Novel Control Strategies for SSR Mitigation and Damping Power System Oscillations in a Series Compensated Wind Park

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***Abstract*-- This paper addresses implementation issues associated with a novel damping control algorithms for STATCOM and SSSC (static synchronous series compensator) in a series compensated wind park for mitigating SSR (subsynchronous resonance) and damping power system oscillations. The IEEE first benchmark model on subsynchronous resonance is adopted with integrating aggregated self-excited induction generator based wind turbine to perform the studies. The potential occurrence and mitigation of the SSR caused by induction generator effects as well as torsional interactions, in a series compensated wind park are investigated. The auxiliary subsynchronous damping control loops for the STATCOM and SSSC based on a novel design procedure of nonlinear optimization are developed to meet the damping torque in the range of critical torsional frequencies. The performances of the controllers are tested in steady state operation and in response to system contingencies, taking into account the impact of short circuit ratios (SCRs). Simulation results are presented to demonstrate the capability of the controllers for mitigating the SSR, damping the power system oscillation and enhancing the transient stability margin in response to different SCRs.**

Index Terms*-- *SSR Mitigation, Damping Power System Oscillations, STATCOM, SSSC, Transient Stability Margin.

NOMENCLATURE

V_C	Series compensated voltage
X_S	Series injected reactance
P_{e1}	Active power transfer based constant reactance control of SSSC
P_{e2}	Active power transfer based constant injected voltage control of SSSC
V_q	Injected series quadrature voltage
$\Delta\omega_r$	Generator rotor speed deviation
ΔX_S	Damping signal series injected reactance of SSSC
ΔV_q	Damping injected quadrature voltage of SSSC
V_t	Terminal voltage of the STATCOM
I_{qref}	Reference reactive current of the STATCOM
I_{qm}	Measured reactive current of STATCOM
I_{dref}	Reference active current of the STATCOM
I_{dm}	Measured active current of STATCOM
dI_q	Modulation protection
θ	Synchronizing phase angle
PLL	Phase locked loop
V_{qm}	Measured quadrature voltage
V_{dm}	Measured quadrature voltage
P_{SSSC}	Active power of the SSSC
ΔV_{damp1}	Damping voltage signal based rotor speed deviation
ΔV_{damp2}	Damping voltage signal based active power deviation
S	Slip

I. INTRODUCTION

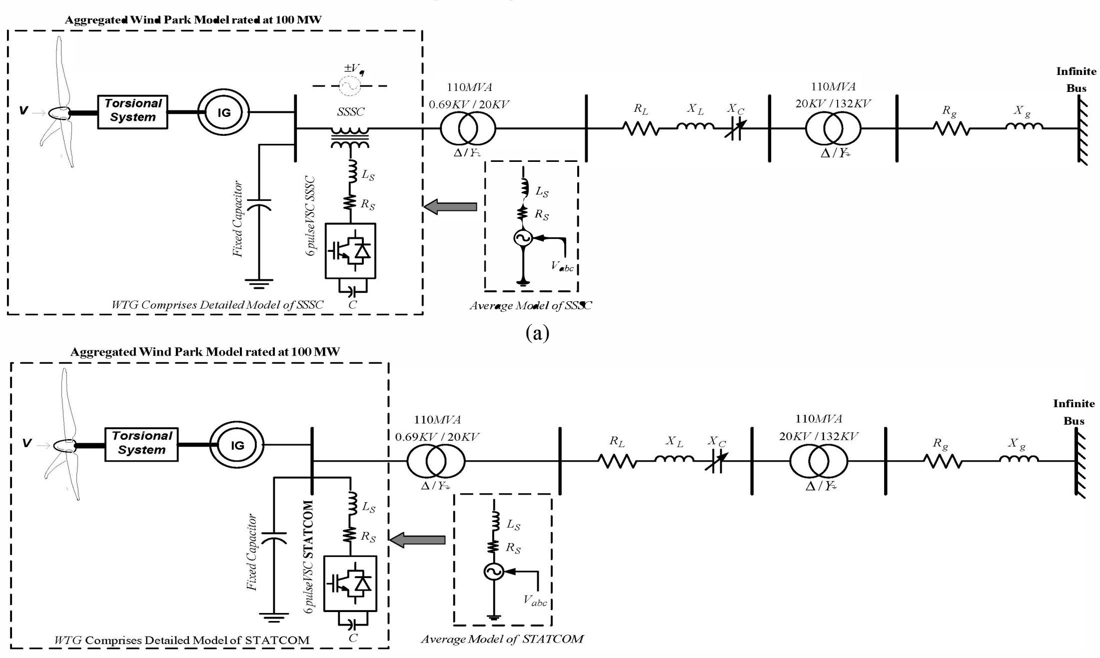
In recent years, the large penetration of wind energy is considered as an effective means of power generation. This shift to wind energy installed in large wind parks requires transmitting the power generation through transmission systems that can sustain large power flows [1]. Due to the continued growth in the wind energy, power utilities' interests have shifted from power quality issues caused by wind power to potential stability problems [2]. Therefore, the series compensation is considered as an effective mean of increasing the power transfer capability of the existing transmission system. However, the series capacitor compensation can produce a significant adverse effect such as subsynchronous resonance (SSR) on the wind turbine generators (WTG) and thermal turbine generator units [3]. Series compensation in transmission network may cause SSR due to negative resistance at SSR frequency, which is called an Induction Generator Effect (IGE) and may be initiated due to the interaction of wind turbines and the network LC resonance mode [4].

