New effective method of subsynchronous resonance detection

Maciej Orman, Przemysław Balcerek, Michał Orkisz

***Abstract*-- The paper presents the novel approach for detection of subsynchronous resonance phenomenon SSR in a series compensated transmission system. The presented method is designed to detect subsynchronous resonance frequency and amplitude in very short time to prevent the failure of transmission systems, which can likely happen if the subsynchronous resonance amplitude will not be mitigated quickly enough. The specific signal demodulation of AC current measurement was introduced in order to detect the subsynchronous resonance. The algorithm was investigated with the use of different test cases- based on IEEE second benchmark model of subsynchronous resonance. The results of calculations indicate that the presented concept is an adequate proposition for detection of subsynchronous frequencies.**

***Keywords*: subsynchronous resonance, series compensated transmission line, torque amplification, torsional interaction, induction generator effect.**

I. INTRODUCTION

SERIES capacitors are commonly used in the high voltage transmission systems to assure reactive power compensation. However, presence of series compensation can cause the effect of subsynchronous resonance phenomenon (SSR). In general, the subsynchronous resonance phenomenon occurs in electrical power systems as a result of the interaction of a turbine-generator with a long-distance series compensated transmission line [1]. There is a condition of an electrical power system where electrical networks exchange energy with the mechanical system of the generator at frequencies less than the nominal frequency of the transmission line (50 Hz for Europe). According to [1] such frequency is within 15 % to 90 % of nominal network frequency.

There are three known reasons for the appearance of the SSR phenomenon:

- Induction generator effect – Self excitation of voltages and currents would be expected when the rotating magnetic field produced by the subsynchronous armature currents circles slower than the rotor. In such cases the rotor resistance to subsynchronous currents viewed from the armature terminals is negative and exceeds the sum of the armature and network resistances. Such a phenomenon is known in the literature as the induction generator effect [4], [9].
- Torsional interaction – If the frequency of the produced voltage component is close to the network natural frequency, there is a possibility of the generator natural mechanical frequency excitation. This mechanical frequency is visible in voltage as a modulation of the nominal line frequency [4], [9], [11].
- Torque amplification (transient torques) – The torque amplification effect can be caused by a three-phase to ground fault [3], [9].

The first two reasons are due to steady state disturbances while the third one is excited by transient disturbances [8].

Low resonance frequency causes a serious problem in on-line detection of the SSR. Therefore to detect such frequency using typical signal analysis method (like Fast Fourier Transform) there is a need to have long (in time domain) signal. On the other hand the longer it takes to acquire the signal the bigger the delay in the response time. Also to take an adequate action it is essential to know the trend of the subsynchronous amplitude. In the case of growing amplitude it is necessary to take preventive actions.

There are several methods known from literature [3], [5] [6], [7], [8], [10] for the SSR detection. The disadvantage of those methods is the presence of a time delay between the appearance of the subsynchronous resonance phenomenon and its detection. This time delay may be too long for SSR frequency detection, which may result in damage to the shaft or maloperation of the transmission line protection relay. Therefore, this paper presents a novel approach for detection of the SSR phenomenon in very short time.

II. ALGORITHM DESCRIPTION

The main idea of the algorithm is on-line analysis of voltage signals. As a result the algorithm gives the amplitude and frequency of the subsynchronous resonance. In figure (Fig. 1.) there is the scheme of the algorithm.

This algorithm contains three main parts:

- Demodulation block - this block is responsible for creation of specific demodulation based on upper and lower signal envelope, which is sent for further analysis.
- Analysis block - this block is responsible for frequency analysis of the signal after demodulation.
- Decision block - this block is responsible for deciding whether subsynchronous resonances appear in the signal or not.

A. Demodulation block.

The idea of demodulation is to find the upper and lower envelopes of the voltage signal and to subtract them from each

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other. To find the envelope, first the zero crossings are identified. Always there are two types of zero crossings. One of them is when the signal value is increasing – positive zero crossing, the other when the signal value is decreasing – negative zero crossing.

