A Comparison of Different Signal Selection Options and Signal Processing Techniques for Subsynchronous Resonance Detection

Yu Xia, Brian K. Johnson, Normann Fischer, Henian Xia

Abstract — **Detecting Subsynchronous Resonance (SSR) in power systems in an accurate and fast manner is a major challenge for steam turbine and doubly fed induction generator (DFIG) protection. Oscillations in DFIGs tend to grow much faster than in steam turbines, putting a tight speed requirement on the detection scheme. Possible input signals to use for SSR detection the include generator terminal voltages, generator currents, generator rotor speeds, or voltages across the series capacitor banks.**

With the powerful arithmetic capability brought by modern microprocessor relays, computation intensive signal processing techniques can be used to analyze the input signals. Traditionally, the Discrete Fourier Transform (DFT) is used to extract magnitude information of given signals. The DFT has a time averaging effect over the whole signal window and can not reveal the relationship between magnitude and time, which is a key characteristic for identifying whether a subsynchronous oscillation is growing. The Short Time Fourier Transform (STFT) and Wavelet Transform (WT) can each be used to decompose the signal in both the time and frequency domains. This paper shows analysis results using DFT, STFT and WT. The advantages and drawbacks of each technique are also reviewed. A real world SSR case is used to provide signals for this study.

Keywords: **SSR, DFIG, WT, STFT, DFT, Protective Relaying, Series Compensated Power Systems.**

I. BACKGROUND

Series capacitors provide an effective and economic way to increase power transfer capabilities of power transmission lines. However, when an electrical disturbance occurs in a power system with series capacitor compensated lines, electromechanical transients in the subsynchronous frequency range can be excited in the rotors of nearby rotating machines. For currents in this range, it looks like the rotor is spinning faster than the electromagnetic field produced by the armature currents and the rotor resistance to subsynchronous currents is negative as viewed from the stator terminals. When this negative resistance is larger than the sum of the stator resistance and network resistance, excessive voltages and currents in subsynchronous frequency range can be expected. This phenomenon is referred to as Induction Generator Effect (IGE), one form of SSR. Other forms of SSR include Subsynchronous Torque Interaction (SSTI), Subsynchronous Torque Amplification (SSTA) and Subsynchronous Control Interaction (SSCI) [1].

Because of the huge economic losses, it is not desirable to have the generator going through undamped subsynchronous oscillations. Over the years, especially during the 1970s and 80s, various detection schemes were developed as the last defense for the generators under SSR condition. For example, TEX relay, torsional motion relay and armature current relay.

Detecting SSR in an accurate and fast manner is a major challenge for steam turbine and doubly fed induction generator (DFIG) protection. Oscillations in DFIGs tend to grow much faster than in steam turbines, putting a tight speed requirement on the detection scheme. Possible input signals to use for SSR detection the include generator terminal voltages, generator currents, generator rotor speeds, or voltages across the series capacitor banks. Advantages and disadvantages of the use of these input signals are explored in this paper.

Computationally intensive signal processing techniques can be used to analyze the input signals in modern microprocessor relays. Traditionally, the Discrete Fourier Transform (DFT) is used to extract magnitude information of given signals. However, when using the DFT the analyzed signal frequencies are limited to integer multiples of the signal resolution frequency. Moreover, the DFT has a time averaging effect over the whole signal window and can not reveal the relationship between magnitude and time, which is a key characteristic for identifying whether a subsynchronous oscillation is growing. The Short Time Fourier Transform (STFT) and Wavelet Transform (WT) can each be used to decompose the signal in both the time and frequency domains. This paper shows analysis results using DFT, STFT and WT. The advantages and drawbacks of each technique are also reviewed. A real world SSR case is used to provide signals for this study.

In this paper, existing techniques for SSR detection are reviewed along with an analysis of signal selection options and different signal processing techniques. This can be used as a guideline to select signal inputs and signal processing tools for SSR detection.

Different signal inputs and signal processing tools are used for these schemes. Section II and III summarize the existing detection methods and signal input options. Existing methods

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either do time domain analysis or frequency domain analysis. Section IV introduces STFT and WT, which simultaneously decompose the signals in both time and frequency domain. The application results of applying different signal processing techniques are presented in section V, followed by conclusions in Section VI.