Wind turbines are subjected to different mechanical modes of vibration related to the mechanical system such as the blades, the shaft, the drive train, the tower, etc [5]. For the radial connected wind parks on the end of a series compensated transmission line, the SSR due to the induction generator effect is highly expected [6]. The energy exchange and the interaction between the mechanical and electrical system, coupled through the generator are potentially the cause of resonant conditions (SSR) with a resonant-frequency below the fundamental frequency. The sudden changes in the network topology due to system disturbances, resulting in sudden change in currents flows that will tend to oscillate at the natural frequencies of the AC network. In a transmission system without series capacitors, these transients are always dc transients, which decay to zero with a time constant that depends on the ratio of inductance to resistance. For networks that contain series capacitors, the transient currents will contain one or more oscillatory frequencies that depend on the network series capacitance as well as the inductance and resistance. In a simple radial RLC system, there will be only one such natural frequency, with exactly the situation described but in a network with many series capacitors there will be many such sub synchronous frequencies. If any of these sub synchronous network frequencies coincide with one of the natural modes of the mechanical system sustained shaft torques might appear, since these torques are directly proportional to the magnitude of the oscillating current. Currents due to short circuits, therefore, can generate very large shaft torques both when the fault is applied and also when it is cleared. In a real power system there may be many different sub synchronous frequencies involved and the analysis is quite complex.

This paper is given focus to the SSSC and STATCOM based on new controller structures. The SSSC control structures are based on the injection of series quadrature voltage into the electric grid in order to shift the electrical resonance depending on the grid impedance [8]. However, the STATCOM does not change the SSR characteristics of the network significantly. Therefore, additional damping control loops are required for damping torsional modes and power system oscillations. The damping control loops should be tuned to reach optimum performance to provide positive damping in the range of torsional frequencies. This paper investigates the self-excited induction generator based wind turbine subsynchronous resonance (SSR) and damping shaft torsional oscillations. The IEEE first benchmark model on subsynchronous resonance is adopted for the integration of an aggregated SEIG-WT. Also the mitigation solution for damping SSR oscillation, voltage stabilization, damping the transient torques, and enhancing the transient stability margin will be investigated in response to different SCRs.

II. POWER SYSTEM DESCRIPTION

This paper considers Wind Park based on self-excited induction generators as the majority of the wind parks employing SEIG-WT. Therefore the grid codes become a challenge for such type of wind turbine in terms of voltage and frequency controls and FRT (fault ride through) capabilities. The study system is derived based on the IEEE first benchmark model of SSR studies [8]. The system is adopted with connecting a SEIG wind park rated at 100 MW to the electric grid through a fixed series compensated transmission system comprising the SSSC and STATCOM respectively as shown in Fig.1 (a, b). There are two system schemes proposed with alternatively employing SSSC and STATCOM shown in Fig.1 (a, b), respectively. The wind park based on SEIGs requires additional substation equipment in order to meet the grid codes. The studies in this paper are conducted with



(a)

(b)

Fig.1 The wind park configurations: a) comprises SSSC and b) comprises STATCOM.

installing substation compensators such as SSSC and STATCOM as central compensators for enhancing the wind park performance. The FACTS devices are associated with auxiliary damping control loops for mitigating SSR, subsequent damping power system oscillations and improving the transient stability margin of the interconnected power system.

III. CONTROLLER DESIGN OF SSSC & STATCOM

Fig.2 illustrates the auxiliary damping control loops for the SSSC and STATCOM [9]. The main function of the SSSC as a series compensation is the control of transmission line power flow. However, the need for SSR mitigation and damping power system oscillations is obtained as secondary operational functions. The shunt FACTS device STATCOM resembles in many respect as a synchronous compensator, but without the inertia [10]. Even though the primary purpose of the STATCOM is to support the bus voltage by injecting or absorbing reactive power, it is also capable of improving the power system stability. It has been proved that the shunt FACTS device give maximum benefit by their stabilized voltage support especially when sited at the mid-point of the transmission line.

