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Dynamic Stabilization of Wind Farms Deploying Static Synchronous Series Compensator

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P A P E R I N F O

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A B S T R A C T

Encountering series-compensated transmission lines, sub-synchronous resonance (SSR) may strike the power system by jeopardizing its stability and mechanical facilities. This paper aims to verify the capability of static synchronous series compensator (SSSC) in mitigating the mechanical and electrical oscillations such as SSR in wind farm integrations. A wind turbine with a self–excited induction generator (SEIG) represents the wind farm and it is connected to the system through a transmission line compensated by a series capacitor. Both the induction–generator (IG) effect and torsional interaction (TI) on SSR occurrence are examined. Simulations are carried out using EMTDC/ PSCAD on the IEEE first SSR benchmark model along with a SEIG based wind turbine. Also a Fast Fourier Transform (FFT) analysis is performed to determine the dominant torsional mode existing in the turbine generator system. The SSSC impact on SSR mitigation is interrogated in various case studies. A SSSC with a simple power flow control in its base case is first considered. It is shown that the SSSC can damp the SSR even without any specific auxiliary controller. In the following the same SSSC is shown to effectively damp SSR when equipped with an auxiliary SSR damping (SSRD) controller.

1. INTRODUCTION

It is now well-recognized that the natural energy resources are getting to be insufficient for meeting human requirements. This awareness and the depletion of fossil fuel resources is the main motivation of all worldwide nations to commence benefitting from renewable energy resources such as wind or solar energies. The initial expansion of renewables proves that by the end of 2020, it has been anticipated that more than 10% of the energy requirements will be provided by the wind energy [1]-[2]. In this way, large wind turbines (WTs) are now being commercialized and in a wide penetration level, are included in the electric power generation facilities. In the sequel, the large amount of generated power by all thermal and wind power plants are transferred toward the consumption points through the long transmission lines. In order to increase the power transfer capability of a long transmission line, the series capacitive compensation is known as one of the most effective remedies in this regard [3]. Making benefit of power transfer capability increase, however, the power system intrinsic features accompanied by series compensation may result to occurring a harmful electromechanical phenomenon known as subsynchronous resonance (SSR). If this phenomenon is occurred in an unstable mode, it will result to electrical and mechanical instabilities in power system [4]-[7].

In the context of SSR prevention and attenuation, the flexible ac transmission systems (FACTS) are now being known as one of the most effective therapies to control and then suppress the SSR [8]-[16]. Quite few papers attempted the application of various FACTS devices to attenuate SSR. Static var compensator (SVC) along with thyristor-controlled series capacitor (TCSC) as the most initial families of the FACTS has been successfully deployed for SSR mitigation in series compensated transmission lines hosting wind power generation facilities [12], [13], and [17]. Also, considering a wind park integrated to the power system, authors in [18] implemented a control strategy based on a static synchronous compensator (STATCOM) intended for SSR alleviation, electromechanical oscillations fast attenuation, and also improving the transient stability margin. In the literature, some studies such as [19] also examined the static synchronous series compensator (SSSC) behavior in damping torsional oscillations. However, the mentioned studies lack a

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good conceptual introducing the SSR and frequency domain or Eigen value analysis for assessing the SSSC performance on SSR mitigation. By a technical content evaluation of the investigated literature, the well performance of versatile FACTS devices in SSR mitigation is obviously proved. This notification justifies further research studies on the performance of the other devices of FACTS family intended for SSR mitigation and dynamic stability enhancement.

