Testing the Quality of PMU Output Data Based Subsynchronous Damping Analysis in Real-Time Simulation Environment

Tuomas Rauhala, Pertti Järventausta

Abstract--This paper describes an approach on subsynchronous damping analysis based on measurement data obtained using Phasor Measurement Unit located in vicinity of a turbine-generator unit. The subsynchronous damping analysis are performed using subsynchronous components extracted from PMU output data using filtering and spectral analysis techniques. The quality and validity of subsynchronous damping analysis based on different output quantities is analyzed and most suitable approach on damping analysis is proposed. The performance of the methods to detect oscillations was evaluated under laboratory conditions using Real Time Digital Simulator. The validity of subsynchronous damping calculation based on PMU output data was verified using well-established benchmark models created for subsynchronous oscillations related studies.

Keywords: Subsynchronous oscillations, SSO, Phasor Measurement Unit, PMU, subsynchronous damping, damping analysis, real-time simulation

I. Introduction

THE stresses caused by high-amplitude subsynchronous oscillations are of interest especially if based on the structure of the transmission network, there is a reason to expect very low subsynchronous damping to occur under certain operating conditions. Typically, subsynchronous damping is determined based on measured post-disturbance behavior of subsynchronous components extracted from generator speed, that can be measured using approaches like acceleration pick-ups, strain gauges and optical measurements [1]. However, if risk of weak subsynchronous damping or extremely high level of torsional oscillations under certain operating conditions was determined to be minor at the time of commissioning of the unit, torsional monitoring system may not be available.

The structure of the power transmission network may experience significant structural changes during the life-time of generator unit. If the effect of the changes from subsynchronous oscillations point of view is not determined to be extremely high, approaches allowing the determination of the damping without need for specific test arrangements may be highly beneficial. In this paper a straightforward approach on estimation of subsynchronous damping based on PMU measurement data is presented, evaluated and verified. The approach presented can be used to approximate the subsynchronous damping of subsynchronous torsional oscillation modes of turbine-generator on modal mechanical frequencies below 20 Hz.

II. Background of the Study

As a turbine-generator with nominal frequency of f_o oscillates on its natural mechanical subsynchronous torsional frequencies f_{mn}, it injects sub- and supersynchronous current and voltage components with frequencies f_{en} into the transmission network.

$$f_{en} = f_o \pm f_{mn} \qquad (1)$$

Subsynchronous torsional oscillations can be observed in the speed of the turbine-generator as small variations in the measured speed ω. The frequency of these speed variations superposed on the nominal mechanical speed ω_o of the unit correspond the subsynchronous natural torsional frequencies ω_{mn} defined by the structure of the unit.

$$\omega = \omega_o + A \cdot \sin(\omega_{mn} t) \qquad (2)$$

The amplitude A of the oscillations is basically dependent on the nature of the stimulus invoking the torsional oscillations and on the physical structure of the turbine-generator unit. As the frequency in vicinity of the turbine-generator unit is related to the speed of the generator unit, also the frequency of subsynchronous components in measured frequency corresponds the frequency of the mechanical torsional oscillations. This relation is used for example in subsynchronous damping circuits used to improve the effect of HVDC on subsynchronous damping seen by generator unit [2],[3].

The subsynchronous oscillations of the generator unit can also be observed in the angle of the generator voltage δ due to the relation between the voltage angle and the speed of the generator unit ω, [4]

$$\frac{d\delta}{dt} = \omega - \omega_o \quad \Rightarrow \quad \delta = \delta_o + \frac{A}{\omega_{mn}} \cdot \cos(\omega_{mn} t) \qquad (3)$$

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T. Rauhala and P. Järventausta are with Tampere University of Technology, Institute of Power Engineering, P.O. Box 692, FIN-33101 Tampere, FINLAND (e-mail: Tuomas.Rauhala@tut.fi).