A) Synchronizing Power & Damping Power of SSSC

The transmitted power of SSSC compensated radial power systems can be accomplished by either direct control of the line current (power) or alternatively by injected control of either compensated series reactance, X_S, or injected series compensated quadrature voltage, Vc**.** The transmitted power of the SSSC for either constant reactance control mode or constant quadrature voltage control mode is expressed respectively as [11]:

$$P_{e1} = \frac{V_S V_r}{X_T - X_S} \sin \delta_S \tag{1}$$

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

The damping power control loop signal should be included in phase with the rotor speed deviation $\Delta\omega_r$ and added to Eqs. (1) and (2). The controllable parameters of SSSC are X_S and V_q for the constant reactance and constant quadrature voltage control modes respectively. Therefore, different control algorithms can be synthesized depending on the desired type of friction. There are different possible functions for the friction $f(\Delta\omega_r)$ that fulfill the following general condition:

$$f(\Delta\omega_r): \begin{Bmatrix} >\mathbf{0} \ \ \mathbf{if} \ \ \Delta\omega_\mathbf{r} > 0 \\ <0 \ \ \mathbf{if} \ \ \Delta\omega_\mathbf{r} < 0 \end{Bmatrix} \tag{3}$$

Some of them are:

a) Linear friction : $f(\Delta\omega_r) = K_C.\Delta\omega_r$

b) Columbian friction : $f(\Delta\omega_r) = K_d sign(\Delta\omega_r)$

c) High order polynomial friction:

$$f(\Delta\omega_r) = \sum_i K_{C1}.\Delta\omega^i, with\, \mathrm{i} = 3,5,7........$$

d) Combination of the above

e) Similar structure to case (a)-(d), but with parameters, K adaptable in accordance with the evolution of the system variables.

Once the injected friction function $f(\Delta\omega)$ is selected, the expression of the control law is designed using eqs. 1 or 2 based on the control mode. The control laws for the damping signals for both constant reactance and constant quadrature voltage control modes respectively are given as:

$$\Delta X_S = K_{d1}.\Delta\omega_r,\ \Delta V_q = K_{d2}.\Delta\omega_r$$

The delays and the effect of the filter delays of the damping controller are omitted in order to provide analytical comparison between the SSSC and STATCOM [12]. The general equations (5) & (6) are linearized:

$$\Delta P_{e1} = \left(\frac{V_S V_r}{X_T - X_S} \cos\delta_S\right)\Delta\delta_S + \left(\frac{V_S V_r.K_{d1}}{(X_T - X_S)^2} \cos\delta_S\right)\Delta\omega_1$$
$$= K_{S1}.\Delta\delta_S + K_{dd1}.\Delta\omega_r \tag{4}$$

$$\Delta P_{e2} = \left(\frac{V_S V_r}{X_T} \sin\delta_S - \frac{V_S V_r}{2X_T} \sin\frac{\delta_S}{2}\right)\Delta\delta_S + \left(\frac{V_S}{X_T} \cos\left(\frac{\delta_S}{2}\right) K_{d2}\right)\Delta\omega_r$$
$$= K_{S2}.\Delta\delta_S + K_{dd2}.\Delta\omega_r \tag{5}$$

Where K_{Si}: Synchronizing power coefficient

K_{ddi}: Damping power coefficient

B) Synchronizing Power and Damping Power of STATCOM

The STATCOM compensates the power system at the midpoint of transmission system. The transmitted power is expressed as the following [12]:

$$P_e = \frac{V_S V_m}{X_T / 2} \sin\frac{\delta_S}{2} \tag{6}$$

The STATCOM is controlling the bus terminal voltage V_t, thus the control law is: $\Delta V_t = K_d.\Delta\omega_r$, by linearizing eq. (6)

$$\Delta P_e = \left(\frac{1}{2} \frac{V_S V_t}{X_T / 2} \cos\frac{\delta_s}{2}\right)\Delta\delta_S + \left(\frac{V_S K_d}{X_T / 2} \sin\frac{\delta_S}{2}\right)\Delta\omega_r$$
$$= K_{ST1}.\Delta\delta_S + K_{dS}.\Delta\omega_r \tag{7}$$

IV. CONTROLLER DESIGN OF SSSC & STATCOM

A) STATCOM Voltage Control Structure

The STATCOM is operated based on the voltage control to regulate the terminal bus voltage V_m to follow the assigned reference voltage, Fig.3. The voltage and current measurements at the 0.69 kV bus are frequently undertaken

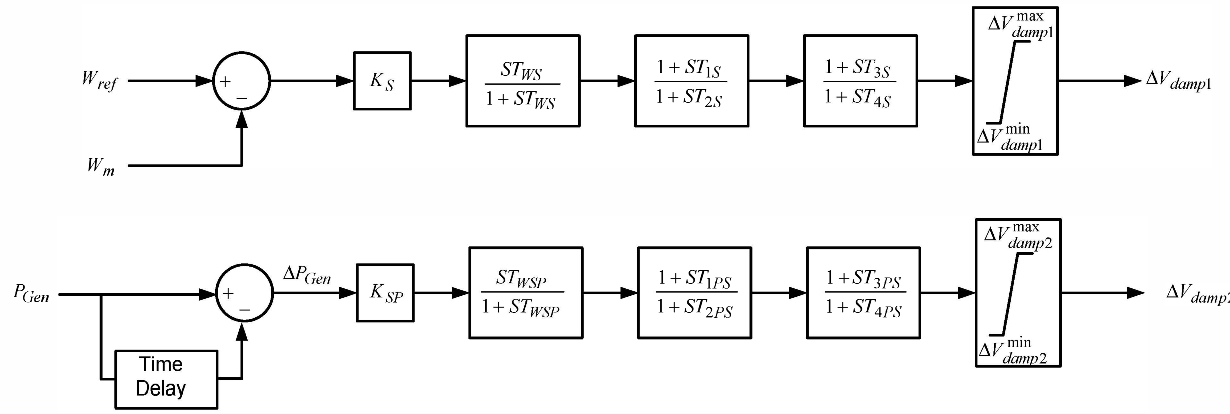


Fig. 2 The damping control loops based on generator speed deviation and active power variation in a specified time interval.

