

Design of a Sub Synchronous Oscillation Condition Protection Relay Using Time Frequency Analysis

Aditi, Prashant Gawande, Sanjay Dambhare

Abstract- To boost a transmission line's capacity for power transfer, series compensation is required. However, when we use series compensation there is risk of sub-synchronous resonance (SSR). With the increasing penetration of renewable generation resources, power grids have become more susceptible to sub-synchronous resonance phenomena, especially to sub-synchronous control interaction, which produces fast-growing oscillations. This leads to mechanical fatigue of the shaft on which the turbine and generator are connected. Till now, different techniques have been proposed, like eigenvalue, frequency scan, and time domain simulation to study sub-synchronous resonance. In this paper we compare methods for detection of SSR. Proposed method is Stockwell transform. Proposed methods were compared with traditional method i.e., Fast Fourier Transform (FFT). The reliability and effectiveness of the method have been validated on IEEE first benchmark model. The model was simulated in ATP and all the important data were extracted for MATLAB. Both the methods were implemented in MATLAB. Based on S transform result a suitable relay is designed. The relay is successfully able to damp

Keywords— FFT, FACTS, HVDC, Prony analysis, Relay, Series compensation, SSR, Stockwell transform.

I. Introduction

Historically, several technologies have been used to increase the efficiency of power system operation. One such technology involves series-compensated lines, which are still widely used to increase the power transfer capability of transmission lines, as well as to improve system stability, voltage regulation, and load flow in parallel lines. Another example involves high-voltage direct-current lines, which not only provide lower losses than alternating-current lines when transmitting power over long distances, but also require one less conductor, improve system controllability, limit short circuit currents, and make asynchronous connections possible. The electrical system of these two technologies, however, may interact with the mechanical system of nearby

frequency, generating a phenomenon known as sub synchronous resonance. The two first known SSI events took place in Nevada, in 1970 and 1971, and were a mechanical-electrical phenomenon [1]. Among other events, the first purely electrical phenomenon occurred in a wind farm in Texas, in 2009 [2]. The incident involved interaction between doubly fed induction generators (DFIG) and a 50% series compensated line. This phenomenon was the first purely electrical type of sub-synchronous interaction and raised concerns all over the world as a fast-growing event that requires special monitoring, protection, and mitigation systems. These concerns also brought an increased need for special risk assessment tools. Eigenvalue analysis, frequency scanning methodology, and time domain analysis are just a few of the analytical techniques used to study SSR. The conventional linear, state-space form of system equations is used in eigenvalue analysis. It offers a useful tool for assessing system parameters for the research of SSR, specifically for effects of the torsional interaction and induction generator. In addition to resonant frequency, system damping can be calculated using the eigenvalues [3]. Studies of frequency scanning are suitable for systems with 100 to 150 buses. The frequency scanning methodology offers a very economical way to filter out system circumstances that could be dangerous from an SSR perspective. By seeing the system impedance from the neutral of the investigated generator, the frequency scan technique calculates the system impedance as a function of frequency. Reactance zero crossing events are the main focus of the analysis. If there is a crossover, the reactance curve's point where it crosses the frequency axis shows a zero reactance. At that point, the frequency is sub-synchronous. When the resistance curve at that frequency is negative, the grid is vulnerable to sub synchronous oscillations that are undamped and thus unstable [4]. In paper [5], wave parameter change during SS0 is used to detect SSR (wave period of positive and negative half cycle)

$$SS = \frac{N_p - N_s}{N_p + N_s}$$

In this detection method, each positive and negative half cycle wave is multiplied by a high-frequency carrier wave. With the help of a comparator number of counts is measured during each cycle. Here N_p and

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conventional turbine generators. may result in oscillations below These interactions the synchronous