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III. Characteristics of Phasor Measurement Unit on Subsynchronous Frequency Range

Phasor Measurement Units (abbr. PMU) are nowadays increasingly used to measure and monitor the state of the power systems. Basically, PMU is designed to measure slow variations of the power system quantities [5] and it has proven to be very useful e.g. in measurement of electromechanical oscillations occurring on frequency range 0.2-2 Hz. However, the accuracy in frequency and angle variation measurements basically allow the detection of subsynchronous oscillations despite the inherent attenuation of PMU on frequencies above 2 Hz. As shown in Fig. 1 for example the commercial PMU [6], which was used in the tests presented in this paper, provides attenuation of only approximately 1 dB up to 10 Hz and a few dB up to 20 Hz. Also, Nyquist criterion allows the detection of subsynchronous components up to 25 and 30 Hz in 50 and 60 Hz system respectively. Thus, it seems justified to presume that the accurate frequency, rate-of-change of frequency (dfreq) and voltage phase angle measurement capability of PMU allows the detection of subsynchronous components corresponding torsional oscillations of frequencies below 20 Hz. Obviously, based on (1) the subsynchronous current and voltage components corresponding the torsional oscillations below 20 Hz cannot be observed in PMU output data due to Nyquist criteria and high attenuation of PMU on frequency range above 30 Hz.

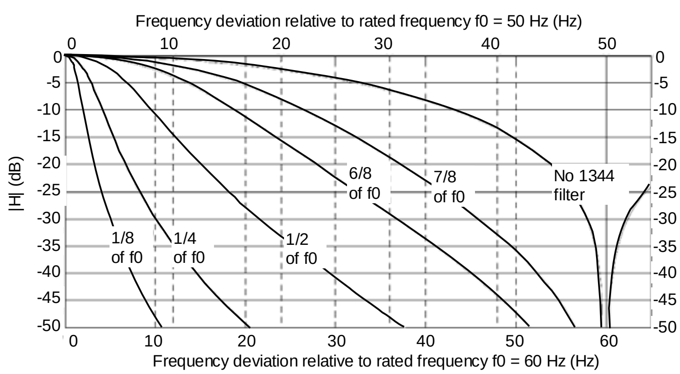

Fig. 1. Attenuation of PMU on subsynchronous frequency range [6]

It's worth emphasizing, that the effect of the speed of the turbine-generator unit on system frequency is not only dependent on the measurement location, but also on the strength of the transmission network in parallel with the studied unit. The higher the short circuit capacity of the parallel AC network is, the less the unit affects the system frequency. This implies, that the quality of the subsynchronous components, that can be detected in frequency related measurements, are greatly dependent on the operating conditions of the network. This, however, cannot be necessarily considered as a factor preventing the effective application of the proposed approach. For example in connection of subsynchronous torsional interaction due to HVDC the subsynchronous damping is of interest especially under operating conditions, where the short circuit capacity of parallel network is low. The suitability of the proposed approach for monitoring the effect of HVDC on subsynchronous damping is also supported by the fact, that HVDC affects the subsynchronous damping mainly on torsional frequencies below 20 Hz.

IV. Structure of the Analysis

The capability of PMU to observe subsynchronous oscillations and the validity of the methods proposed for analysis of subsynchronous damping were tested using Real Time Digital Simulator RTDS [7]. Three different approaches were used in the analysis. First, the subsynchronous response of PMU was tested using amplitude, frequency and angle modulated signals. As high amplitude torsional oscillations cause all the three forms of modulation in electrical system quantities, the subsynchronous response was also studied by modulating the speed reference signal of a generator model [8] connected to a voltage source as shown in Fig. 2.

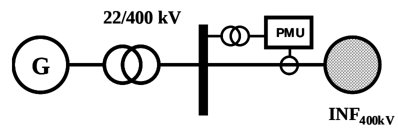

Fig. 2. Structure of the network models used in speed modulation studies

In the second part of the analysis the validity of the methods used for subsynchronous damping analysis were evaluated using simulation model corresponding the System-1 presented in the 2nd IEEE SSR benchmark [9].

In the third part subsynchronous damping was analyzed using simple AC-DC-system model shown in Fig. 3. The HVDC system structure is based on CIGRE HVDC benchmark [10] and the subsynchronous torsional frequencies f_n and corresponding modal inertias H_n used for 1072 MVA 50 Hz generator models [8] are shown in table I. No mechanical damping was modeled in the studies. In the tests subsynchronous oscillations were initiated by simulating voltage dip of 5-30 % lasting 100 ms at the rectifier bus. The short circuit capacity in parallel with the generator units was varied between values 2000 MVA and 10 000 MVA.