and sampled. The sampled voltage measurement is sent to the voltage control, which is compared to the reference voltage assigned for the terminal bus. The voltage error drives the voltage regulators (PI Controller) considering the regulation slope K. The voltage control determines the reference reactive current and sends it directly to the inner current control of the STATCOM for fast voltage response.

1) Auxiliary damping control loops

Introducing the STATCOM controllers at an appreciate location, by itself does not provide adequate damping, as the primary task of the controller is to control voltage. Hence, in order to increase the system damping, it is necessary to add additional control blocks with an adequate input signals. There are two damping control loops specified based on the rotor speed deviation and the variation of active power in a specified time interval. The two damping control loops are structured using the analytical approach for synchronizing power and damping power as described in sec. II. The lead-lag control structure is chosen for the two control loops as shown in Fig.2. The damping control loops consists of: a gain block, a signal washout block and a two-stage phase compensation blocks. It is preferably that the additional control signal is local to avoid the impact of communication time delay. The damping signal is fed through a washout control block to avoid affecting the steady state operation, and an additional lead-lag control block is used to improve the dynamic system response. The washout block performs as a high-pass filter which allows signals associated with oscillations to pass unchanged. The damping loops utilize the integral time absolute error of the rotor speed and the active power are taken as the following objective functions:

$$J_1 = \int_{t=0}^{t=t_{sim}} \left(\left|\Delta\omega_r\right|\right) t \ dt, \qquad (8)$$

$$J_2 = \int_{t=0}^{t=t_{sim}} \left(\left|\Delta P\right|\right) t \ dt, \qquad (9)$$

$\Delta\omega_r$: The rotor speed deviation

ΔP : The active power deviation in a specified time interval

The target is to minimize the objective functions in order to improve the system response. Therefore, adopting the parameters of the control loops should be tuned to achieve an appreciated system response.

2) Transient Model of STATCOM

The average transient model of the STATCOM is much convenient for the following studies in this paper as it will speed up the simulation time by factor of 20. The detailed model of the STATCOM is modified by replacing the switching converter by controllable voltage source as shown in Fig.3. The output three phase voltages from the park transformation (dq-abc) are used directly as input signal of the controllable voltage source.

The decoupled current control consists of two control loops, which are controlling the direct, and quadrature components of the STATCOM current. The direct component of the STATCOM current, I_{dref}, is responsible for controlling dc link voltage while the STATCOM operating in capacitive or inductive mode of operation. The quadrature component of the STATCOM current, I_{qref}, controls the reactive power exchange between the converter and a.c system. The reference direct and quadrature STATCOM currents are compared with the measured values of I_d and I_q and the errors drive the current regulators. The output of the current regulators are the controlling voltage signals V_d and V_q, which are added to the feed forward signals of the direct and quadrature components of the three phase terminal voltage. For higher performance, the voltage drop across converter inductors is also added to the controlling voltage signals. The determined direct and quadrature- controlling voltages are transformed from D-Q frame to three phase voltages, which are used directly to control the controllable voltage sources.

B) SSSC Control Structure

Fig. 4 shows a constant injected quadrature voltage control, which is independent of the line current. A phase locked loop (PLL) which synchronizes on the positive sequence component of the line current is used. The output of the PLL is angle, θ which is used to transform the direct axis and

