

Mitigation of SSR with STATCOM using Subsynchronous Damping Controller on Series-Compensated Transmission Line

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Abstract

Objective: The phenomenon of Sub Synchronous Resonance (SSR) on series-compensated long transmission line with steam turbine generator results into adverse oscillations. Therefore, occurrence of SSR should be reduced to the lowest possible level. **Method/Analysis:** In this paper, the use of STATCOM and subsynchronous damping controller (SSDC) is proposed to alleviate SSR. The rotor speed deviation of generator is being captured and given to the STATCOM. The IEEE second benchmark model (IEEE SBM) on SSR is adopted to analyze and validate the proposed controller. For this, the controller is applied on STATCOM, which in turn is regulating the line. **Findings:** SSR generates due to the presence of frequency other than the nominal frequency in the system. By calculating frequency response and FFT analysis, the resonant frequency present in the system, is calculated. Then conventional STATCOM is applied, which shows that STATCOM with no auxiliary control is not capable of damping the SSR oscillations. But with auxiliary SSDC on same STATCOM, effectively mitigate the SSR. **Novelty/Improvement:** The SSR alleviation is done by conducting transient simulations using MATLAB environment on detailed three-phase model, which is non-linear in nature. Fast Fourier Transform (FFT) analysis is also performed to demonstrate the capability of proposed controller.

Keywords: Damping torque, FACTS, FFT, SSR, SSDC, STATCOM, Voltage Source Converter (VSC)

1. Introduction

The improvement in capability of transferring power in power networks is generally achieved by providing series compensation to the transmission line¹. However, the interactions between the turbine generators with this series-compensated line may cause Sub-Synchronous Resonance² which leads to adverse oscillations. Various techniques and devices are reported in literature to mitigate SSR damages from the system³.

Power System Stabilizers⁴ and FACTS (Flexible AC Transmission Systems)⁵⁻⁸ enhanced with auxiliary controller which provide damping signal are used as a best way to

mitigate SSR. So far, many countermeasures have been employed such as SSSC (Static Synchronous Series Compensator)⁶, TCSC (Thyristor-Controlled Series Compensation) and UPFC (Unified Power Flow Controller)⁷ from FACTS family to suppress SSR. SSR suppression in a wind system⁸ having series compensation was provided by using SVC (Static Var Compensator) and TCSC. Some other researchers also used techniques⁹ other than FACT devices like doubly fed induction generator, etc to damp SSR. However, among all the available FACT devices for SSR mitigation, STATCOM is the most adaptable one¹⁰.

The second generation FACT device STATCOM is a SVC based on VSC which generally used for reactive

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power support or voltage regulation but with the auxiliary controller, it is capable of SSR damping¹¹. A novel STATCOM controller¹² is used for SSR mitigation in a wind system integrated to the IEEE first benchmark model (FBM). Based on the theoretical and practical reports available in literature survey, various papers or work has been done for attenuating SSR on IEEE FBM by FACT devices but very few papers applied the FACT devices in attenuating SSR on IEEE SBM.

This paper contributes in the mitigation of SSR on IEEE SBM through STATCOM. However, the SSR characteristic of network is not significantly effected by STATCOM alone. Therefore, additional damping control loop has been considered to be connected. In this way, three different cases are considered for the system. First, the base case in which neither SSDC nor STATCOM is connected. Next, only the conventional control of STATCOM is connected to the base case. The latter case shows that only STATCOM is not capable to mitigate SSR and therefore a controller is needed. In the third case, auxiliary SSDC is integrated with the conventional control of the STATCOM. Accordingly, the capability of STATCOM with auxiliary SSDC improving the stability of power system is achieved.

2. Analysis of SSR

This section provides the SSR fundamental mathematics⁶. The system under consideration is IEEE SBM¹³⁻¹⁴ which consist of High Pressure (HP) and Low Pressure (LP) steam turbines, the Rotating Exciter (EX), the Generator (G) and infinite bus as shown in Figure 1. The generator of 600 MVA and 22 kV is connected to an infinite bus through transformer and compensated and uncompensated parallel transmission lines of impedances Z_{L1} and Z_{L2} respectively.

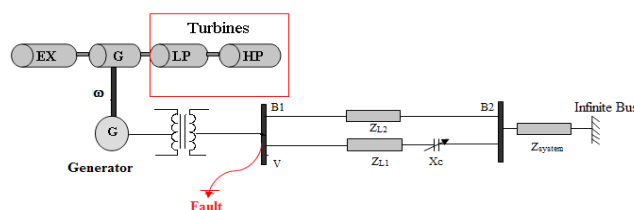


Figure 1. IEEE SBM model considered for analysis of SSR.