II. OVERVIEW OF EXISTING SSR DETECTION METHODS

TEX relay utilizes the phenomenon that negative sequence current calculation will produce nonzero output when the incoming signal is in the subsynchronous frequency range even if the signal is in subsynchronous positive sequence.

The torsional motion relay, developed in the late 1970s, uses a toothed wheel and speed transducer to monitor the speed of the shaft. The output of the speed transducer is a DC voltage as well as an AC voltage whose magnitude and frequency is dependent on the magnitude and frequency of the shaft oscillation. This voltage is processed by a wide band pass filter to retrieve the part of the signal in subsynchronous frequency range. The filtered signal is then used to detect SSO situations.

An armature current relay detects subsynchronous frequency range currents and determines if these currents represent a potential risk of damage to the turbine generator. The block diagram of the input signal extraction for this relay is shown in Figure 1:

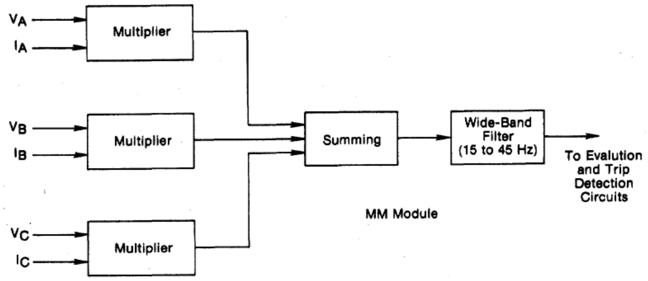

Fig. 1 Armature current relay subsynchronous current extraction [1]

The static relays described above were developed as a compromise between performance and cost. The filters used in these relays have a long time delay, which can be as long as 500ms [1].

Several SSR detection algorithms were developed on microprocessor relays as well. One method assumes that the signal in subsynchronous frequency range is superimposed on the fundamental frequency component. Modulation of the 60Hz voltage wave by subsynchronous current creates short and long half cycles in the voltage wave both in amplitude and frequency. Therefore, the method detects subsynchronous resonance by determining changes in the wave parameters of successive half cycles of the voltage wave [2].

Another method creates a demodulated signal of voltage by adding the minimum value of the negative half cycle of the voltage waveform to the maximum value of the positive half cycle of the voltage waveform for time intervals having a signal length T. Then a root mean square value for the demodulated signal of voltage is calculated and compared with the value of another constant parameter designated by the user. When the value is smaller than the setting, it indicates that there is no subsynchronous resonance, and vice versa if there is [3]. However, the theoretical basis for this algorithm was not explained.

Another microprocessor based relay measures voltages and currents in the range of 5-40Hz. The algorithm uses a 1 sec signal window and based on the Fourier analysis results, calculates the ratio of subsynchronous current magnitude to nominal CT current magnitude as well as the ratio to fundamental current magnitude [4].

Table 1: Signals, extracted signatures and tools used for SSR detection in existing relay types

Relay	Signal input and processing technique
TEX relay	Armature current, based on which negative sequence current is calculated.
Torsional Motion Relay	Shaft speed, processed by band pass filters to retrieve speed information at particular frequencies.
Armature Current Relay	Armature current, modulated by voltages at nominal frequency and then processed by band pass filters.
Southern California Edison Company patent	Generator terminal voltage. Wave parameters of successive half cycles are analyzed. It is an exclusive time domain analysis.
ABB Research Ltd. patent	Generator terminal voltage, demodulated by adding the minimum value of the negative half cycle to the maximum value of the positive half cycle.
ERLPhase Power Technologies algorithm	Generator terminal voltages and currents. Frequency spectrum analysis is done to compare subsynchronous frequency component with fundamental component.

III. COMPARISON OF POSSIBLE INPUT SIGNALS

Several signal inputs or combinations of these inputs can be used to perform SSR detection. Mechanical signals include the speed of the different masses of the shaft. Electrical signals include the terminal voltages and currents, multiplication of voltages and currents, negative sequence current or voltages over the capacitor banks.