N_s represent the number of counts in positive and negative cycle respectively. The percentage of modulation or sub-synchronous current present in the fundamental frequency wave determines how the half cycle period changes. When SS is constant but is alternatively positive and negative, the constant magnitude of SS indicates neither increasing nor decreasing SSR. When SS is increasing and is alternatively negative and positive, the rate of SS growth will show how soon intervention is required. When SS is positive and is decreasing. Actions for control are not required. The use of this technology distinguishes between SSR and DC offset current. In reference [6] there has been discussion about low frequency SSR detection methods. The SSR can be quickly detected with the proposed method within 0.15 seconds. To detect SSR of low frequency using the standard method, a long-time domain signal is required. After determining that a power grid is vulnerable to sub synchronous resonance, we must make sure that the necessary protection and mitigation measures are put in place to ensure the grid's reliable operation. This paper [7] GCSC, UPFC, and SSSC are used in series compensated ac systems to dampen torsional oscillations. One of the FACTS components that has been examined to dampen SSR is the thyristor-controlled series capacitor (TCSC). If TCSC modulates its firing angle in response to rotor angle fluctuation, SSR can be damped. SSR can be damped by the static synchronous series capacitor (SSSC). Compared to the TCSC and GCSC, the SSSC is a more adaptable device. However, it is far more expensive and complex. The unified power flow controller (UPFC) is another FACTS component that helps reduce SSR. It does have a series and shunt converter, though. Compared to the SSSC, it is more expensive and sophisticated. The paper [8] introduces a damping strategy that makes use of a FACTS controller like SVC. In the late 1960s, the Static VAR Compensator (SVC) was introduced. SVC is distinguished by its quick reaction time, dependability, affordability, and flexibility. Static, dynamic, and dynamic stabilizer filters were also covered in this paper. A dynamic stabilizer's advantage is that its performance is insensitive to changes in the system frequency or ambient temperature. Also, the requirements of maintenance are expected to be minimal. The drawback of a dynamic stabilizer is that it does not offer protection against transient torque issues because dampening is only provided in the presence of rotor oscillations. In this paper [9], in depth research is done on the impact of various excitation

system types, both with and without PSS, on the SSR damping properties. Excitation systems of the IEEE AC1A, AC2A, and ST1A varieties are used as examples. To determine the unit's sub synchronous electrical damping characteristics, frequency scanning is done in the sub-synchronous frequency band. The effects of excitation systems with moderate or high responsiveness on electrical damping are being looked at. Investigations are also conducted into how the PSS's settings affect electrical dampening. In paper [10], it is suggested to reduce stator sub synchronous current by using rotor side PR control. To reduce reactive power and DC-link voltage sub-synchronous oscillation, grid side PR control is introduced. A PR controller only operates at a single frequency, has a high gain at the resonant frequency, and is ineffective at other frequencies. As a result, it may directly regulate an AC component to reduce SSR Voltage and reactive power while tracking the current signal without experiencing steady-state inaccuracy. The paper discusses an appropriate supplemental excitation damping controller to prevent the excitation of the torsional modes [11]. Most of the countermeasures are made to ensure that sub synchronous oscillations are effectively dampened and protected from affecting the turbine-generator unit. A generation unit could occasionally be exposed to sub synchronous oscillations notwithstanding all safety measures. It's possible that the countermeasures in use are disabled or not functioning properly. It is not a risk that can be tolerated that such an unforeseeable incident may cause the generating unit to sustain long-lasting or intensifying sub synchronous oscillation. SSR relays are therefore typically placed to ensure that the unit life is protected even under extremely unlikely circumstances. The paper [12] introduces different types of protective relays for the mitigation of SSR.

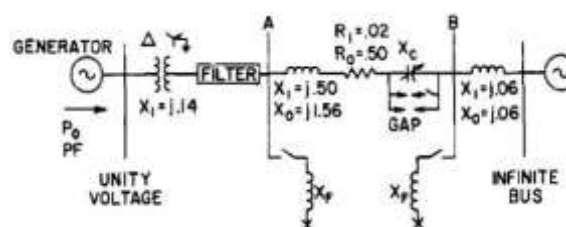


FIGURE 1 IEEE FIRST BENCHMARK MODEL

II. Test System

A single-line diagram of the IEEE first benchmark model is presented in Fig. 1. This system was proposed by IEEE sub-synchronous resonance task force group to study the SSR phenomena. The

parameters of single line diagram are expressed in per unit on the generator MVA rating of 892.5 MW and 60 Hz. The generator rotor consists of six masses. Given: $X_d = 1.79$, $X_d' = 1.69$, $X_d'' = 0.135$, $X_L = 0.13$, $X_q = 1.71$, $X_q' = .228$, $X_q'' = .200$, $T_{do}' = 4.3$ sec, $T_{do}'' = .032$ sec, $T_{qo}' = .85$ sec, $T_{qo}'' = .05$ sec

Mas s	H(sec)	Shaft	K(PU)	Pu torque/ rad
HP		0.09287		
	HP-IP		72,77	34.929
IP		0.155589		
	IP-LPA		13,168	52.038
LPA		0.858670		
	LPA-LPB		19,168	70.858
LPB		0.884125		
	LPB-GEN		26,713	
GEN		0.868495		
	GEN-EXC		1,064	2.822
EXC		0.034216		

In Fig 1 the generator-turbine shaft system consists of six masses. The six torsional masses represent the rotors of the generator, two low-pressure (LP) turbine sections, an intermediate-pressure (IP) turbine section, a high-pressure (HP) turbine section and exciter driven by the same shaft.