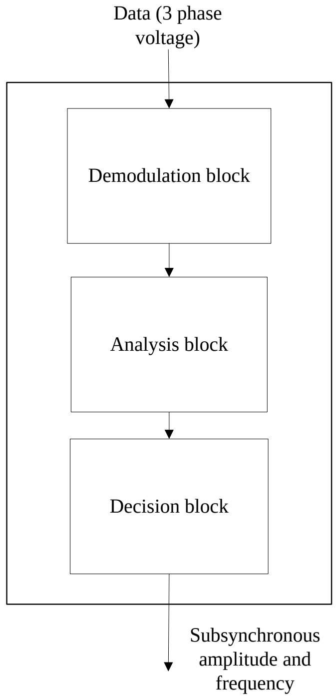

Fig. 1. Scheme of SSR detection algorithm

A positive zero crossing is detected when the signal changes its value from negative to positive and when this value is above the positive hysteresis value (established as a parameter). A negative zero crossing is detected when the signal changes its value from positive to negative and when its value is below the negative hysteresis. In the presented method the absolute values of positive and negative hystereses are equal. The hystereses are established in order to avoid spurious zero crossings caused by noise, which always appears in signals collected from real electrical power systems.

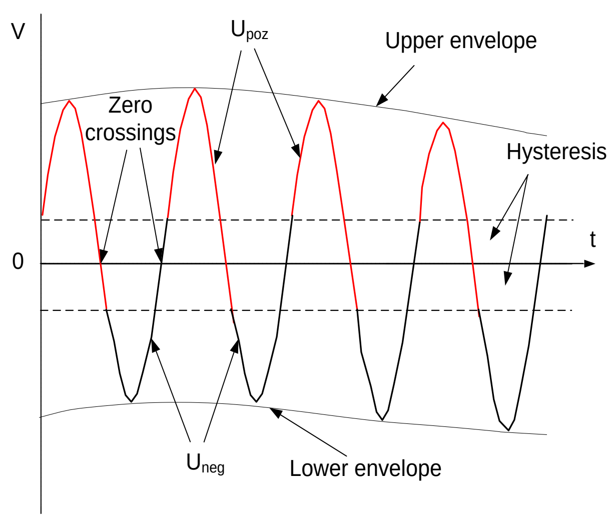

Fig. 2. Visualization of upper and lower envelop

After finding the first zero crossing point, which can be positive or negative, the next zero crossing point, which is negative or positive respectively, is found. The time interval between these zero crossing points is determined as the interval for calculating the positive part U_{poz} and the negative part U_{neg}. The sequence of maxima from each interval U_{poz} is creating the upper envelope E_{up} of voltage signal. The sequence of minima from each interval U_{neg} is creating the lower envelope E_{low} of the voltage signal. Such envelopes are presented in figure (Fig. 2.) as lines when in fact there are discrete points (one for one nominal line period).

Demodulated signal U_{dem} is created by simple operation:

$$U_{dem} = E_{up} - E_{low} \tag{1}$$

where E_{up} is the upper envelope of voltage signal amplitude, E_{low} is the lower envelope of voltage signal amplitude.

B. Analysis block.

In this block the demodulated signal U_{dem} is analyzed. For the case of a sinusoidal shape of the line voltage waveform with no subsynchronous frequency such demodulated signal should be a constant line. However, if additional low frequency appears, then it is visible in the demodulated signal as f_{ssr}. (Fig. 3.).