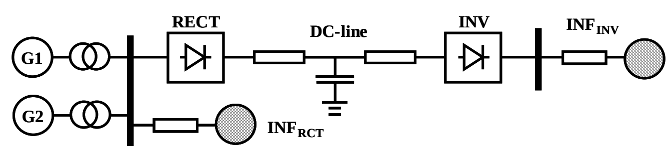

Fig 3. Structure of the AC-DC-system model used in tests

TABLE I
Torsional Characteristics of the Turbine-Generator Models

	GEN1 [7]					GEN2				
	Mode1	Mode2	Mode3	Mode4	Mode5	Mode1	Mode2	Mode3	Mode4	Mode5
f_n [Hz]	6.8	12.4	15.8	17.5	93.2	9.9	19.5	25.5	31.3	33.4
Hn	3.0	3.6	1.6	260.3	13.5	2.9	2.1	9.1	9.2	316.0

V. Methods Used for Subsynchronous Damping Analysis

In analysis of subsynchronous damping based on PMU measurement data two different approaches, one based on spectral analysis and other on band-pass filtering, were tested.

A. Method based on spectral analysis

Fast-Fourier-Transformation (FFT) with sliding window was used to extract subsynchronous components from PMU voltage phasor, frequency and rate-of-change of frequency. Similar approach has been used previously to analyze electromechanical oscillations between 0.2 and 2 Hz from PMU output data [11] and subsynchronous oscillations from generator terminal voltage [12]. In this study FFT was performed once in eight 50 or 60 Hz cycle intervals, i.e. every 0.16 seconds for 50 Hz, using windowing lengths 2^8 and 2^9, that proved to provide most suitable signal for analysis.

In Fig. 4 two post-disturbance spectrums of PMU frequency measurement are shown for AC-DC-system shown in Fig. 3. In Fig. 4 all the subsynchronous frequencies below 20 Hz can be clearly observed as well as the electromechanical mode of 1 Hz. Additionally, frequency component corresponding 25.5 Hz torsional mode can be seen in the spectrum due to aliasing.

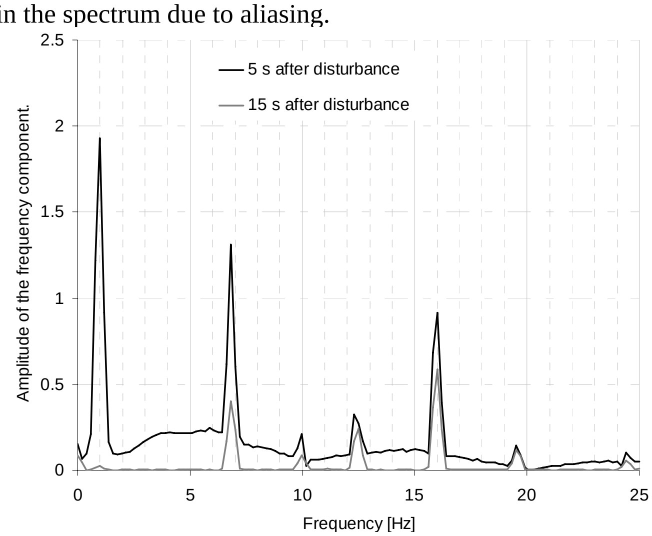

Fig 4. Post-disturbance frequency spectrum determined based on PMU frequency measurement signal

The behavior of the spectral analysis based frequency components as function of time is further illustrated in Fig. 5, that represents the three main subsynchronous components corresponding the torsional mode of 6.8 Hz. From Fig. 5 can also be seen that the inherent delay related to the approach is dependent on length of the data window used in the analysis. In Fig. 5 the window length of 2^8 (= 5.12 s at 50 Hz sampling rate) results in delay of approximately 5 seconds.

Based on the shape of the subsynchronous components shown in Fig. 5 it is obvious that the damping factor can be determined in a straightforward manner using simple equation for logarithmical decrement (log dec). In order to further minimize the effect of small variations on the calculated damping, logarithmical decrement was determined as a mean damping over three consecutive samples i.e. in this case over period of 0.48 s,

$$Log\ \ Dec = \frac{1}{3}\cdot\left(\ln\left(\frac{A_n}{A_{n-1}}\right)+\ln\left(\frac{A_{n-1}}{A_{n-2}}\right)+\frac{1}{2}\cdot\ln\left(\frac{A_n}{A_{n-2}}\right)\right) \qquad (4)$$

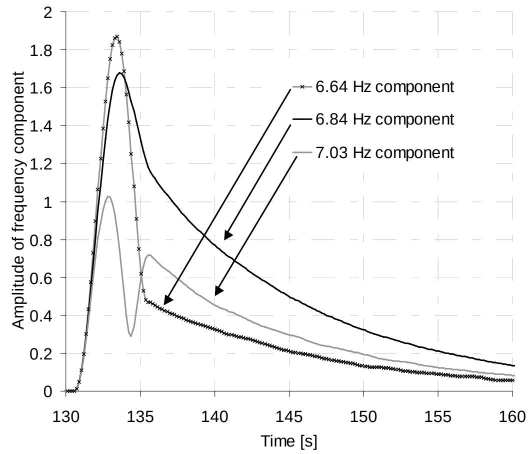

Fig 5. Shape of the subsynchronous frequency components

Based on the tests spectral analysis based damping calculation provides good approximations on subsynchronous damping on frequencies up to 15 Hz. Between 15 and 20 Hz the quality of the approximation is moderate. These conclusion were later verified based on measurements performed in Finnish 400 kV transmission system [13].