This research assesses the contribution of SSSC to the SSR alleviation in wind farm connections by series-compensated lines. SSSC is rather cheaper FACTS devise among the most recent ones which justifies its real-world implementation and functionality evaluation in SSR damping process. A wind farm is consisted of numerous wind turbines; however, it is a common practice in dynamic studies to represent their dynamic behavior through an equal large WT in conjunction with a self-excited induction generator (SEIG). The IEEE first SSR benchmark model along with a wind farm is simulated using EMTDC/PSCAD. In order to perform an exact investigation on the issue, an FFT analysis is also carried out. The power sending end of the line is assumed to be equipped with a SSSC. Different control strategies are considered for the SSSC. First of all, the SSSC is applied in its base case. In this case, it is inferred that a simple SSSC is also able to alleviate SSR which validates its application. In the next case, the SSSC is equipped with a SSRD control loop. If SSRD control loop is tuned effectively, the SSSC will manifest a better damping performance than the former case. Hence, the application of an SSSC equipped with an SSRD controller is suggested as an effective countermeasure of SSR in future wind farm integrations.

The remainder of the paper is as follows. A brief introduction regarding the different types of SSR are summarized and categorized in Section 2. As well, Section 3 gathers the established power system configuration intended for investigating the SSR phenomena. Section 4 briefly demonstrates the occurrence circumstances of SSR in a wind farm connection. The fundamentals of SSSC and its associated control strategies for SSR mitigation are included effectively in Section 5 based on which the performance of SSSC in SSR suppression is numerically assessed in Section 6 . As an ending point, the concluding remarks are provided in Section 7.

2. REVIEW OF SUBSYNCHRONOUS RESONANCE PHENOMENA

A brief introduction about the SSR phenomena and its governing circumstances is presented herein [4]-[5]. Figure 1. demonstrates the generic equivalent circuit of a SEIG. As it is obviously seen, the series capacitive compensation of the transmission line results in subsynchronous currents with electrical frequency of f_e as stated in (1). These subsynchronous currents will be interacted in the generator which will result to the mechanical torque variations.

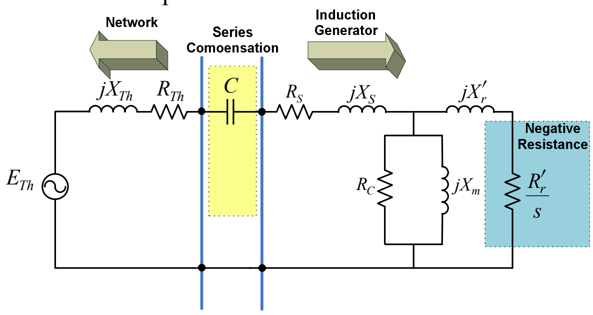


Figure 1. Equivalent circuit of a wind driven induction generator integrated to the main grid.

$$f_e = f_0\sqrt{\frac{X_C}{X_{L(eq)}}} \quad (1)$$

Where, X_c represents the series capacitive reactance and $X_{L(eq)}$ demonstrates the summation of some reactances including that of the transmission line, generator, and transformer. Also, f_0 denotes the nominal frequency of the investigated power system. As mentioned earlier, the generated subsynchronous currents due to series resonance will definitely bring about the rotor torques at the complementary frequencies stated in (2).

$$f_r = f_0 - f_e \quad (2)$$

As it can be easily inferred from (1), the electrical resonance frequencies, namely f_e in higher compensation levels would be less than the system nominal frequency. A rotating magnetic field with subsynchronous speeds will be a direct effect of the resonant currents taken by the electrical network. This is while contemplating the synchronous generators; the generator rotor is typically rotating at synchronous frequency. This observation will cause the synchronous machine to be seen as an IG. On the other hand, the wind farms, such as the case herein, inherently comprise SEIGs. At both of these cases, the slip of the machine which is calculated based on (3) would be negative. Hence, from the armature terminals viewpoint, the resistance of the rotor would be negative. This observation in turn could result in a self-excitation circumstance when the magnitude of the negative resistance goes beyond the sum of the armature and network resistance.

$$s = \frac{f_e - f_0}{f_e} \quad (3)$$

The other type of SSR being associated with the mechanical system's dynamics, referred as torsional interactions (TIs), may be triggered in the overall electrical-mechanical system. The excitation of TI is rather different than the IG effect. If the generator rotor shows torsional oscillations with the frequency f_m , , it will directly result in armature voltage components at the frequencies given in (4). If the subsynchronous frequency component $f_{e(ind)}$ approaches to any of the electric resonance frequency, f_e , the mutual excitation of the torsional oscillation and electrical resonance will be the system instability origin.