For subsynchronous frequency currents components, the negative sequence current calculation will produce non-zero values. While it is a simple approach, as the subsynchronous frequency increases and approaches nominal frequency, the negative sequence current magnitude decreases and the relay sensitivity deteriorates. This is opposite to the required sensitivity under self excitation conditions.

The power systems in this work are supplied by sources that can be view as voltage sources. As a result, the amount of voltage distortion in this system is proportional to the subsynchronous current and the effective impedance of the voltage source at that frequency. Because of the low frequency range of subsynchronous current and the relatively low source impedance, total harmonic distortion of generator terminal voltage is smaller than that of the current. As a result, SSR is more recognizable in the current than in the voltage.

Suppose the subsynchronous frequency is f_{er} and system frequency is f_o. When the phase current measurements are modulated by positive sequence phase voltages, the outputs of these multipliers typically include a dc component and other frequency components at (f_o+ f_{er}) and (f_o - f_{er}). This doubling of the frequency components provides an excellent opportunity to filter out the dc component and the supersynchrounous components while decreasing the requirements for the filter and decrease response time [1].

Subsynchronous resonance can be detected by measuring the generator terminal voltages, but because the series capacitor impedance is higher for low frequency currents, the subsynchronous resonance condition is amplified in voltages over the capacitors and can be detected easier. However, the series capacitors may not be installed near the generator. If this is the case, additional communication devices are needed to communicate with the generator protection devices, which add scheme complexity and cause more avenues for failures.

Generator speed is the most direct measure for SSR detection. Under normal operation, the shaft will rotate at synchronous speed. With SSR excited, the shaft will oscillate at the unstable mode on top of the synchronous speed. It is relatively easy to extract subsynchronous frequency range signal from the speed. However, the shaft speed of wind turbines can vary over a relatively wide range. This property makes SSR detection more complicated.

IV. SIGNAL PROCESSING TOOLS

With the powerful mathematical capability brought to us by microprocessor relays, various signal processing tools can be used for SSR detection. In this paper, Fourier Transform (FT), Short Time Fourier Transform (STFT) and Wavelet Transform (WT) are compared.

A. *Fourier Transform*

The Fourier transform of a signal x(t) is represented in equation (1):

$$X(j\omega) = \int_{-\infty}^{\infty} x(t) \cdot e^{-j\omega t} dt \;\; for\; every\; real\; number\; \omega. \quad (1)$$

Fourier transform is an average representation of the frequency characteristic of the time signal. Therefore, the Fourier transform of a signal does not have the time localization capability. While is has a very good frequency resolution, it does not tell anything about when a particular frequency component shows up or about the duration of the component.

B. *Uncertainty Principle*

Different techniques can be used to decompose signals in both time and frequency domain. However, there is a fundamental limit for the precision of decomposing the signal in both time and frequency domain, which is called the uncertainty principle. In the context of signal processing, particularly time frequency analysis, uncertainty principle is referred to as the Gabor limit [5]. When applied to digital filters, the result is that one cannot achieve high time resolution and frequency resolution at the same time, which means a signal cannot simultaneously have a compact support in both time and frequency [6].

C. *Short Time Fourier Transform (STFT)*

In 1946, Gabor proposed STFT to localize frequency spectrum in sound signal [6]. The definition of the STFT is:

$$STFT_s(u,\varepsilon) = \int x(t) g^*(t-u) e^{-j\varepsilon t} dt = < x(t), g(t-u) e^{j\varepsilon t} > \quad (2)$$

g(u) is used to localize x(t) in time domain. The STFT coefficients of a given signal x(t) are calculated by moving u and doing Fourier transform to the localized signal. Time resolution of STFT is determined by the width of the windowing function g(u) and frequency resolution is determined by the width of the frequency spectrum of g(u). Figure 2 shows the relationship of the time center, frequency center, time resolution and frequency resolution.