B. Method based on band-pass filtering

The other approach used to produce subsynchronous components, that can be used in subsynchronous damping analysis, was based on band-pass filtering of PMU measurement signals. In Fig. 6 subsynchronous frequency components of 6.8 ad 12.4 Hz obtained using 6^{th} order Butterworth band-pass filters from measured frequency are shown. Especially 6.8 Hz frequency component illustrates nicely the damping of the torsional mode. 12.4 Hz component, however, shows that especially on frequencies located in vicinity of pure subharmonic frequencies, the amplitude of the signal is distorted by superposed low-frequency oscillation. The low frequency oscillation must basically be due to the computation used in phasor calculation, as no such component were detected in frequency determined in simulation environment. As the exact algorithm used in phasor determination is not known, this conclusion cannot be verified.

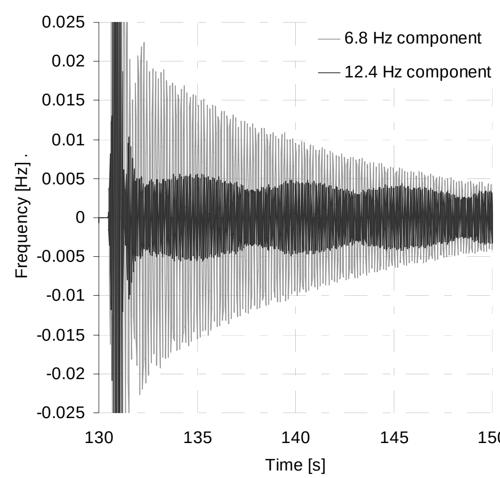

Fig 6. Frequency components for 6.8 Hz and 12.4 Hz torsional mode obtained from measured frequency using narrow band pass filters

With regard the subsynchronous damping analysis, the low quality of the band-pass filtered frequency, and similarly rate-of-change of frequency, signal is further illustrated in Fig. 7, where the envelope curves of two subsynchronous components shown in Fig. 6 are presented.

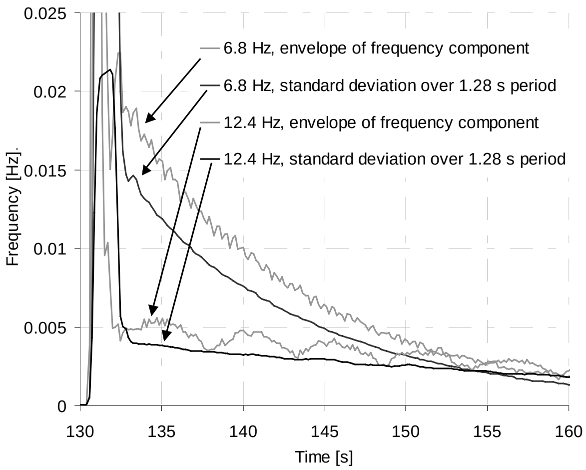

Fig 7. Envelope curve and standard deviation of 6.8 Hz and 12.4 Hz frequency component

Based on the envelope curves shown in Fig. 7, it is obvious that further filtering is required before the quality of band-pass filtered signals is good enough for damping analysis. After investigating several different approaches for additional filtering, most significant improvements in quality of signals were obtained by determining standard deviation of frequency components over 64 samples or 1.28 seconds at 50 Hz sampling rate.

$$s = \sqrt{\frac{\sum_{i=1}^{64}\left(x_i - \bar{x}\right)^2}{n-1}} \qquad (5)$$

In Fig. 7 also the effect of the standard deviation calculation over sliding window of 64 samples is illustrated. The improvement in the shape of the subsynchronous signal is evident, although the small amplitude distortion prevents the analysis of subsynchronous damping using logarithmical decrement calculation as given in (4). However, good estimations of subsynchronous damping can be obtained using manual curve fitting with ideal exponentially damped or undamped functions. The main drawback of this approach is the attenuation of the amplitude of the subsynchronous component as shown in Fig. 7. That basically prevents usage of this approach in connection of small amplitude oscillations.