The system is analyzed in terms of the following assumptions and initial conditions.

- Zero per unit power is delivered to the transmission system by the generator.
- 0.55 per unit series compensation in the line is set by using capacitor.
- A fault of three phases to ground is generated at the generator terminal at 0.022 sec and cleared after 0.017sec.

The electrical frequency of subsynchronous currents in series-compensated line is

$$f_e = f_o \sqrt{\frac{X_C}{X_{Leq}}} \quad (1)$$

Where

f_o (nominal frequency) = 60Hz,

X_C = series capacitor reactance,

X_{Leq} = equivalent reactance of the generator, transformer and transmission line.

To test the above system about subsynchronous resonance, frequency response of the system was measured at generator terminals, showing that f_e of the system is near about 33Hz which is less than the nominal frequency (60Hz) Figure 2.

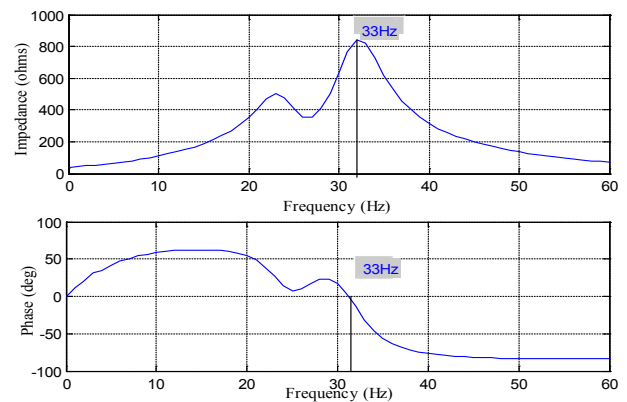


Figure 2. Frequency response of the 55% compensated transmission network.

Therefore, currents will generate, which is subsynchronous in nature at the frequency equal to $f_r = f_o - f_e$ in the rotor torque and leads to torque amplification Figure 3. The f_r should be equal to about 27Hz according to this equation and it can be clearly depicted from the that the maximum destabilization exists at around 27Hz. Figure 4 shows the generator's rotor speed deviation by FFT within time interval of 3 to 4 s.

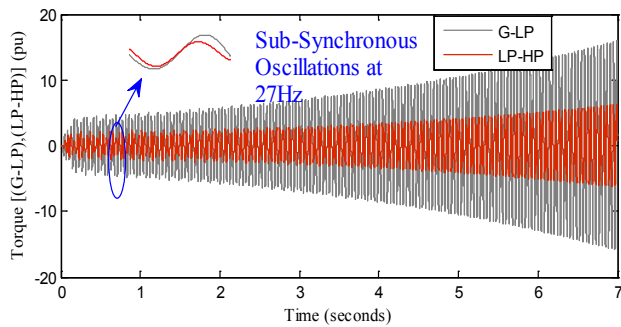


Figure 3. Simulation result for un-damped torque oscillations.

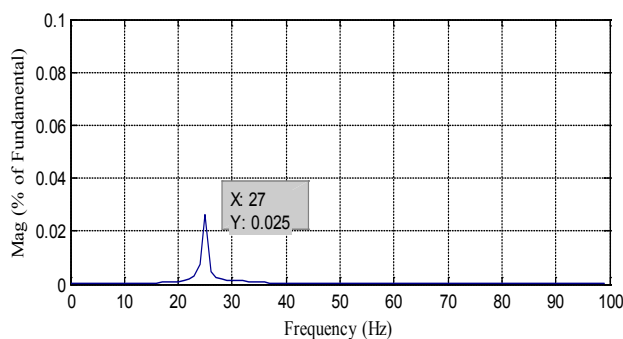


Figure 4. FFT plot of rotor speed deviation on generator shaft for the validation of resonant frequency.

3. Case Study

The IEEE SBM system is modified for further analysis with STATCOM and auxiliary SSDC as shown in Figure 5. The study is performed for the cases given:

Case A: without STATCOM.

Case B: with STATCOM only.

Case C: with both STATCOM and subsynchronous damping controller.