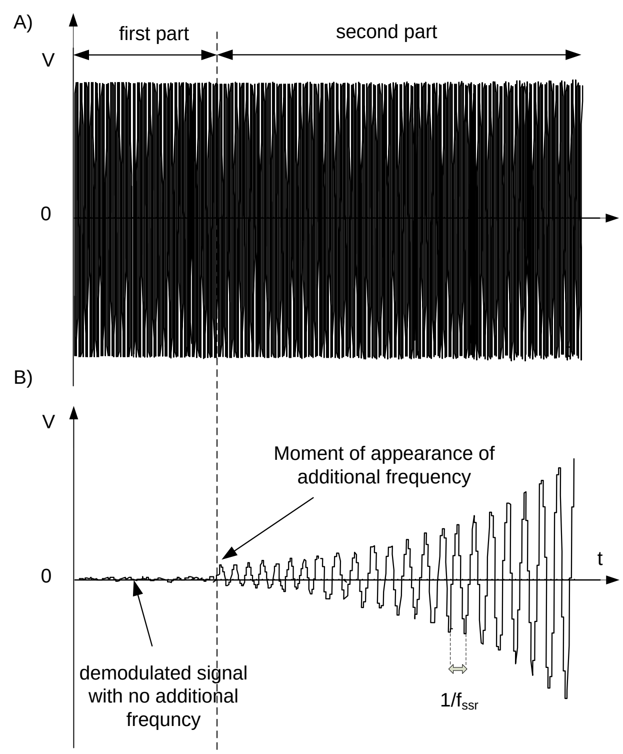

Fig. 3. Voltage signal after demodulation

In the presented method the Fast Fourier Transformation is calculated from demodulated signal. FFT analysis of demodulated signal U_{dem} gives amplitudes and frequencies of SSR contained in the original voltage signal. Figure (Fig. 4.) presents an example of demodulated signal FFT result.

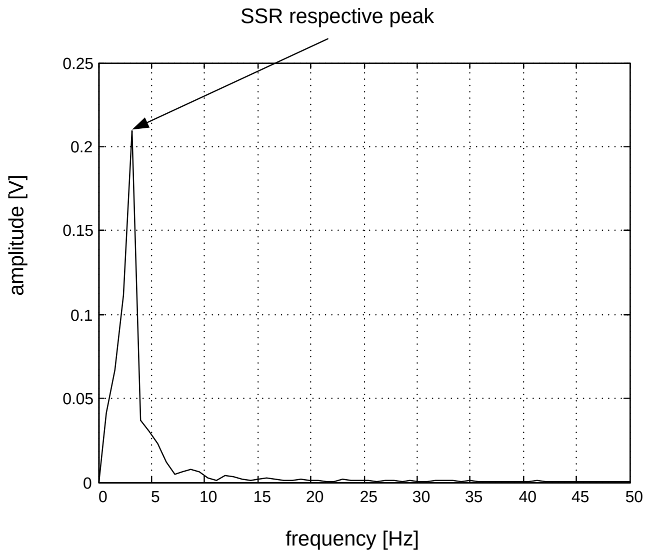

Fig. 4. FFT of demodulated signal with dominant SSR frequency

It is possible to notice that SSR frequency is the dominant one in the whole spectrum range. However, it is very important to detect the SSR frequency in the shortest possible time. Reducing the length of the analyzed signal results in deterioration of FFT results. The resolution of FFT is a function of signal length and the sampling frequency. Inaccurate amplitude and frequency values of the candidate for f_{ssr} may be obtained, if the peak value and location are taken from the discrete highest spectral element. There are many known methods which can be used to improve the FFT results [12]-[17]. In the presented approach the accuracy of amplitude and frequency calculations is improved by adding to the highest spectral element corrections of amplitude and frequency based on a specific interpolation using ratios involving three samples around the FFT output peak.

The result of the analysis block is the maximum amplitude and corresponding frequency of the signal after demodulation.

C. Decision block.

The decision block determines whether obtained f_{ssr} frequency and respective amplitude can be considered as SSR. Figure (Fig. 5.) present the structure of the decision block.

First the highest peak is removed from the spectrum of demodulated signal. Then the mean value of the FFT is calculated. The mean value is compared with the highest peak. Its frequency is considered as candidate for SSR if the difference between the highest peak and the mean value is higher than a specified threshold value (which is an input parameter).

Then it is checked if the candidate for SSR frequency f_{ssr} is within 15 % to 90 % of the nominal line frequency. If this condition is fulfilled than it is decreed that the SSR is present in measured voltage signal. In this case the result of algorithm is the f_{ssr} frequency and its amplitude. If the distance between mean and highest peak value is not exceeding the threshold or the corresponding frequency is not in the range of 15 % to 90 % of nominal line it is decreed that no SSR has been detected. In such case the algorithm returns zero for the amplitude and the frequency of SSR.