$$f_{e(ind)} = f_0 \pm f_m \quad (4)$$

3. INCROPORTING WIND FARM AND SSSC IN IEEE FIRST SSR BENCHMARK

IEEE first SSR benchmark has been elected as the basic test case and through some modifications such as the inclusion of SSSC and wind farm is put under numeric explorations [4]. At the mentioned system, the wind farm is typically represented by a number of coherent IGs each of 1000 HP (0.746 MW) power nameplate which is a general practice in dynamic assessments of power system. As it can be seen form Figure 2. the established wind farm is integrated to the main bulk power system through a fixed series capacitive compensated transmission line. Based on the practical implementations such as [1] and [20], the output power of the wind farm may be even greater than 500 MW which depends on the installed capacity of WTs. Similar ratings values are assumed herein. Regarding the series capacitive compensation percentage of the transmission lines, it is commonly set at the maximum 65% of the line's reactance. However, herein, the series compensation level is raised to the values greater than 75% to effectively study the system performance and deeply dig its performance in a wide range of operating conditions. A two-mass torsional system is utilized to represent the mechanical system of the wind turbine. One mass corresponds to the wind turbine system and the other one represents the set of IGs. The nominal values are including the rated voltage of 539 kV and frequency of 60Hz. To provide an effective reactive power support at the IG terminal, a fixed shunt capacitor of 2000 μF is installed at the generator terminal. Regarding the complete electrical and mechanical data for the system, Appendix A provides the required data in detail. Also, the system is integrated with a SSSC which can provide numerous steady-state or transients control options. It is worthy to note that in the investigated system, the SSSC is mainly considered as a device mainly controlled for SSR suppresion and its steady state performance has been disregarded.

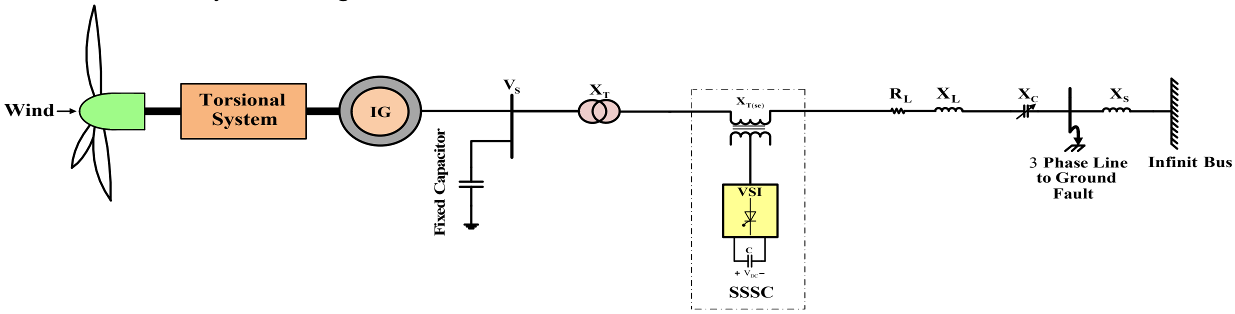


Figure 2. Wind farm comprises SSSC connected to a series compensated power system.

4. INVESTIGATING THE PROBABLE OCCURRENCE OF SSR IN WIND FARMS

In the literature, there are some recent studies published in the area of SSR phenomena in series-compensated wind farms in which both the IG effect and TI are deeply interrogated and figured our [13]-[14]. In this section, a brief review of concluding remarks and influences of different parameters on SSR happening in wind farm integration are provided.However, interested readers are referred to the mentioned studies to get access for more details and information. Base on the numerical analysis of the implemented system and removing the SSSC from the test system, it is deduced that the output power of a WF and the series compensation ratio are the main two factors resulting in SSR occurrence following a three phase fault. It is seen that in bulk power transmissions such as 500 MW and also higher capacitive compensations such as 85%, the unstable SSR makes the system to face with electromechanical instabilities.