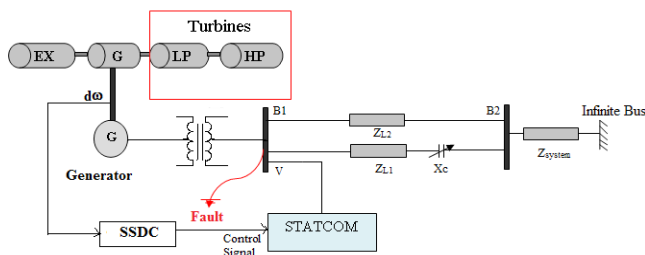


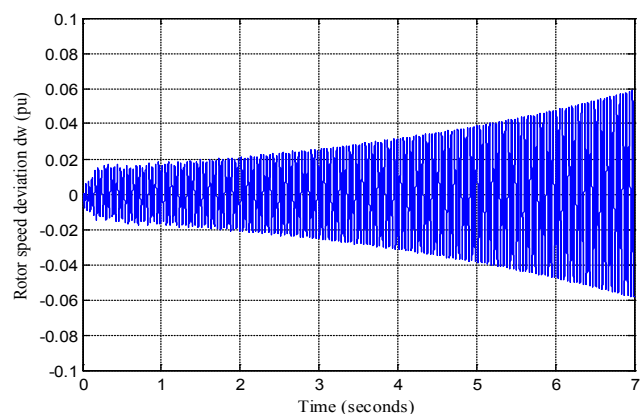
Figure 5. Modified IEEE SBM model aggregated with SSDC on STATCOM.

3.1 Case A. Without STATCOM

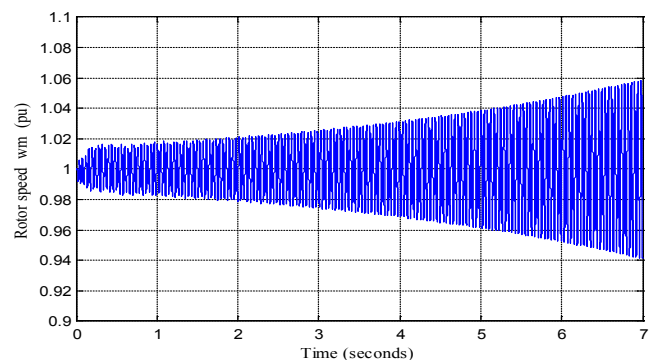
In the case A, the system analysis is performed for the original IEEE SBM system as given in Figure 1. The main objective is to understand the fact that, without any controller, adverse oscillation produces in the system which further damages the rotor.

3.1.1 Simulation Results for Case A

The results for the rotor speed deviations and the rotor speed are depicted in Figure 6a and 6b and the torque oscillations are given in Figure 3. It has been observed that the rotor speed deviation and torque oscillations are gradually increasing because of the presence of unstable mode in the system. Hence, system is completely unstable.



(a)



(b)

Figure 6. Results for case A, (a) Rotor speed deviation (b) Rotor speed.

3.1.2 FFT Analysis for Case A

The FFT plot for torque oscillations and rotor speed deviation is given for the interval of 0–4 s with the division of 1 s in Figure 7 and 8 respectively. From these figures, it can be clearly noted that, with the time, the magnitude of the unstable mode is increasing significantly. This increasing unstable mode is dangerous for the system. Hence, there is need of some controller for the mitigation of this oscillatory response from the system.

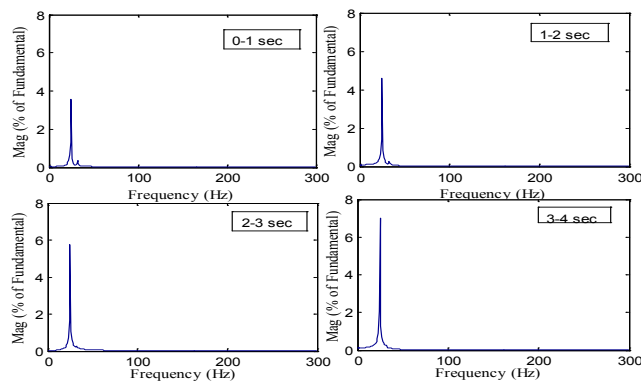


Figure 7. FFT analysis for case A on undamped torque oscillations.