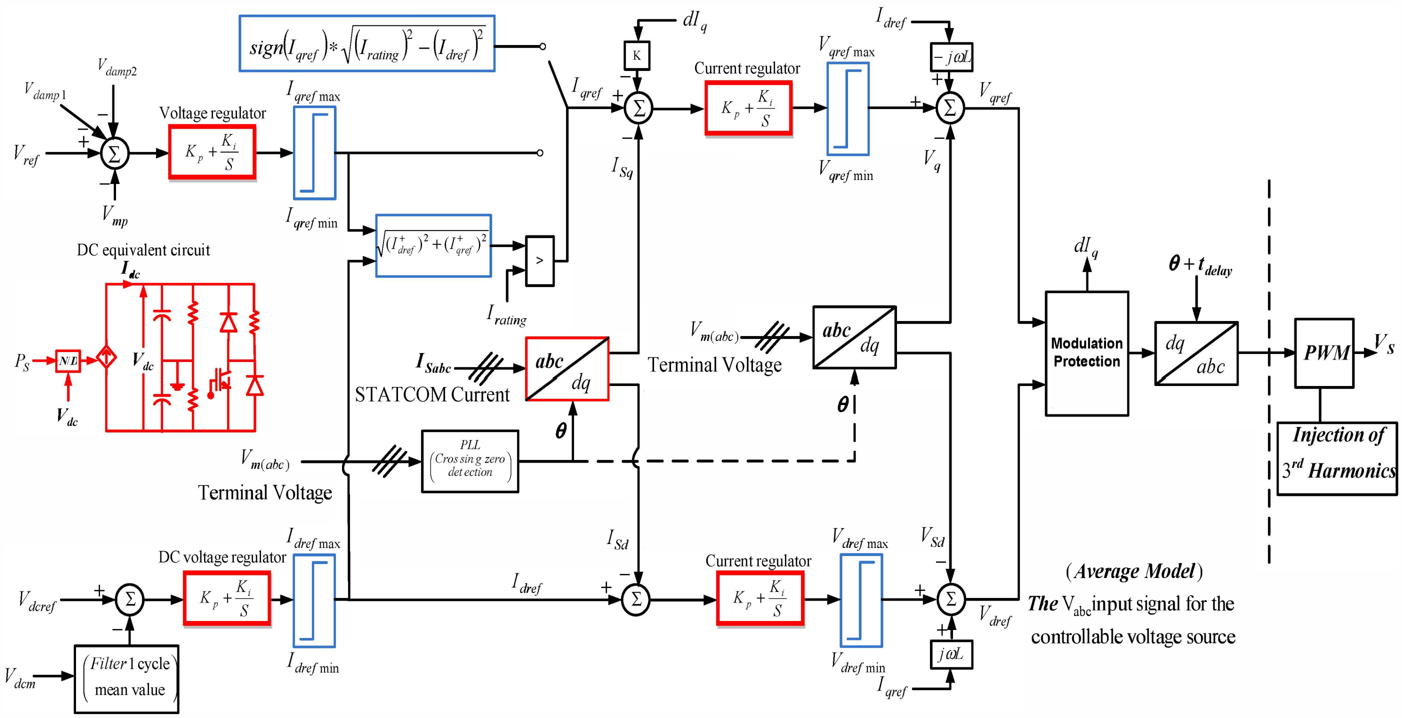


Fig.3 The control scheme of the STATCOM.

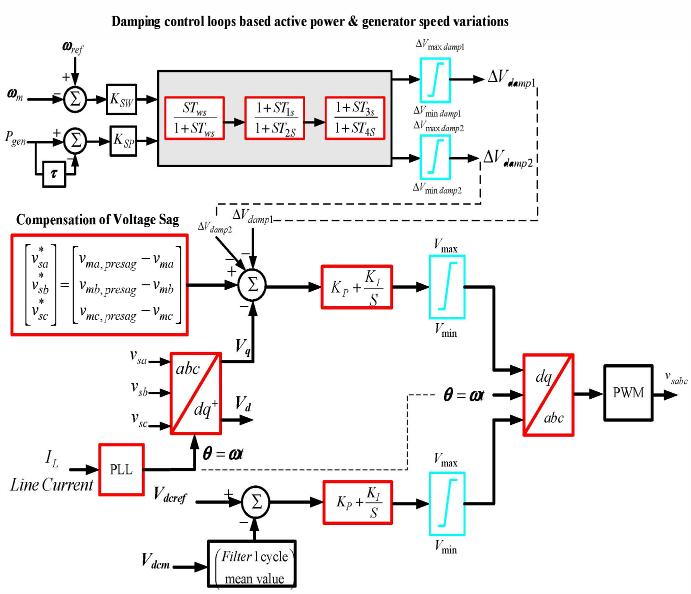
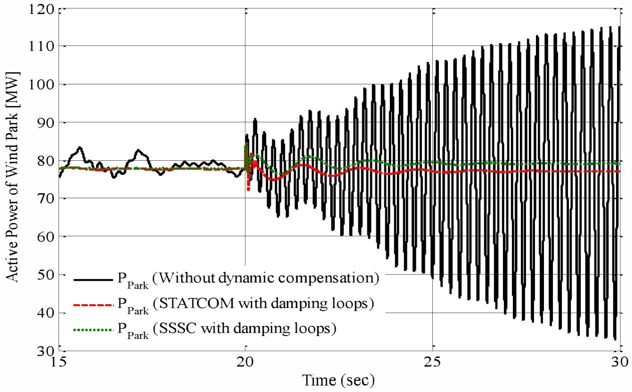


Fig.4 SSSC controller in positive and negative sequence reference frame associated with damping control loops.