To provide a good understanding of the issue regarding the dominant torsional mode for the unstable case namely, 85% series compensation and 500 MW power transfer, the generator rotor speed has been extracted and an FFT analysis is conducted among 3-7 sec with the time division of 1 sec. The FFT analysis helps the experts to have a good notion about the controller design for suppressing the SSR oscillations shown in Figure 3. This figure reveals that a dominant torsional mode at frequency 23 Hz is seen at the investigated case. This figure demonstrates that as the time passes, the excited mode grows in magnitude which jeopardizes the system unstable.

5. PROPOSED CONTROL SYSTEM OF SSSC FOR SSR ALLEVIATION

This section is devoted to explore the control capabilities of SSSC and extending its corresponding circuits functionality to result in an effective SSR damping. Two cases are designed and explored in the control process of the SSSC.

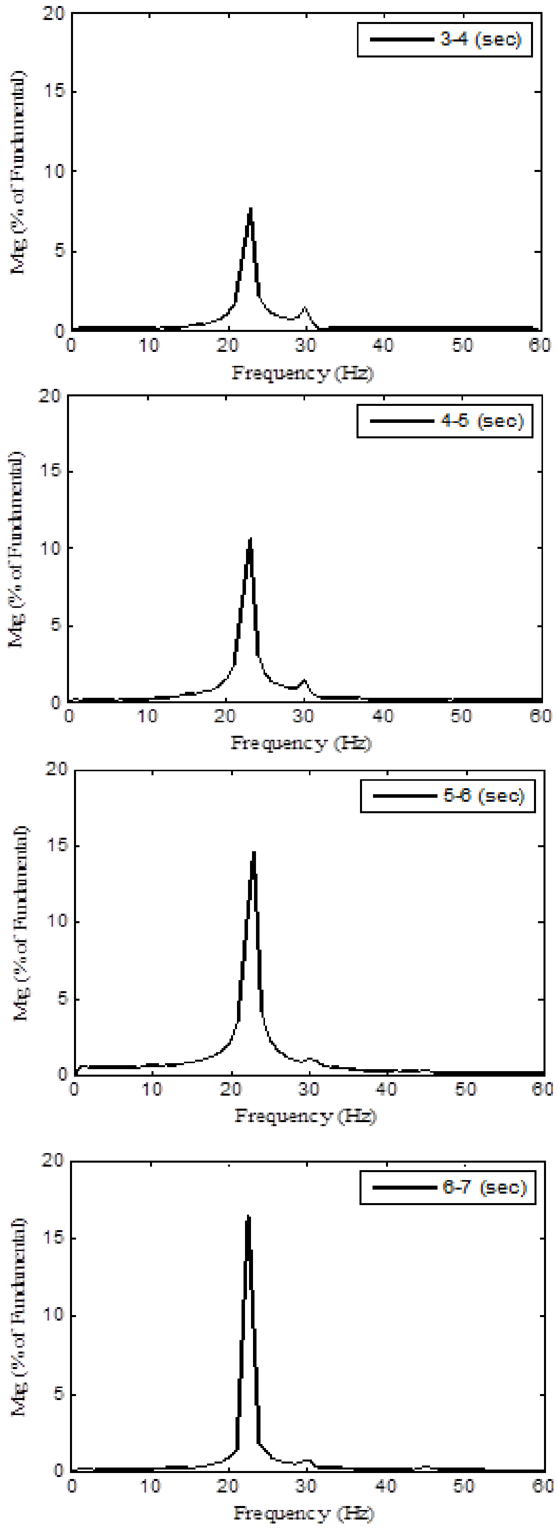


Figure 3. FFT analysis on generator rotor speed (non-FACTS power system).

The first one is referred as the *"base case"* in which the SSSC is mainly corresponding to the power flow adjustment. The second one is identified as "with SSRD controller" in which the main objective is to restrain the frequency deviations limited.