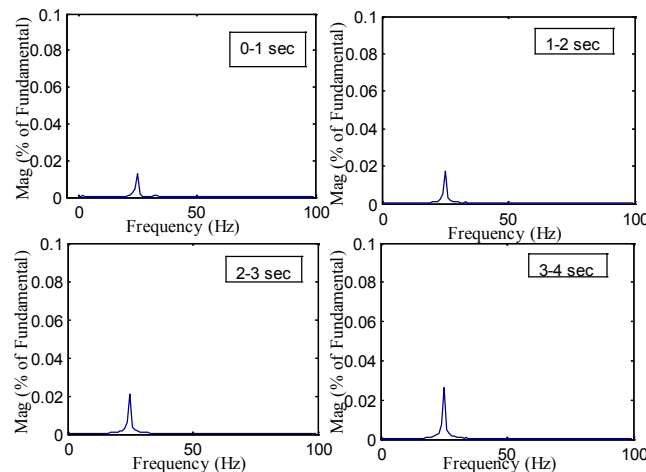


Figure 8. FFT analysis for case A on rotor speed deviation of generator.

3.2 Conventional STATCOM for Mitigation of SSR

This section provides the STATCOM control circuits used for the mitigation of SSR. Two cases (case B and

case C) are discussed, with the STATCOM only and with both STATCOM and SSDC. The algorithm of the controller used in the case B where only STATCOM is considered, corresponds to the voltage regulation¹⁵ while SSDC in case C add further objective for the mitigation of unstable mode.

3.2.1 Case B. With STATCOM Only

STATCOM is used as shunt compensation device, which is capable of generating and receiving reactive power. The main task of STATCOM is to maintain voltage, but some of the ancillary services are generally expected such as improvement in stability and SSR damping etc. The STATCOM consist of four 12-pulse, three-level, 48-pulse inverter in VSC and two 3000 μF capacitors in series which behave as a variable DC voltage source. The detailed mathematical modeling of a converter or STATCOM is provided in^{16–17} which is not repeated here. Figure 9 shows the conventional control system of STATCOM, which is considered here. It can be seen that control system requires four inputs including bus reference voltage V_{ref} , converter current I_s , ac system bus voltage V and capacitor dc voltage V_{dc} . The control signal is zero in this case. The reactive component of the output current I_Q is extracted and compared to the produced reactive current reference, I_{Qref} . Ultimately the obtained error signal is utilized to provide angle γ , which keeps the phase shift between the ac system voltage and converter's output voltage as per the requirement. Similarly, phase-locked loop (PLL) determines basic synchronizing angle θ by using V as input. The output θ and γ generates firing pulses for the inverters from the firing pulse generator. To reduce non characteristic harmonics, DC balance regulator keeps the positive and negative voltages of the dc bus equal.

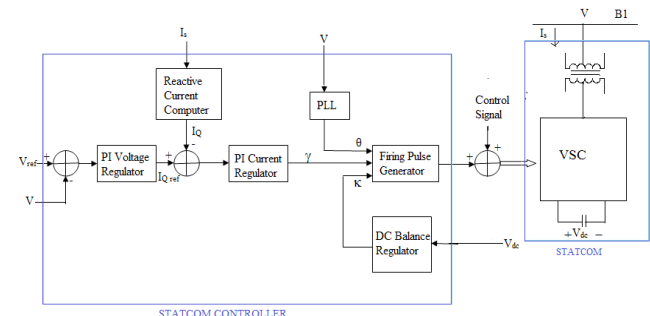


Figure 9. STATCOM & STATCOM controller structure.

3.2.1.1 Simulation result for the case B

Figure. 10 displays oscillations in torque between generator and LP turbine and LP and HP turbine for case designated above. This figure shows the capability of STATCOM in the mitigation of SSR. It is observed that only STATCOM is also capable of suppressing unstable mode or the torque amplification. However, the suppression or damping of oscillation is poor. This shows the need of control signal for the STATCOM to mitigate this unstable mode.

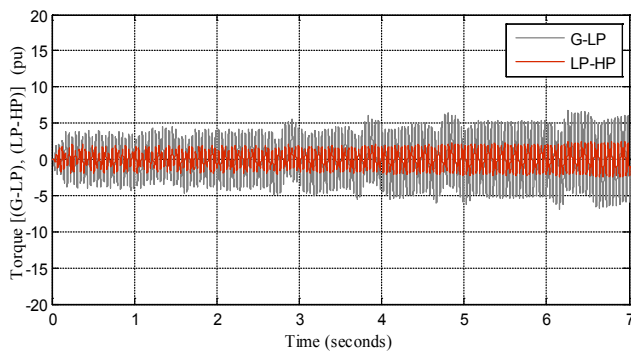


Figure 10. Result for case B, the torque oscillation between generator and LP turbine & between LP and HP turbine.