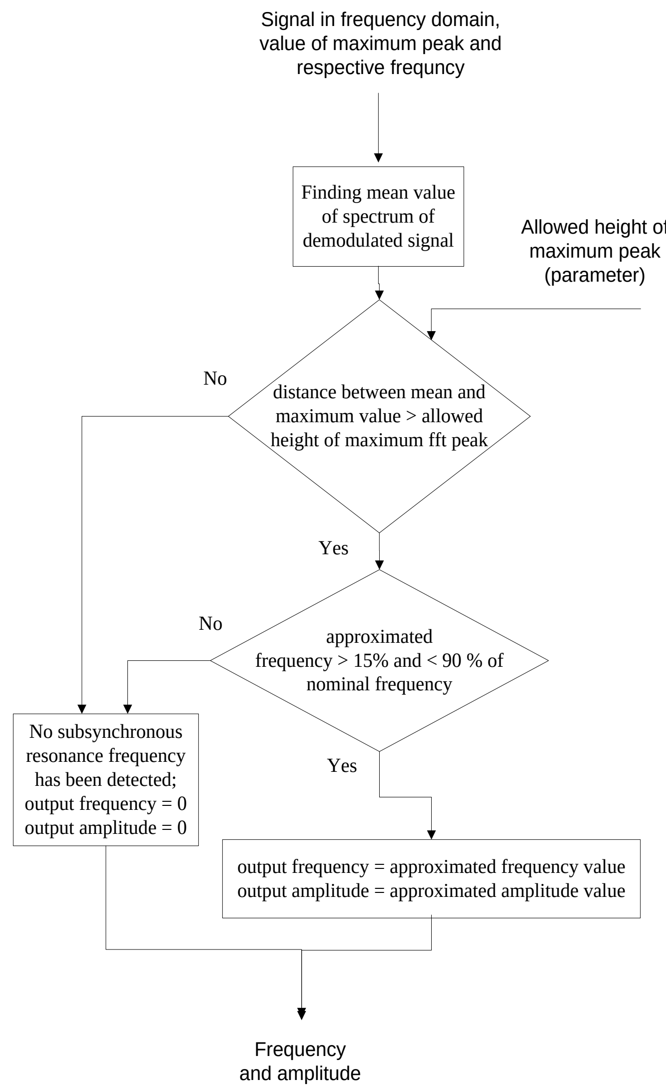

Fig. 5. Scheme of decision block

III. NUMERICAL CALCULATION

IEEE second benchmark model of subsynchronous resonance [2] is a well known and commonly use model of series-compensated transmission system for study of subsynchronous resonance phenomena. Therefore, the discussed SSR detection algorithm has been evaluated with using the input data obtained from Matlab Simuling second benchmark model of power network containing the 500 kV, series compensated transmission line [17].

Signal is generated by the model and the SSR detection algorithm is taking the signal for on-line analysis at discrete points in time. The length of signal taken to analysis is 0.2 s. This length determines the maximum delay between the SSR appearance and its detection.

Frequency sampling was set to 1 kHz in all simulations, which is a commonly used value in protection of the power systems. Decreasing the sampling frequency could result in incorrect estimation of the sequence of maxima and minima from each interval U_{poz} and U_{neg}, which would lead to poor quality results. In such case the shape of each interval U_{poz} and U_{neg} can be interpolated by any known technique (order>1). From the interpolated signals it is possible to find the sequence of maxima and minima. By increasing the sampling frequency, the maxima and minima can be identified with higher accuracy. Since the number of samples in the signal envelopes is not affected, the computation time will not increase significantly.

To test the induction generator effect, initial difference between generator rotor position and the rotating magnetic field was set to 2°. In standard synchronous machines the difference between positions of magnetic field and rotor is equal to zero. Fig. 6. shows the results of SSR frequency and amplitude determination in the case of induction generator effect simulation.