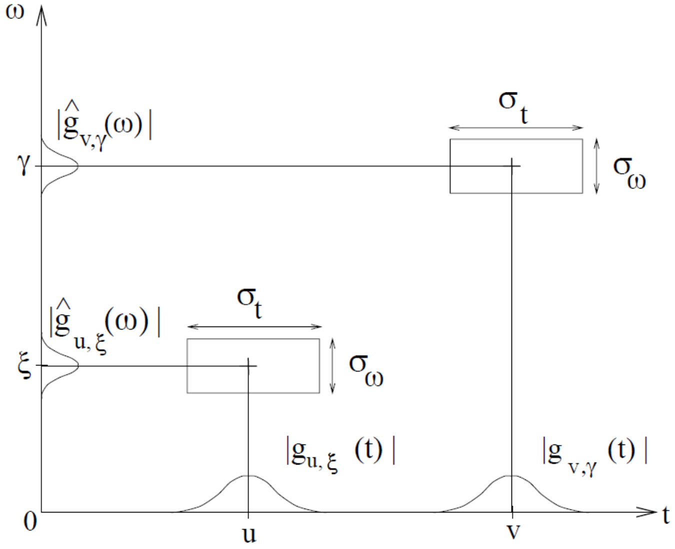

Fig. 2 Heisenberg boxes of two windowed Fourier atoms $g_{u,\varepsilon}$ and $g_{v,\gamma}$ [6]

The length of the rectangles in Fig. 2 represents the time resolution of the signal, σ_t the vertical height represents the frequency resolution, σ_ω. The center of the box represents the time center (u for one box and v for the other) and frequency center (ξ for one box and for γ the other). While the compromise between time and frequency information made by STFT is useful, the drawback with this approach is that once a particular size for the time window is chosen, that window is the same for all frequencies in the signal. Notice that σ_t and σ_ω do not change when the center changes, which means a STFT has the same resolution across the time-frequency plane. Many signals require a more flexible approach, with which the window size can be varied to determine either time or frequency more accurately.

For signals that change rapidly, a good time resolution is needed to observe the fast changing part as the duration of the signal is short. This means the observation time width has to be small. Limited by the uncertainty principle, frequency resolution is decreased. For slowly changing signals, a good frequency resolution at low frequency range is more desirable. Therefore, a time frequency analysis algorithm that can automatically meet these requirements is needed. As stated before, STFT has time resolution and frequency resolution both fixed. However, wavelet transform has this capability.

D. Wavelet Transform (WT)

By definition, the continuous wavelet transform is a convolution of the continuous signal x(t) and the predefined mother wavelet function g(t), as shown in the following equation (3) [7]:

$$CW(u,s) = \frac{1}{\sqrt{s}}\int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-u}{s}\right)dt \quad (3)$$

where s and u are the continuous coefficients of the scale and translation respectively. The scale sets the time duration of the wavelet while the translation sets the wavelet position in the time domain.

And in contrast to STFT, which uses a single analysis window, the CWT uses short windows at high frequencies and long windows at low frequencies. This partially overcomes the resolution limitation of the STFT. The relationship between time resolution, frequency resolution, time center and frequency center is shown in Figure 3 below.

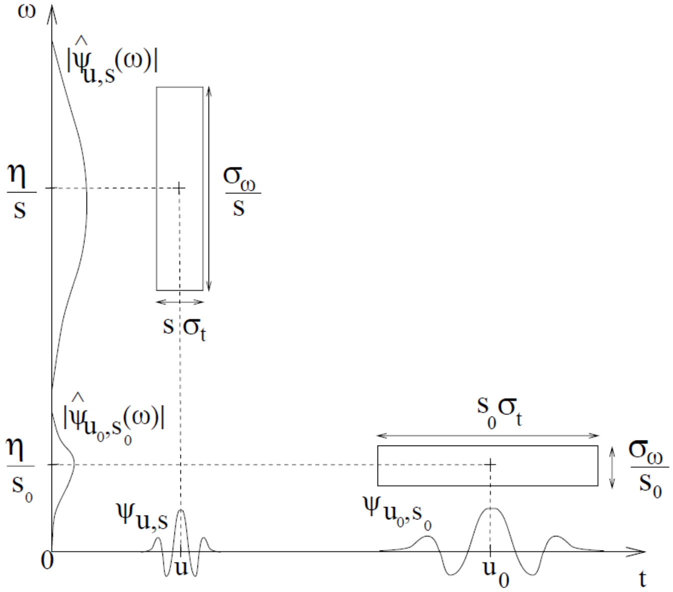

Fig. 3 Heisenberg boxes of two wavelets [6]

