subsynchronous resonance*”, In the Proceedings of IEEE Power & Energy Society General Meeting (PES Gen. Meeting 2011) Detroit,**USA**, pp.**1-7**, **2011**.

[42] K.R. Padiyar , AMKulkarni, “*Control design and simulation of unified power flow controller*”, IEEE Transaction,Vol.**13**,Issue.**42**, pp.**1348–1354**, **1998**.

[43] Sajjad Golshannavaz, Farrokh Aminifar, and Daryoush Nazarpour, “*Application of UPFC to enhancing oscillatory response of series-compensated wind farm integrations*”, IEEE Transaction,Vol.**5**, Issue.**4**, **2014**.

[44] K.R. Padiyar and N. Prabhu, “*Investigation of SSR characteristics of unified power flow controller*”,ELSEVIER,EPSR,Vol.**74**, Issue.**2**,pp.**211–221**, **2005**.

[45] L. Gyugyi, T.R. Rietman A. Edris, "*The unified power flow controller: New approach to power transmission control*", IEEE Transaction,Vol.**10**, Issue.**2**,pp.**1085–1097**, **1995**.

[46] Wang. L, Hsu. Y., "*Damping of subsynchronous resonance using excitation controllers and static VAR compensations: a comparative study*", IEEE Transaction,Vol.**3**,Issue.**1**,pp.**6–13**, **1988**.

[47] Hailian Xie, Marcio, M de Oliveira, "*Mitigation of ssr in presence of wind power and series compensation by SVC*", In the Proceedings of Int. Conf. on Power System Tech.,(POWERCON 2014), Chengdu,**China**,pp.**2819-2826**, **2014**,.

[48] S. A. Khaparde, V. Krishna, "*Simulation of Unified Static VAR compensator and power system stabilizer for arresting subsynchronous resonance*",IEEE Transaction,Vol.**14**,Issue.**3**, pp.**1055-1062**, **1999.**

[49] LASZLOGYUGYI, "*Reactive power generation and control by thyristor circuits*", IEEE Transaction,Vol.**15**, Issue.**5**,pp.**521-532**, **1979**.

[50] A. E. Hammad, MEI- Sadek, "*Application of a thyristor controlled VAR compensator for damping subsynchronous oscillations in power system*", IEEE Transaction,Vol.**103**, Issue.**1**, pp.**198-212**, **1984**.

[51] J. Urbanek, R. J. Piwko, EV Larsen, B. L. Damsky, B. C. Furumasu, W. Mittlestadt. , "*Thyristor controlled series compensation prototype installation at the Slatt 500kv substation*", IEEE Transaction,Vol.**8**, Issue.**3**, pp. **1460-1469**, **1993**.

[52] Rajesh Rajaraman, Ian Dobson, Robert H Lasseter, Yilchih Shern, "*Computing the damping of subsynchronous oscillations due to a thyristor controlled series capacitor*" , IEEE Transaction, Vol.**11**, Issue.**2**, pp.**1112-1119**, **1996**.

[53] R. J. Piwko, C. A. Wegner, S. J. Kinney, J. D. Eden, "*Subsynchronous resonance performance tests of the Slatt thyristor- controllled series capacitor*", IEEE Transaction,Vol.**11**, Issue.**2**,pp.**1112-1119**, **1996**.

[54] Shou Bao Zou, Dariusz C. Zarkowski, "A novel phase- control topology to improve characteristics of thyristor controlled compensation in AC transmission system", In the Proceedings of IEEE Power & Energy Society (PES Summer Meeting 1999), Edmonton, Alberta, **Canada**,pp. **1134-1119**, **1999**.

[55] Y. Tanaka, HTaniguchi, MEgawa, "*Using miniature model and EMTP simulations to evaluate new methods to control and protect a thyristor controlled series compensator*", In the Proceedings of IEEE Power & Energy Society (PES Summer Meeting 1999), Edmonton, Alberta, **Canada,** pp.**1196-1201**, **1999**.