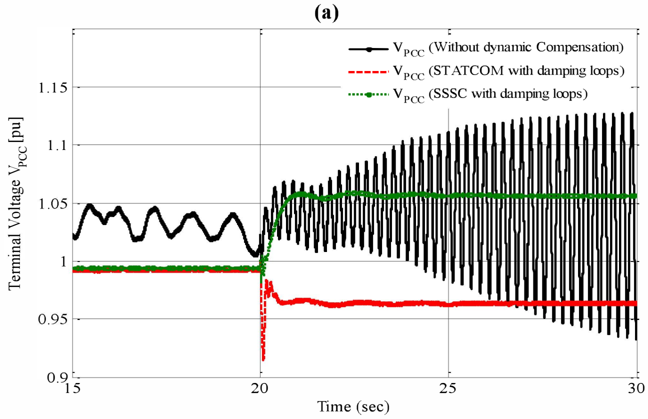
quadrature axis components of the ac three phase voltage and current. The voltage drop across the leakage reactance of the series coupling transformer is measured to compute the injected quadrature voltage with respect to the line current. The measured quadrature voltage is compared with the desired reference voltage to the input of the ac voltage regulator which is a PI controller. Thus the voltage regulator provides the quadrature component of the converter voltage. Also the measured dc voltage of the SSSC is compared with the reference dc link voltage; this driven error is an input to the dc voltage regulator which is a PI controller to compute the direct component of the converter voltage. Both direct and quadrature components of the converter voltage are used to determine the modulation index which is varied (0<M<1), thus it controls the injected quadrature series voltage based on the desired injected quadrature voltage, V_{qref}.

V. SSR MITIGATION IN A SERIES COMPENSATED WIND PARK

The series compensated wind park is tested in response to the variation of series compensation by increasing the level of series capacitive compensation from 0.18 up to 0.33 pu. This is done in the simulation at time t=20s. The analysis of SSR with STATCOM and SSSC associated with damping control loops are conducted based on damping torque analysis and transient simulation. The damping torque analysis is considered in the design of the damping control loops. The concept of the control design is to secure a net positive damping torque at any of the torsional mode frequencies. Therefore, at any given oscillation frequency of the generator rotor, the electrical torque should be in phase with rotor speed acting as damping torque. The damping torque analysis is an approach to design in the auxiliary control loops for FACTS devices. It enables the developer to provide a robust control design upon a countermeasure for the mitigation of the determined effects of SSR. It helps to secure the torsional mode stability with adopted tuning parameters of the control



(a)



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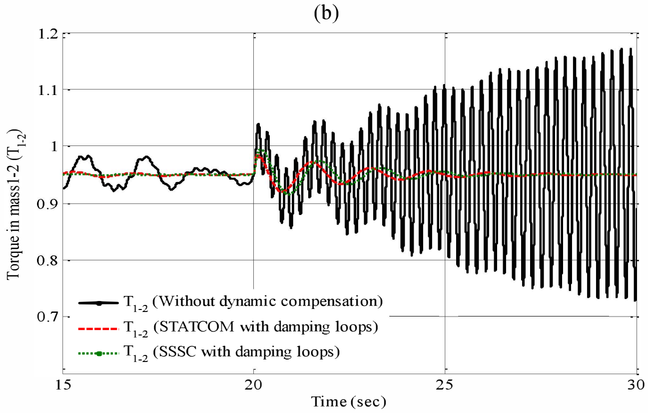

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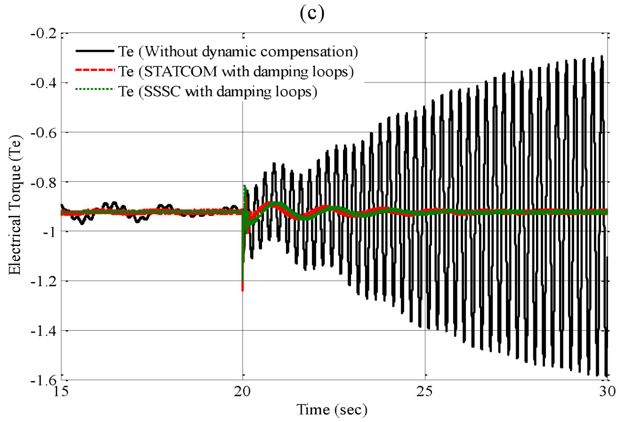


(d)

Fig.5 The SSR due to the variation of the capacitive series compensation of the series compensated Wind Park and performance.

loops. The proposed system observes the SSR resonance due to torsional modes which tends to instability as shown in Fig. 5 (a) for the generator speed. The system comprising either STATCOM or SSSC show superior performance for mitigating sub-synchronous resonance, subsequent damping power system oscillations. The STATCOM and SSSC associated with auxiliary damping control loops improve the damping of torsional modes. The controllers minimize the peaks of the negative torques and secure the system stability Fig. 5 (a, b, c and d).

VI. DYNAMIC PERFORMNACE OF DAMPING CONTROLLERS

The damping performance of the SSSC and STATCOM control algorithms are evaluated in response to system disturbances such as Torque excursion and three phase to ground faults at the terminal of the wind park which is interconnected at level of SCR =2.