3.2.2 Case C. With both STATCOM and SSDC

The conventional application of STATCOM as given in previous case B, is not capable of providing the required damping of oscillations by itself, as the primary function of STATCOM is only voltage regulation of the system. Therefore, additional damping control loop is required for damping SSR. As frequency is key parameter for system stability. Hence, rotor speed deviation and rotor speed are generally used as controller feedback signals¹². The input signal to mitigate SSR, used here is rotor speed deviations, dw (p.u.). A subsynchronous damping controller (SSDC) is implemented which is shown in Figure 11 to provide control signal to the conventional controller of STATCOM (Figure 9). The gain block, low band filter, medium band filter and high band filter are the building blocks of SSDC. The frequency response of all the filters of SSDC is given in Figure 12.

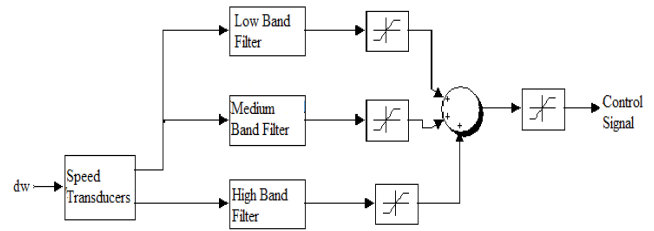


Figure 11. SSDC block diagram for STATCOM.

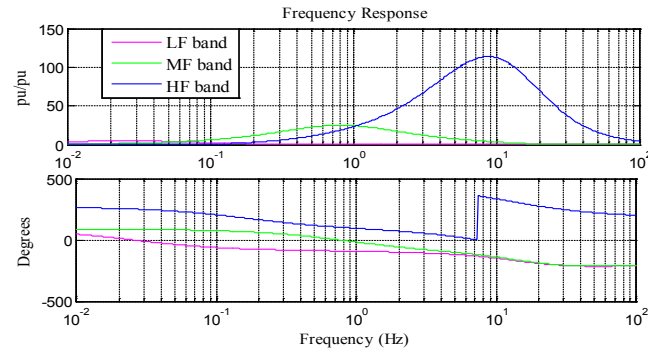


Figure 12. Frequency response of the different filters of SSDC.

Here, hit and trial method is used for the tuning of different parameters of SSDC. The damping loop utilizes the time integral of absolute value of the rotor speed deviations¹⁴, which is set by an objective function:

$$I = \int_{t=0}^{t=t_1} (|dw|) t dt \quad (2)$$

Where dw stands for rotor speed deviation and t_1 stands for simulation time. The objective function is minimised in order to achieve better performance.

3.2.2.1 Simulation Results for the Case C

To better understand the capability of the SSDC controller towards damping, time domain simulations are carried out for third case. Figure. 13a, 13b and 13c b and c represents the torque oscillations, rotor speed deviation and rotor speed respectively. From these figures, it can be clearly observed that the subsynchronous oscillations are greatly reduced when SSDC operates and the system become stable.