[56] Carlos Gama, Ricardo Tenorio",*Improvements for power system performance: Modelling, analysis and benefits of TCSC*", In the Proceedings of IEEE Power & Energy Society (PES Winter Meeting 2000), pp.**1462-1467**, **2000**.

[57] Tang Yi, Yu Rui-quin, "*Mechanism analysis of using thyristor controlled series compensation to mitigate subsynchronous resonance*",In the Proceedings of IEEE International Power Electronics Conference(IPEC 2010), Sapporo, **Japan**,pp.**1094-1099**,**2010**.

[58] Khosro Kabiri, Sebastian Henschel a, Hermann W Dommel, " *Resistive Behaviour of Thyristor- Controlled Series Capacitors at Subsynchronous Frequencies*",IEEE Transaction,Vol.**19**,Issue.**1**, pp.**374-379**, **2004**.

[59] S. Sajedi, F Khalifeh, T Karimi, Z Khalifeh, "*A New Method for Subsyncronous Damping Using TCSC*", Australian Journal Of Basic and Applied Sciences,pp. **875-881**, **2011.**

[60] Xiang Zheng, Zheng Xu, Jing Zhang, " *A supplementary Damping Controller of TCSC for Mitigating SSR",* In the Proceedings of IEEE Power & Energy Society General Meeting (PES Gen. Meeting 2009), Calgary, Alberta,**Canada**, pp.**1-5**, **2009**.

[61] F.D. Jesus, E. H. Watanbe , L. F. W. Souza, F .D. Jesus, "*Analysis of SSR mitigation using gate-controlled series capacitors*", In the Proceedings of IEEE Power Electronics Specialists 2005(PESC 2005), Recife, **Brazil**,pp.**1402-1407**, **2005**.

[62] A. Binaco, "*GCSC-Gate Controlled Series Capacitor: A New FACTS device for Series Compensation of Transmission Lines*", In the Proceedings of IEEE Transmission and Distribution Conference and Exposition 2004(ITDCE 2004), Chicago, IL, **USA**,pp.**981-986**, **2004**.

[63] F.D. de Jesus ; E.H. Watanabe ; L.F.W. Souza ; J.E.R. Alves, "*SSR Mitigation Using Gate-Controlled Series Capacitors*", In the Proceedings of IEEE(Power & Energy Society General meeting2006), Montreal, Quebec, **Canada**, pp.**7**, **2006**.

[64] Swakshar Ray,Ganesh Venayagamoorthy, "*Nonlinear Modified PI Control Of Multi-Module GCSCs in a Large Power System*", In the Proceedings of IEEE Industry Applications Conference Forty-First IAS Annual Meeting (IAS Annual meeting 2006), pp.**1345-1351**, **2006**.

[65] Fabio Domingues de Jesus, Edson Hirokazu Watanbe, Luiz Felipe Willcox de Souza, Jose Eduardo RAlves "*SSR and Power Oscillation Damping Using Gate- Controlled Series Capacitors*" IEEE Transaction,Vol.**22**, Issue.**3**, pp.**1806-1812**, **2007**.

[66] B. S. Umre, J. B. Helonde, J. P. Modak, Sonali Renkey (Rangari), "*Application of Gate- Controlled Series Capacitors (GCSC) for Reducing Stresses due to Sub-Synchronous resonance in Turbine-Generator Shaft*", In the Proceedings of IEEE Energy Conversion Congress & Exposition (ECCE 2010), Atlanta, **Georgia**,pp.**2300-2305**, **2010**.

[67] Hossein Ali Mohammadpour, Enrico Santi, "*Modelling and Control of Gate-Controlled Series Capacitor Interfaced With a DFIG- Based Wind Farm*",IEEE Transaction,Vol.**62**,Issue.**2**, pp.**1022-1033**, **2015**.