A) Torque Excursion

In this case the damping performances of the SSSC and STATCOM are tested in response to a mechanical torque reduction of 0.5 pu for a period of 1 sec. The damping of the SSSC and STATCOM in mitigating torsional interaction is investigated and the following signals are examined:

- Generator rotor speed (ω_r);
- Mechanical torque between Mass 1 and Mass 2 (T_{1-2});
- Delta mechanical speed
- Electrical Torque (T_e)

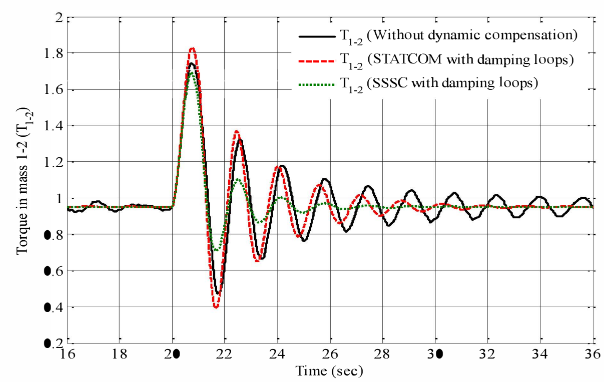


Fig.6 The mechanical torque between Mass1 and Mass 2.

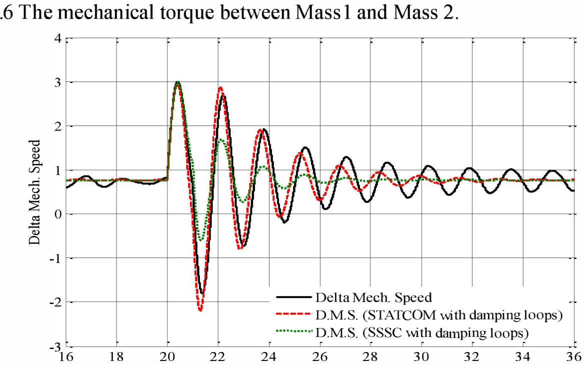


Fig.7 The delta mechanical speed for the system without dynamic compensation, with STATCOM and with SSSC.

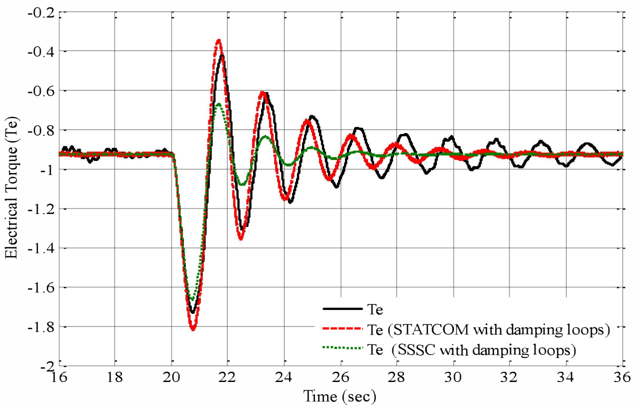
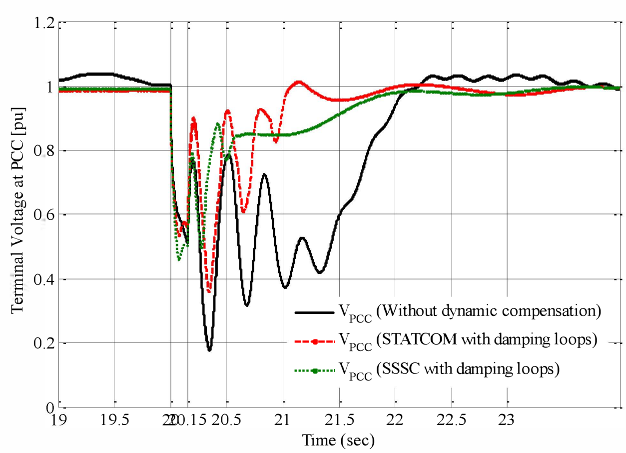


Fig.8 The electrical torque for the single unit of SEIG based wind turbine.

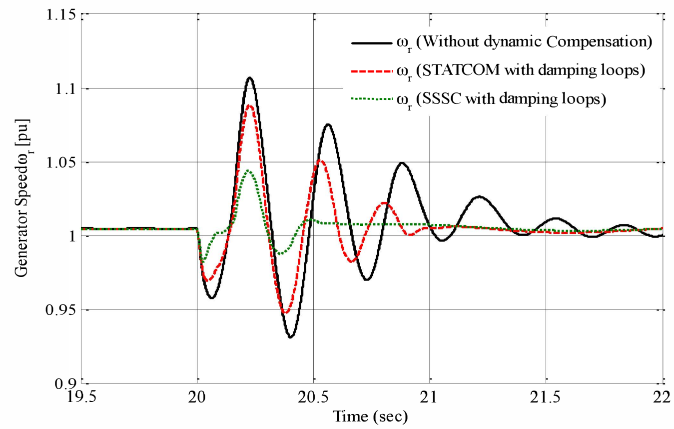
The examined signals are plotted for the system without any FACTS devices, with STATCOM and with SSSC associated with the damping control loops. Even though the STATCOM based voltage control associated with damping control loops improves the damping of the mechanical torque between Mass 1 and Mass2, the SSSC associated with damping control loops provides significant faster damping and reduction of the sharp negative torque as shown in Figs. 6, 7 and 8.