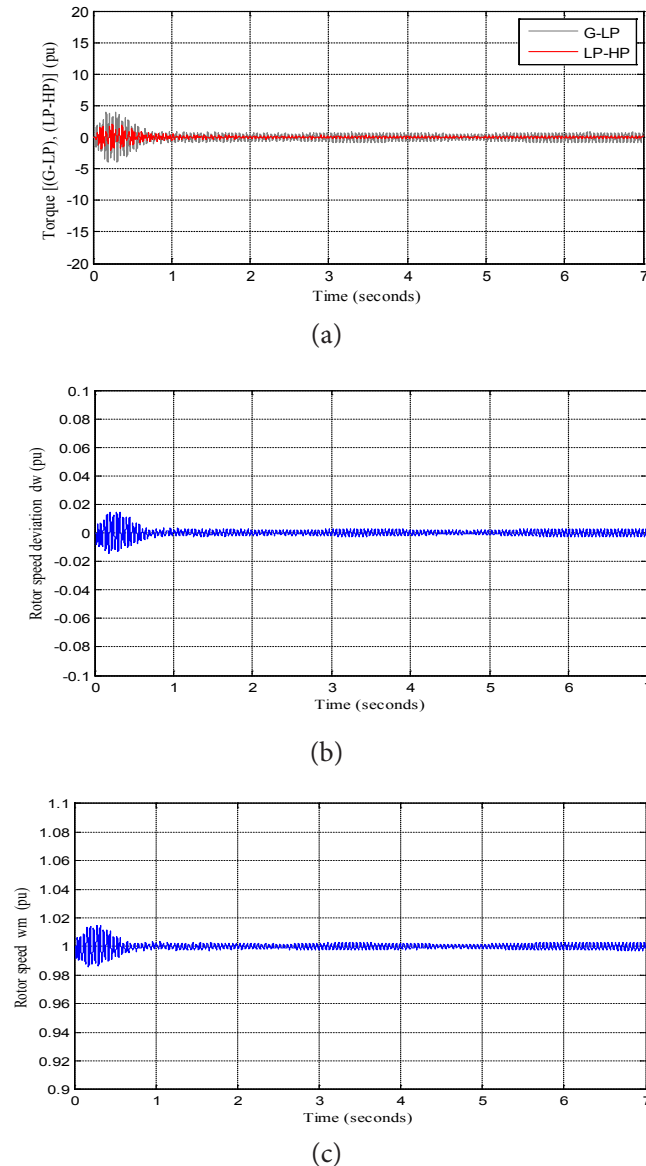


Figure 13. Results for case C, (a) the torque oscillation between generator and LP turbine and between LP and HP turbine (b) Rotor speed deviation (c) Rotor speed.

3.2.2.2 FFT Analysis for the Case C

The FFT analysis on the torque oscillations and on rotor speed deviations with SSDC on STATCOM is performed between 0-2 s shown in Figure 14 and 15 respectively. It has been observed that the unstable mode magnitude at 27 Hz frequency is decreasing with time and the controller is effective in mitigating SSR.

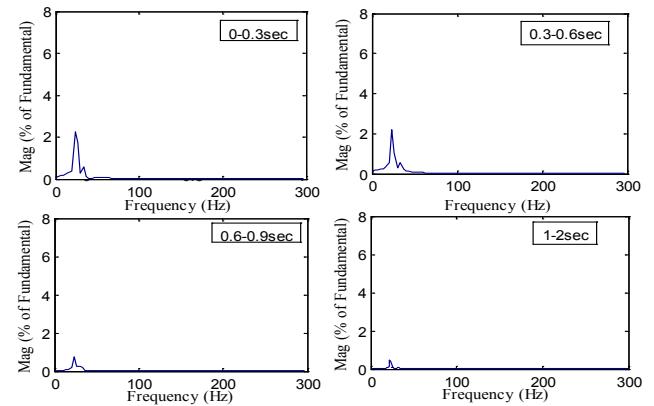


Figure 14. FFT analysis for case C on torque oscillation when both STATCOM and SSDC are integrated.

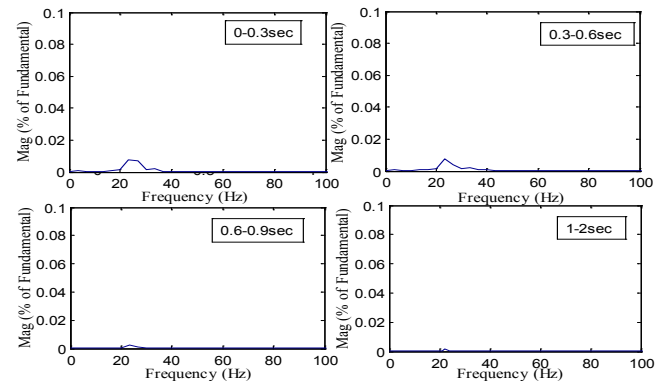


Figure 15. FFT analysis for case C on rotor speed deviation when both STATCOM and SSDC are integrated.

The comparison of FFT's given in Figure 7 and 14 reveals that the magnitude of torque oscillations is reducing effectively, by using SSDC with STATCOM. Similarly, with the case of rotor speed deviations which is given in Figure 8 and 15, its magnitude is also decreasing with the use of SSDC with STATCOM.

4. Conclusion

The SSR phenomenon has briefly been explained. The principle of mitigating the SSR by capturing rotor speed deviation has been applied on IEEE SBM. It is shown that without any device, destabilization occurs. With the use of STATCOM only, torque oscillations stabilize up to some extent. And, with STATCOM using SSDC, the torque and rotor speed deviation fall.

5. References

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