[68] K. R. Padiyar, K. Uma Rao",*Discrete Control of series compensation for stability improvement in power system*", In the Proceedings of IEEE International Conference on Control Application (ICCA 1995),pp.**246-25**, **1995**.

[69] Fahd A Alturki, Adel Ben Abdennour "*Neuro-Fuzzy Control of a steam Boiler-Turbine Unit*" , In the Proceedings of IEEE International Conference on Control Application(ICCA 1999), pp.**1050-1055**, **1999**.

[70] Sasidharan Sreedharan, J G Singh, I Made Wartana, Kittavit Buayai ",*Development of PSO Based Control Algorithms for Maximizing Wind Energy Penetration*", In the Proceedings of IEEE Power & Energy Society Gen. Meeting (PES Gen. Meeting 2011), Detroit, Michigan, **USA**. pp.**1-6, 2011**.

[71] Yu Xia, Henian Xia",*Application of Modern Techniques for Detecting Subsynchronous Oscillations in Power System*", In the Proceedings of IEEE Power & Energy Society General Meeting(PES Gen. Meeting 2013),Vancouver,B.C.,**Canada**, pp.**1-5**,**2013**.

[72] Xiaoliang Dong, Xiaorong Xie, Yingduo Han,Liang Wang, Dawei Sun",*Coordinated Parameters Design of SEDC and GTSDC for SSR Mitigation*" In the Proceedings of IEEE Power & Energy Society General Meeting(PES Gen. Meeting 2014),National Harbor, Washington, D.C.,pp.**1-5**, **2014**.

[73] Xinyao Zhu, Haishun Sun, Jintu Wen, Shijie Cheng ",Improved Complex Torque Coefficient Method Using CPCM for Multi- Machine System Analysis", IEEE Transaction,Vol.**29**, Issue.**5**,pp.**2060-2068**, **2014**.

[74] Yesar, Kucukefe, Adnan Kaypmaz, "*Damping Subsysncronous Resonance Oscillations by Delayed feedback Control*", In the Proceedings of IEEE Power & Energy Society General Meeting (PES 2010), Minneapolis, Minnesota, **USA**, pp.**1-7**, **2010**.

[75] Atia Adrees, Jovica V Milanovic, "*Optimal Compensation of Transmission Lines Based On Minimisation of the Risk of Subsynchronous Resonance*", IEEE Transaction,Vol.**31**,Issue.**2**, pp.**1038-1047**, **2016**.

[76] Po-Hsu Huang, Mohammed Shawky, EI Moursi, Weidong Xiao, James L Kirtley",*Subsynchronous Resonance Mitigation for series-Compensated DFIG-Based Wind Farm by Using Two-Degree-Of Freedom Control Strategy*",IEEE Transaction,Vol.**30**,Issue.**3**, pp.**1442-1454**, **2015**.

[77] H. Bora Karayaka Ali Keyhani, Gerald Thomas Heydt, Baj L Agarwal , Douglas A Selin, "*Neural Network based Modelling of a large steam turbine-Generator Rotor BodyParameters from on-Line Disturbance Data*", IEEE Transaction,Vol.**16**,Issue.**4**, pp.**305-311**, **2001**.

[78] H. Bora Karayaka, Ali Keyhani, Baj LAgarwal, Doughlas A Selin, Gerald Thomas Heydt, "*Identification of Armature, Field and Saturated Parameters of a large Steam Turbine-Generator from Operating Data*", IEEE Transaction,Vol.**15**,Issue.**2**, pp.**181-187**, **2000**.

[79] Quiang Fu, Yi Shen, Jian Qiu Zhang, Shengli Liu “An Approach to Fault Diagnosis Based On a Hierarchical Information Fusion Scheme”, In the Proceedings of IEEE Instrumentation and Measurement Technology Conference(IMTC 2001),Budapest, **Hungary**, pp.**875-878**, **2001**.