The energy spread of a wavelet atom $\psi_{u,s}$ corresponds to a Heisenberg box with a length of $s * \sigma_t$ and a width of σ_ω/s and therefore the produce of time resolution and frequency resolution is a constant. As a result, with a large scaling factor, the wavelet transform achieves good frequency resolution for slow changing signals while sacrificing time resolution. For fast changing signals, a small scaling factor is used to achieve good time resolution at the expense of frequency resolution. In particular, this allows for the analysis of high frequency components very close to each other in time, and low frequency components very close to each other in frequency. These properties are indeed suitable for the study of transient waveforms produced by SSR.

Table II shows the short summary of a comparison of FT, STFT and WT.

Table II. Comparison of different analysis tools

Tool	Properties
DFT	Decompose signal only in frequency domain; Analyzed signal frequency has to be integer multiples of resolution frequency.
STFT	Decompose signal in both time and frequency domain; Fixed time and frequency resolution; Not good for signal with a wide frequency range.
WT	Decompose signal in both time and frequency domain; Flexible time and frequency resolution (constant Q analysis).

V. APPLICATION RESULTS

There was an SSCI event in 2009. A single phase to ground fault developed on a 345 kV transmission line when an overhead static wire failed and was cleared as expected in 2.5 cycles. After the removal of the fault, two wind plants with a capacity of 485 MW from approximately 300 doubly-fed induction generator wind turbines were left connected to the transmission grid through a single 50% series-compensated 345 kV transmission line which was 80 miles long. Within 200 milliseconds, subsynchronous oscillations between the series capacitor and the wind turbine controls developed and grew sufficiently large to damage the wind turbines as voltages exceeded 1.5 per unit [4]. Following figure shows the current waveform of the stator.

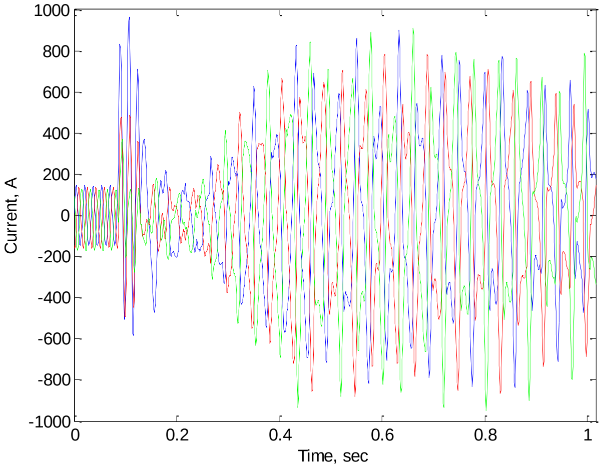

Fig. 4 Generator Current Waveform for a SSCI case

The following graphs correspondingly show DFT, STFT and WT results for the signal window of 0 sec to 0.5 sec.