As Figure 4. demonstrates, the structure of SSSC as one of the famous FACTS controller is mainly composed of three-phase voltage source converter (VSC), an interfacing DC capacitor and transformer. As well, a filtering stage is commonly included at the output of the VSC which is mainly included for voltage harmonic alleviation due to switching actions [11].

Indeed, the series insertion of SSSC makes it possible to envisage it as an advanced type of controlled series compensation approach. However, its successful performance in controlling the power flows or implementing some ancillary duties such as oscillations damping necessitates effective and precise controller designs. Figure 4. rather than the series schematic of SSSC, also manifests its main control system structure. In the control process, V_{qref} denotes the magnitude of the injected voltage which determines the required reactive power exchange in series compensation. To make it more clear, the series voltage injection by SSSC makes it feasible to implement a virtual variable reactance X_q which results in effective controlling the total line reactance. This technical achievement makes SSSC apt for effective power flow control, voltage control, oscillation damping and etc.

Maintaining the DC bus voltage in a constant value is prerequisite constraint for successful operation of SSSC which is obviated by the illustrated control system as well. To this end, an error amplifying control box is sensibly included in the system in which the suitable control signal is produced by comparing the reference value with that of the measured values of DC bus voltage.

It is clear that the basic control circuit of SSSC intended for power flow control, addressed in Figure 4. does not demonstrate a good damping performance for oscillations curbing. This shortcoming can be improved by a proper modulation of SSSC main control parameters. Hence, coordinated tuning of SSSC with SSRD controller is proposed to provide an effective damping of SSR. In this regard, an auxiliary damping controller as in Figure 5. is thought of which consists of a gain block, a washout circuit, and a phase compensator.

In this controller, $\Delta\omega$ represents the angular frequency difference utilized as the feedback input signal in control process based on its direct influence from the machine performance following the SSR happening. This is while, the other measurable signals including current or power flows, voltage magnitude, or machine frequency can be also selected [11], [21].

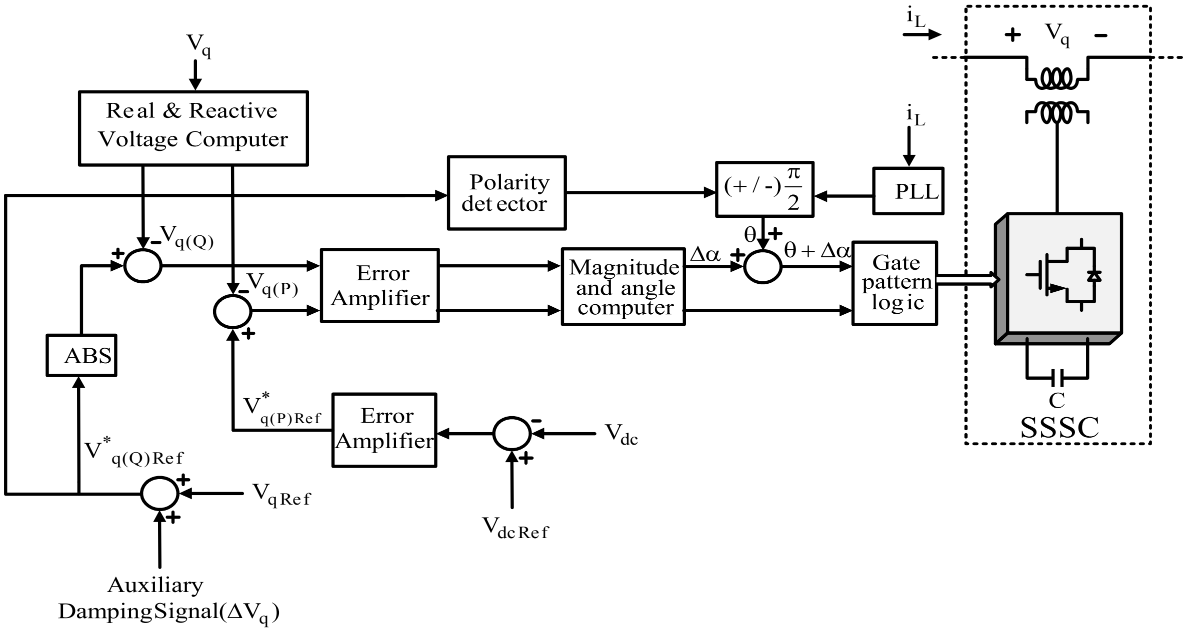
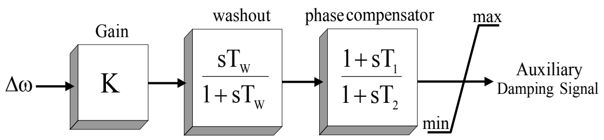