III. SSR Detection

In this paper Stockwell transform is proposed to detect SSR phenomena. The proposed methods are compared with conventional FFT result. Detail of the algorithm are covered in this section.

A. FFT Results

The FFT is utilized in a variety of applications, this transform enables the conversion of a value from the continuous time domain, for instance, into the continuous frequency domain, which contains both magnitude and phase information. A succession of subsequent discrete values must be recorded in the test equipment at regular intervals to digitally record a waveform. The data cannot be translated into the frequency domain using the usual Fourier transform since the time domain waveform is measured at time intervals. The Discrete Fourier Transform (DFT), an alternative to the Fourier transform, must be used. While the FT approach is useful for identifying the harmonic content of waveform, DFT performs well

for fundamental frequency, accurately identifying both the amplitude and frequency. When processing audio or video signals in the time and frequency domain, fast Fourier transform is more advantageous than discrete Fourier transform. A faster version of the Discrete Fourier Transform (DFT) is FFT. An n point Fourier transform is reduced to $\frac{n}{2} \log_2 n$ using FFT algorithm, which increase the speed of computation. The DFT Sequence U_n for $n=0, 1 \dots N-1$. Represented as

$$V_k = \sum_{n=0}^{N-1} U_n e^{-j2\pi k n / N}$$

Where $K=0, 1 \dots N-1$

Two-point FFT is utilized in this paper. As a result, we are only able to analyse waveforms of set lengths 512 points, 1024 points, 2048 points etc. The detail equations are covered in [13], [14]. Fig.2 shows torque between LPA-LPB turbine section and Fig.3. shows FFT result between LPA-LPB turbine section.

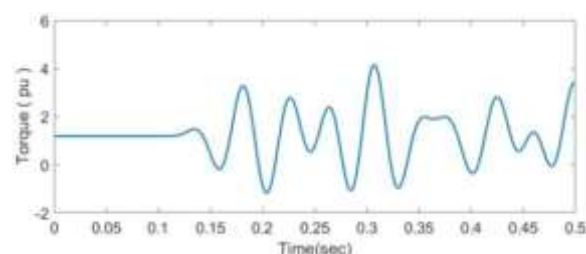


FIGURE 2 TORQUE BETWEEN LPA-LPB

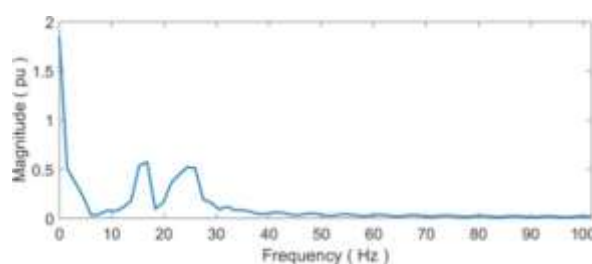


FIGURE 3 FFT RESULT BETWEEN LPA-LPB

B. Stockwell Transform

The Fourier transform is inappropriate for a wide range of practical applications because it cannot identify the time distribution of different frequencies even though the Fourier transform of the complete time series does contain information about the spectral components in time series. The accuracy of the Fourier Transform highly depends on the length of the input signal and it works best for stationary signals. To increase Fourier Transform's precision, we assume that some portion of the non-stationary

signal is stationary and take a Fourier Transform of each stationary part along the signal and add them up. This process is called Short Time Fourier Transform (STFT). The STFT is most often used. But the STFT cannot track the signal dynamics properly for nonstationary signal due to the limitations of fixed window width. The Stock well transform is one particular use of the STFT with a Gaussian window function. The S transform was proposed by Stock well and his co-workers in 1996. The frequency resolution of the S transform is determined by the size of the window in the time domain. By employing a bigger time window, the S transform can achieve a high resolution of frequency for lower frequency values. On the other hand, S transform can get a better resolution of time for higher frequency values with a shorter window. The STFT of a signal $v(t)$ is expressed as,

$$STFT(\tau, f) = \int_{-\infty}^{\infty} v(t)g(\tau - t)exp^{-j2\pi ft} dt$$

In above equation $g(t)$ represent window function. By replacing this with Gaussian function, equation becomes

$$STFT(\tau, f) = \int_{-\infty}^{\infty} v(t) \frac{|f|}{2\pi} e^{-\frac{(\tau-t)^2}{2}} exp^{-j2\pi ft} dt$$