B) Performance Following Disturbances

The system of Fig. 1 is now subjected to a 3Φ fault at the terminal of the wind park at instant t = 20 sec. for a duration of 150 ms. The STATCOM is adjusted to regulate the terminal bus voltage to 1 pu and the reference injected series quadrature voltage set point of the SSSC is adjusted. The simulation results are compared with the results obtained from the base case without installing the dynamic shunt or series compensation. The transient responses of the control algorithms associated with damping control loops are evaluated and tested in response to short circuits at SCR=2. The simulation results illustrate the superior performance of the SSSC for damping the generator speed, and much faster voltage recovery compared with the STATCOM as shown in Fig. 9 (a, b), respectively. The SEIG measurement signals demonstrate the effectiveness for damping generator speed in



(a)



(b)

Fig.9 The measurement signal for the generator speed voltage at the PCC.

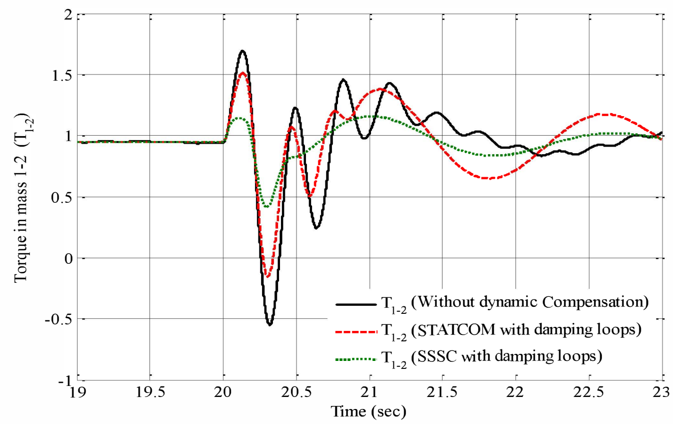


Fig.10 The measured torque in mass 1-2.

response to the short circuits and significantly reduce the sharp negative torque as shown in Fig.10. Therefore, the transient stability margin is significantly improved for the system installing SSSC.

VII. TRANSIENT STABILITY MARGIN ENHANCEMENT

To evaluate the transient stability margin of the generator. The digital simulation is carried out in order to demonstrate the capability of the FACTS compensator devices to increase the global transient stability margin of the proposed power system. Therefore, the 3Φ fault is simulated on the power system and is applied at the terminal of wind park for the system shown in Figs.2 (a, b). The transient response is evaluated while both the STATCOM and SSSC are alternatively connected. It is essential to observe and compare the most relevant variables of the transient stability such as phase angle of the machine, rotor speed, terminal voltage and the reactive power. Avery common indicator of the transient stability of SEIG is the critical clearing time (CCT) of fault, which is defined as the maximum duration of the fault which will not lead to lose the stability of the induction generator. The transient analysis is performed for a weak power system connection of SCR =2. The three phase to ground faults is applied at the terminal of wind park at instant t=20 sec. with varying the duration time to investigate the effectiveness of the FACTS devices for improving the transient stability margin. The simulation results are concluded in Table 1.

Table 1: The maximum critical clearing time (MCCT) of the applied fault for the wind power plant.

SCR	Without Compensation	STATCOM	SSSC	SSSC with FRT option
2	0.2 s	0.48 s	0.55 s	1.038 s
3	0.464s	0.725s	0.9 s	1.5 s
4	0.7 s	0.935 s	1.04 s	1.76 s
5	0.88 s	1.01 s	1.11 s	1.92 s
6	0.97 s	1.15 s	1.36 s	1.96 s

The SSSC with FRT capability demonstrates much higher maximum critical clearing time and critical speed. The SSSC is adopted to operate in FRT mode when the system voltage is below 0.5 pu and injects the maximum voltage compensation to compensate the power system. Furthermore, it provides the highest reference series injected quadrature voltage to restore the terminal voltage of the wind energy system. Hence, it significantly improves the transient stability margin for the system with SSSC compared with installing the STATCOM. This study provides a new approach of using SSSC for large series compensated wind parks and the possibility to improve the transient stability margin especially for a weak interconnected electric grid.

VIII. CONCLUSION

Two novel damping control schemes for the STATCOM and SSSC have been proposed, designed, analyzed and investigated in this paper. The simulation results demonstrate superior performance of the controllers for mitigating SSR due to the increase of the capacitive series compensation of the series compensated Wind Park. The damping torque analysis is used in the design of the damping control loops for both STATCOM and SSSC. Hence, it provides a net positive damping torque for torsional mode frequencies. Therefore, at any given oscillation frequency of the generator rotor, the electrical torque is in phase with rotor speed acting as damping torque. The SSSC demonstrated much higher performance for mitigating SSR, damping the torsional torque and power system oscillations. The SSSC significantly reduces the peak of the negative torque and secure higher stability margin in terms of the values of the maximum clearing time of the fault and critical rotor speed of the wind park induction generators. The simulation results provide a new approach of using SSSC for large series compensated wind parks which significantly improves the transient stability margin especially while operating with FRT capability.

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