Figure 4. The SSSC main control system.

Introducing the auxiliary controller in Figure 5. a supplementary control signal is suitably produced and added to the main control circuit in Figure 4. for effective SSR alleviation. This auxiliary signal is used to modulate the series injected voltage by which it leads to additional electrical torque in phase with the speed deviation [22]. To achieve an appropriate damping ratio, the gain setting for SSRD is implemented effectively, while a washout filtering stage is included in the system to prevent the auxiliary controller from steady state interacting with main controller. Because of the power system non-linearity in the time-domain simulations, the trial-and-error approach is deployed for determination of the different parameters of SSRD controller.



ure 5. Auxiliary SSRD controller structure.

6. TIME-DOMAIN SSR DAMPING ENHANCEMENT SERIES-COMPENSATED WIND FARM INTEGRATED WITH SSSC

The unstable features of SSR in series-compensated transmission lines hosting wind farm integrations is thoroughly discussed in the preceding sections and effective control strategies are designed for steady state operations and SSR damping by SSSC. Herein, some time domain analysis are included to evaluate the proposed SSSC-based SSR damping.

To analyze the performance of the SSSC in IG effect SSR attenuation, the output power of the wind farm is set as high value of 500 MW which is integrated with the bulk power system in a series compensated line with 85% of series capacitive reimbursement. Different cases are considered to interrogate the SSSC performance in different control strategies namely in the power system *"Without SSSC"*, *"With SSSC"*, and *"SSSC equipped with a SSRD controller"*. The originated oscillations in generator rotor speed are demonstrated in Figure 6. This figure reveals that the SSSC itself has the ability to suppress the IG effect in contrast with the instability without SSSC. However, it is remarkable that the damping performance is noticeably poor. But, it can be easily deduced that the case in which SSSC is equipped with SSRD controller have better damping performance. It was discussed that the auxiliary damping signal is superimposed on the series injected voltage reference, V_{qref} through a *max* and *min* limiting values equal to 0.05 and -0.05 (pu), respectively. The auxiliary damping signal produced by the corresponding SSRD controller is shown in Figure 7.

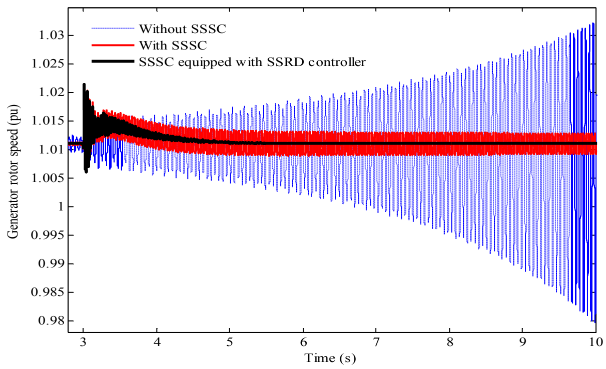


Figure 6. Mitigating IG effect, rotor speed behavior.