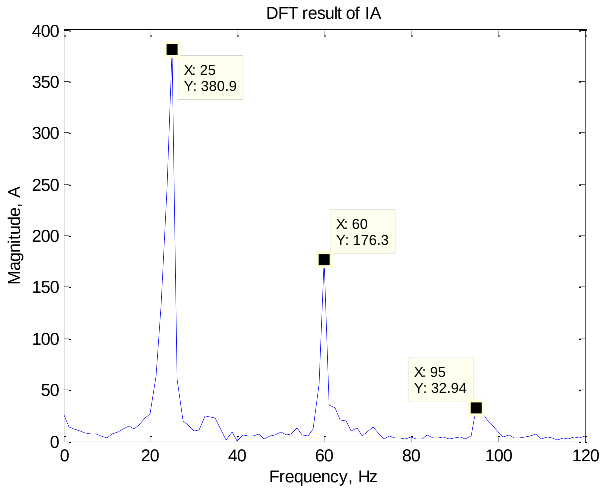

Fig. 5 DFT analysis of current IA

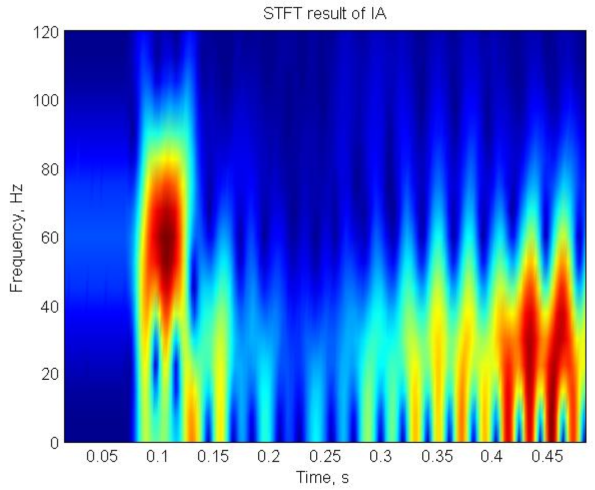

Fig. 6 STFT result of current IA

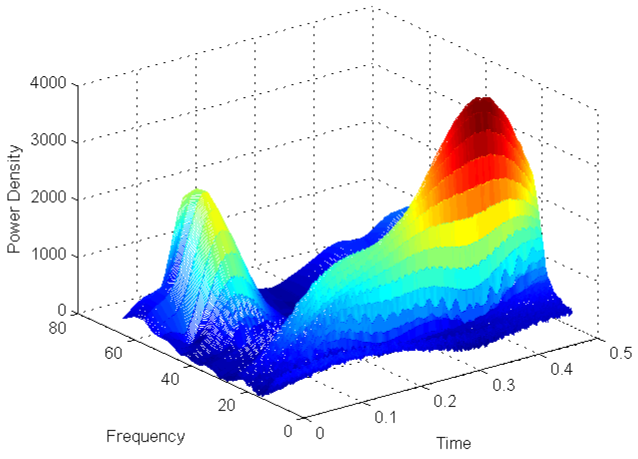

Fig. 7 WT result of current IA

Fig. 5 shows that while DFT has a good frequency resolution, it does not have any support in time domain. The fundamental frequency component, the subsynchronous frequency component and the supersynchronous frequency component are shown clearly by DFT analysis. However, there is no indication as to whether the oscillation is growing or damped.

The STFT decomposes the signal in both time and frequency domain as shown in Fig. 6. However, the magnitude of the STFT coefficients oscillates at the subsynchronous frequency and does not give a clear indication of whether the oscillation is growing or damping. What is more, in the frequency spectrogram, energy is present for frequency components that do not exist in the original signal due to the frequency leakage problem.

With WT result shown in Fig. 7, it is clearly shown that the fundamental component current magnitude increases as the fault develops and decreases once the fault clears. After the fault is cleared, the subsynchronous frequency component increases rapidly with time. The WT coefficients clearly indicate SSR is excited and the wind turbines should be taken off-line. The results prove that with a flexible time and frequency resolution, WT overcomes the drawback of DFT and outperforms STFT. This makes the WT approach a promising tool for SSR analysis.

VI. CONCLUSION

Researchers have been trying to develop fast, dependable and secure SSR detection algorithms for a long time. In this paper, various existing SSR detection methods were reviewed and analyzed. Different signal selection options and signal processing techniques were compared. Conclusions were drawn on the advantages and disadvantages of the different input signals. Existing methods either do exclusively time domain analysis or exclusively frequency domain analysis. STFT and WT decompose signals simultaneously in time and frequency domain, which fit well to find the growing oscillation signature of SSR. Theoretic analysis on FT, STFT and WT was done and they were used to analyze a field case for SSR. Comparison results show that WT overcomes the drawbacks of FT by doing time frequency analysis. With a flexible time and frequency resolution, WT shows a clear relationship between the magnitudes of different frequency components and time, which is a critical signature to identify SSR. These virtues make WT an ideal tool to do SSR detection.

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