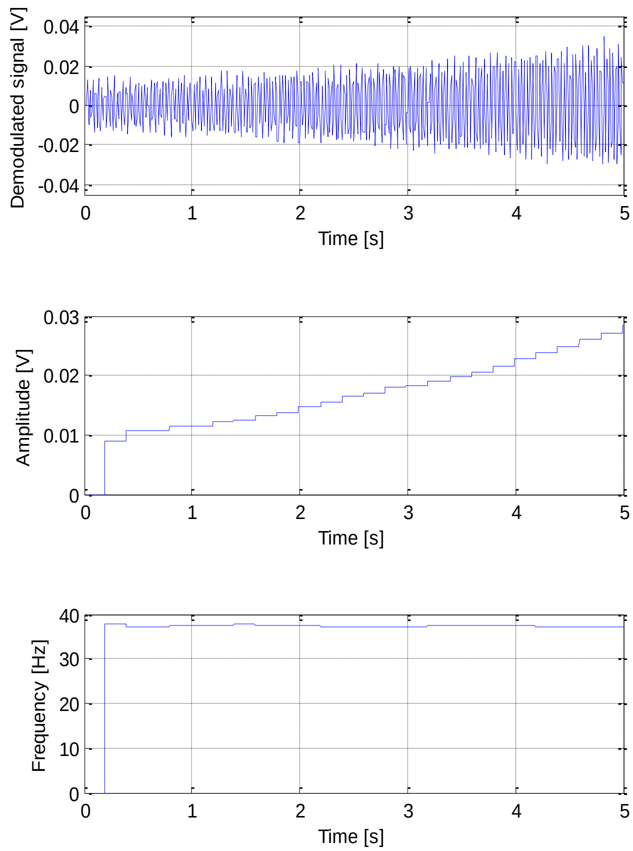

Fig. 6. Simulation of induction generator effect. Example of one phase of demodulated signal [V], amplitude response of algorithm [V] and frequency response of algorithm [Hz] respectively.

As seen in (Fig. 6.) the algorithm detects the SSR after 0.2 s, which is exactly the value of the window length. However, in the original voltage signal (not presented here) it is hard to notice any significant changes. The detected amplitude is gradually increasing while the frequency is equal to 37 Hz and its constant for all simulation time – matching the SSR of the simulated test case.

To test the torsional interaction, the generator's rotor speed was distorted with certain additional frequency corresponding to the SSR frequency. Figure (Fig. 7.) presents the results of SSR frequency and amplitude determination in the case of induction torsional interaction simulation.

The subsynchronous frequency was detected by the algorithm in 0.2 s, which is exactly the value of the window length. Like in the previous case, it is hard to notice any significant changes in the original voltage signal (not presented here). The amplitude and frequency for SSR in this case remain constant for the whole simulation length. The frequency is equal to 37 Hz, matching the SSR of the simulated test case.

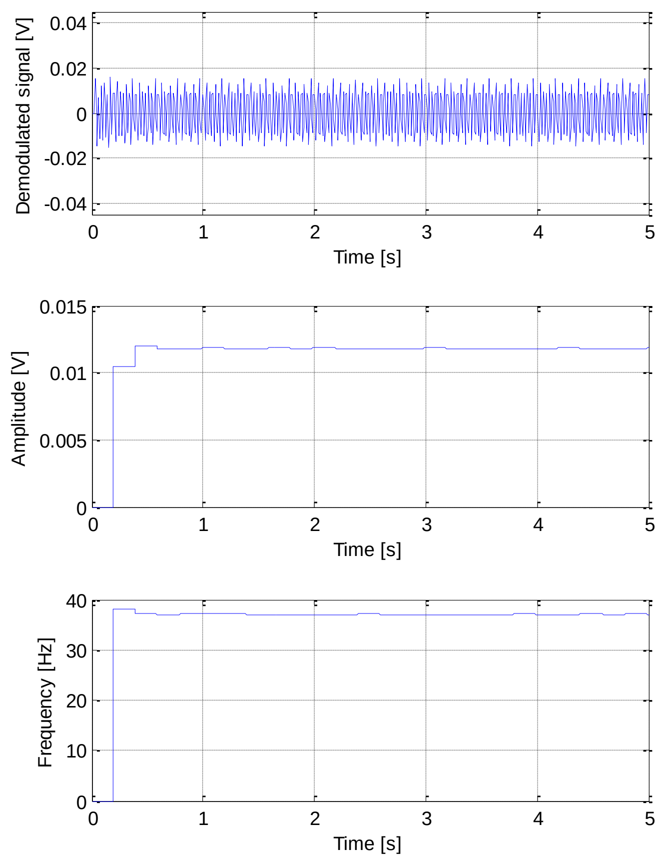

Fig. 7. Simulation of torsional interaction effect. Example of one phase of demodulated signal [V], amplitude response of algorithm [V] and frequency response of algorithm [Hz] respectively.