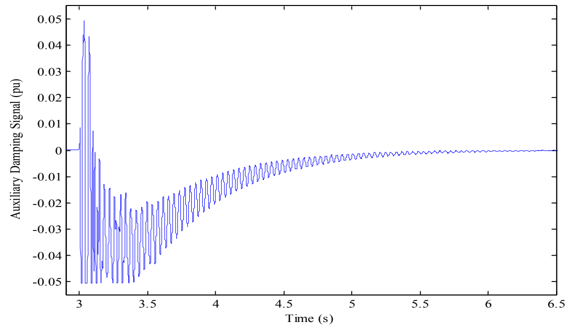
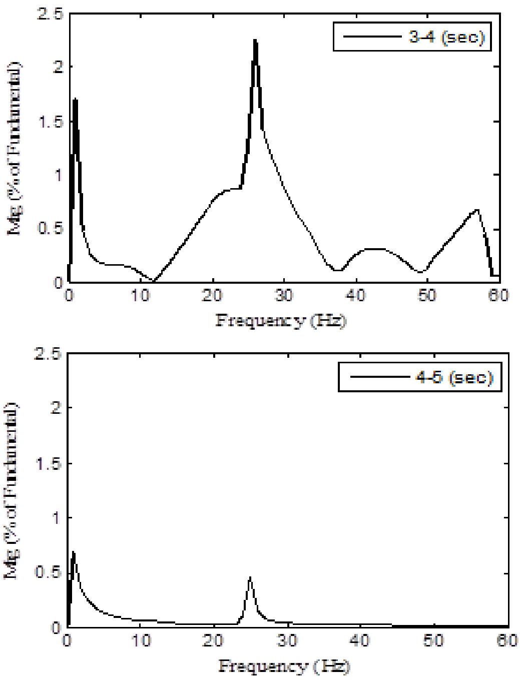


Figure 7. Auxiliary signal added to the voltage reference value.

Figure 8. exhibits the FFT analysis on the generator rotor speed when the SSSC is equipped with SSRD controller. It can be seen that as the time passes, the magnitude of the excited mode decreases and becomes smaller than the former section which ensures the stability of the system.

In regard to evaluating the dynamic response of control strategies, versatile simulation studies are considered to assess their performance in SSR mitigation. To this end, the generator rotor speed is extracted to investigate the settling time *(t_s)* index of oscillations, defined as the time required for getting constant or staying within a certain acceptable range, herein 2% of steady state value. This index determined a greater value in order of 85 sec in the case where only the SSSC is integrated with power system in its basic structure.

This is while the benchmark itself, without SSSC, will be unstable after the fault occurrence. On the other hand, the settling index is obtained as 2.2 sec when SSRD controller is supplemented on the control loop of SSSC.



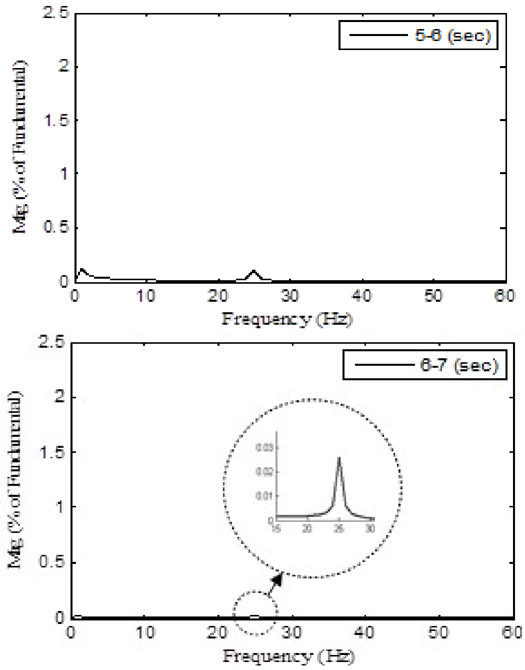


Figure 8. FFT analysis on generator rotor speed (SSSC equipped with SSRD controller).