STFT with Gaussian window function. If the window of S transform is wider in time domain, S transform can provide better frequency resolution for lower frequency. While the window is narrower, it can provide better time resolution for higher frequency. The Stock well transform $S(\tau, f)$ is used to breakdown these signals into a two-dimensional S matrix. The Each row in this matrix corresponds to a specific frequency, whereas each column of this matrix provides definite time. The components of the S matrix are complex magnitude values. Here $S(\tau, f_0)$ is one dimension function of time for constant frequency which shows change in magnitude and phase with respect to time, while a local spectrum $S(t_0, f)$ is a one-dimensional function of frequency f for a constant time t_0 that represents the different frequencies present at particular time t_0 . In contrast to the traditional Fourier transform which only provides the signal's frequency content, the S transform does a joint time frequency analysis, which is constituted of elements of short time Fourier transform and wavelet transform. The S transform has the advantage that it may be used to accurately estimate the instantaneous frequency for some higher-order signals. Fig. 4 S transform result between LPA-LPB.

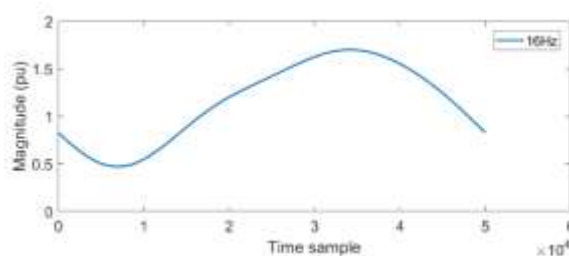


FIGURE 4 S TRANSFORM BETWEEN LPA-LPB

IV. Mitigation

Most of the countermeasures are made to ensure that sub synchronous oscillations are effectively dampen and protected from affecting the turbine-generator unit. Despite all precautions, generation unit might occasionally be exposed to sub-synchronous oscillations. It is possible that the countermeasures in use are disabled or not working properly. If such an unforeseen event occurs, it will create a growing oscillation in system that may cause severe damage to the machine shaft. Therefore, SSR relays are usually installed to guarantee that the unit life is protected even under conditions that are extremely rare. In this project, a time-based relay is proposed using S transform. S transform provides time frequency relationship. With the help of S transform result, which show magnitude of torque with respect to time a SSR relay is designed. An algorithm is developed in MATLAB for relay design. The input to this is S transform result of torque between two shafts. In the test system, which is used for the SSR study, three-phase fault is created at 0.1 seconds. After the fault, the magnitude of torque is increasing in nature. SSR relay was designed which keeps checking the magnitude of torque. When this magnitude increases beyond a threshold limit, it generates trip command to circuit breaker connected at the generator terminal. Breaker disconnects transmission line for 5 cycles. After 5 cycles, it re-closes the breaker and checks the magnitude of torque. The result of shaft torque between LPA-LPA without and with relay is shown in Fig.5. and Fig. 6 respectively.

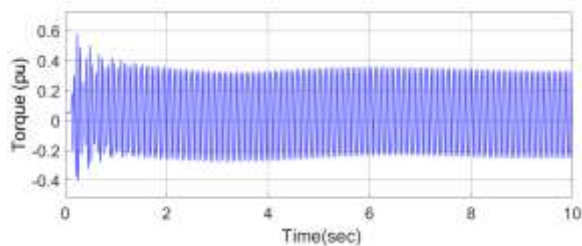


FIGURE 5 TORQUE BETWEEN LPA-LPB WITHOUT RELAY

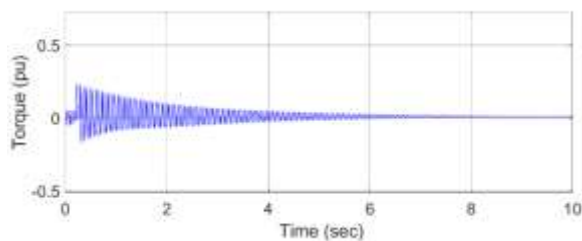


FIGURE 6 TORQUE BETWEEN LPA-LPB WITHOUT RELAY

V. Conclusion

This paper was focused on sub-synchronous resonance analysis and mitigation. This dissertation was mainly divided into two main parts: SSR detection and mitigation. Stockwell transform was proposed for the detection of SSR. Proposed methods were compared with conventional FFT results. In contrast to the Fourier transform which only provides the signal's frequency content, the S transform does a joint time-frequency analysis. Based on the S transform result, SSR relay was designed that was able to detect SSR within 0.04 sec. The relay was successfully able to damp SSR. This paper provides a fast method for identification of sub-synchronous resonance at an early stage.

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