The torque amplification effect was generated by a 3-phase to ground fault. The fault has occured at 0.15 s of simulation and disappeared after 0.01 s. Fig. 8. presents results of SSR frequency and amplitude determination in the case of torque amplification effect simulation.

The SSR appears in the signal after 0.15 s via a 3-phase to ground fault. The algorithm detected it in 0.2 s which means that the delay is equal to 0.05 s. At first the detected amplitude (due to the phase-to-ground fault) is very high, then it rapidly decreases and after 1 s of simulation it starts to increase. The detected frequency is equal to 37 Hz for all of the simulation time, which corresponds to the SSR of the simulated test case.

Due to the small amplitude of SSR in the simulation it is hard to notice any changes in time domain voltage signal (similarly to the case presented in Fig. 3). However, it is easy to notice signal changes after demodulation.

In order to investigate the accuracy of the method proposed, all simulations where carried out for an ideal model of the VT's. In further steps the research should include the impact of the VT's response, which will require a detailed model of VT's, especially the magnetization characteristics shape.

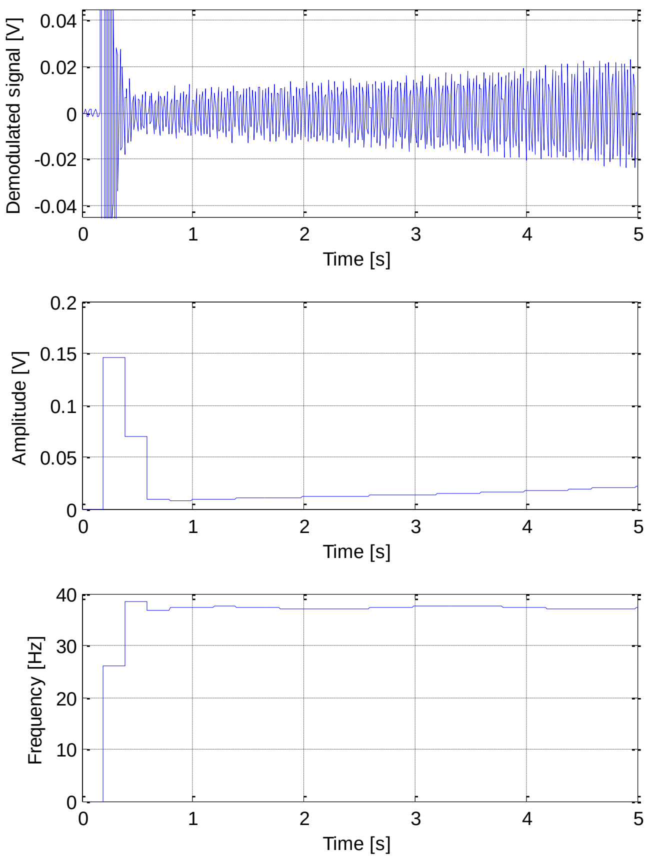

Fig. 8. Simulation of torque amplification effect. Example of one phase of demodulated signal [V], amplitude response of algorithm [V] and frequency response of algorithm [Hz] respectively.

IV. Conclusions

This paper presents a novel technique for detecting a subsynchronous resonance phenomenon in a transmission system. The suggested algorithm is based on the measurement of phase voltages. The main identification procedure utilizes relations between the upper and the lower envelope of the measured voltage signal.

This specific demodulation process is characterized by filtering out all signal components of frequencies equal to and higher than the nominal line frequency. Due to its character such demodulated signal is easy to analyze for SSR detection, for example by Fast Fourier Transform.

The results show that the presented method has the ability to detect the appearance of the SSR within 0.2 s. In order to detect SSR faster it is possible to add window overlapping and to perform analysis over shorter time periods. Detected amplitudes and frequencies correspond to the simulated SSR in all cases.

Calculation results indicate that the presented concept is an adequate proposition for the detection of subsynchronous frequencies and can be applied to a real system.

V. References

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