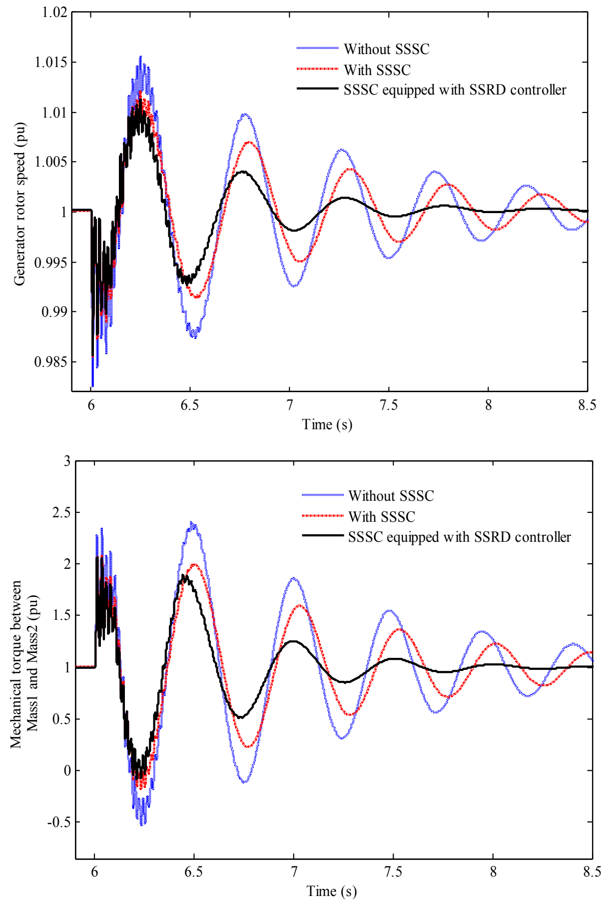


Figure 9. TIs mitigation (a) generator rotor speed (b) mechanical torque in multimass system.

Considering the TI, the performance of SSSC is investigated considering the working point of 50 MW output power by WF and 85% series compensation. In a same approach to the preceding section, different cases are considered to interrogate the performance of SSSC in different control strategies namely the power system *"Without SSSC"*, *"With SSSC"*,and *"SSSC equipped with a SSRD controller"*.Figure 9. displays the simulation results obtained for this case. The dominant excited mode reflects a frequency about 2.08 Hz which characterizes with a poor damping performance. Also this figure exhibits that the SSSC auxiliary damping controller provides an effective damping of these sorts of oscillations.

7. CONCLUDING REMARKS

This paper intended to verify the capability of SSSC to improve the dynamic performance of the series compensated transmission lines hosting renewable WFs. As the SSSC leads to justifiable costs for real-world implementations, the notion of SSSC for SSR damping was recognized as the research importance herein. Two major factors comprising output power of a WF and the series capacitive compensation level are elaborated as the most effective origins in unstable SSR happenings. It was found that for the 85% series compensation with 500 MW power transfer, there is a dominant mode with the corresponding frequency around 23 Hz which makes the system unstable. The simulation results demonstrate that a SSSC even with a simple voltage regulator is apt to mitigate the SSR unstable behavior. However, it was shown that although, utilizing SSSC in the transmission lines can lead to versatile steady-state operating merits, it also can be deployed for auxiliary tasks by including supplemental controllers. Hence, an SSRD controller is successfully designed and superimposed on the main control process of the SSSC by which, the superior damping of IG effect and TIs is achieved. The well performance of the SSRD controller is also certified by the FFT analysis which demonstrated the good damping performance of SSR oscillations in a WF including SSSC.

Appendix A

Self-Excited Double-Cage Induction Generator (SEIG) Data

Power rating = 1000 hp; V_{LL} = 26.0 kV; RS = 0.015 p.u.; X_{Ls} = 0.091 p.u; R_{r1} = 0.0507 p.u.; R_{r2} = 0.0095p.u.; X_{L1} = 0.0 p.u.; X_{L2} = 0.0539 p.u.; and X_{m12} = 0.1418.

Torsional System Data

Rated Power = 100MW; H_T = 12.5 p.u.; H_G = 0.5 p.u.; K_{GT} = 0.15 p.u.

Appendix B

Auxiliary SSR Damping Controllers Data

K = 100, K_W =1, T_W = 10, T_1 = 0.01, T_2 = 0.001

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