[80] Chin-Pao Hung, Mang-Hui Wang, Chin-Hsing Cheng, Wen-Lang Lin, “*Fault Diagnosis of Steam Turbine- Generator Using CMAC Neural Network Approach*”, In the Proceedings of IEEE International Joint Conference on Neural Networks(IJCNN 2003), Portland, **USA**,pp.**2988-2993**, **2003**.

[81] Un-Chul Moon, Kwang Y Lee”,*A Boiler-Turbine System Control Using A Fuzzy Auto-Regressive Moving Average(FARMA) Model*”, IEEE Transaction,Vol.**18**, Issue.**1**, pp.**142-148**, **2003**.

[82] Edward W.B. Lo, Huafeng Liu, Pencheng Shi”,H_∞ *Filtering And Physical Modeling For Robust Kinematics Estimation*”, In the Proceedings of IEEE International Conference on Image Processing(ICIP 2003),Barcelona,Catalonia,**Spain**,pp.**169-172, 2003.**

[83] Qinglin Guo, Ming Zhang, “*A Novel Approach for Fault Diagnosis Of Steam Turbine Based On Neural Network And Genetic Algorithm*”, In the Proceedings of IEEE International Joint Conference on Neural Networks(IJCNN 2008),Hong Kong, **China**,pp.**25-29**, **2008**.

[84] Jong S. Kim, Kody M Powell, Thomas F Edgar, “*Nonlinear Model Predictive Control For a Heavy Duty Gas Turbine Power Plant*”, In the Proceedings of American Control Conference (ACC 2013), Washington, DC, **USA**,pp.**2952-2957**, **2013**.

[85] Jan Aril d Wiik, Fransisco Danang Wijaya and Ryuichi Shimada, “*Characteristics of the Magnetic Energy Recovery Switch (MERS) as a Series FACTS Controller*”, IEEE Transaction,Vol.**24**, Issue.**2,** pp.**828-836**, **2009**.

[86] Narain G. Hingorani, “*A New Scheme for Subsynchronous Damping of Torsional Oscillations and Transient Torque- Part I*”, IEEE Transaction,Vol.**100**, Issue.**4**, pp.**1852-1855**, **1981**.

[87] Zhao Xueqiang, Chen Chen, “*Damping Subsynchronous Resonance Using an Improved NGH SSR Damping scheme*”, IEEE Transaction,PESS,pp.**780-785**, **1999**.

[88] Yu Yang, Xiaolin Li, Zilong Mu, Xingyuan li, Yuhong Wang, “*Rapid Risk Assessment of SSR Caused by Series Capacitors Compensations in Large Power Grid* “, In the Proceedings of IEEE Asia-Pacific Power and Energy Engineering Conference (APPEEC 2010), Chengdu, **China**, pp.**1-4**, **2010**.

[89] Xu Jinfeng, Song Ruihua, Xiang Zutao, Wang Xiaojun, Du Ning, “*Simulation Studies on Mitigating Subsynchronous Resonance with Coaxial Double Fed motor*”, In the Proceedings of IEEE International Conference on Power System Technology (POWERCON 2012), Auckland,**New Zealand**, pp.**1-4**, **2012**.

[90] Gajanan V. Gotmare,Vasudeo B. Virulkar, “*Eigenvalue Analysis of Subsynchronous Resonance Study in Series Compensated Wind Farm*”, International Journal of Modern Trends in Engineering and Research, IJMTER,Vol.**2**, Issue.**2**, pp.**267-275**, **2015**.

[91] Ajinkya Pachghare, “ *R.M.SaharVoltage regulation and reactive power compensation by SSSC based on 48-pluse GTO (VSC)*”, International Journal of Scientific Research in Computer Science and Engineering, ISROSET,Vol.**5**, Issue.**4**, pp.**41-44**, **2017**.

[92] Sabbella. V.V.S.K. Reddy, K. Satyanarayana, “*Sensing of Ground Fault in Bipolar LVDC Grid*”, IJSRNSC,Vol.**6**, Issue.**6**,pp.**19-24**, **2018**.

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