VI. The Main Results of the Analysis

All the analysis were performed after the real-time simulations using the data recorded by PMU during the test period. Due to the output sampling rate and the inherent attenuation the subsynchronous damping was basically analyzed only using frequency and rate-of-change of frequency related signals, that provided significantly better resolution than subsynchronous components extracted from measured voltage angle. Also, in current and voltage phasor measurements subsynchronous torsional oscillations were detected, but the quality of the subsynchronous signals did not allow damping analysis with decent accuracy.

A. *Subsynchronous frequency response of PMU*

In Fig. 8 response of PMU output frequency and rate-of-change of frequency are shown, as the frequency of PMU voltage input was modulated using subsynchronous sinusoidal modulation signal with peak-to-peak amplitude of 10 mHz. Correspondingly, in Fig. 9 peak-to-peak variations observed in band-pass filtered frequency measurement are shown for speed modulation signal with peak-to-peak amplitude of 2.5 mHz. The short circuit capacity of the parallel network used was set to 3000 MVA.

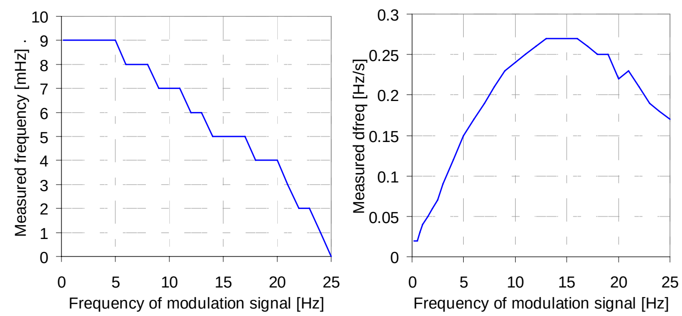

Fig 8. Inherent attenuation of PMU for frequency modulation using peak-to-peak amplitude of 10 mHz on subsynchronous frequency range

From Fig. 8 and 9 it is evident, that both the approaches provide very similar response characteristics. For pure frequency modulation subsynchronous frequencies below 20 Hz are clearly visible in PMU output frequency as expected. At 20 Hz the measured variation in frequency is 40 % of the real frequency variation. The maximum response in rate of change of frequency output of PMU is obtained on frequency range between 10 Hz and 20 Hz.

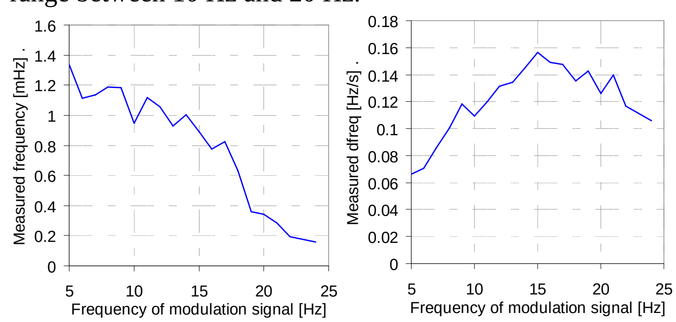

Fig 9. Frequency response of PMU for small amplitude (2.5 mHz) modulation of generator speed on subsynchronous frequency range

Also the subsynchronous components corresponding the frequency of speed modulation signal can be clearly observed in the frequency measured at the high voltage side of the step-up transformer up to 20 Hz. Together with the results shown earlier in this document, Fig. 8 and Fig. 9 clearly indicate that subsynchronous torsional oscillations below 20 Hz can be observed in PMU output presuming, that studied generator unit affects the system frequency and the measurements are performed in vicinity of the unit.

B. Validity of Subsynchronous Damping Calculation Methods

The validity of the approaches used in the subsynchronous damping calculation was analyzed using simple series compensated power system model System-1 presented in 2nd IEEE SSR benchmark [9]. In Fig. 10 the results of the analysis performed are compared with the results presented in [9]. As shown in Fig. 10 the correspondence between the PMU output based results and the results given in benchmark is very good even though the inherent attenuation of PMU is high around the studied frequency of 24.65 Hz. In Fig. 11 the validity of the damping calculation approach is presented on frequency range below 25 Hz comparing the results of PMU based analysis with similar frequency scanning analysis performed in PSCAD transient analysis environment [14]. Again, the correspondence of the results is very good.

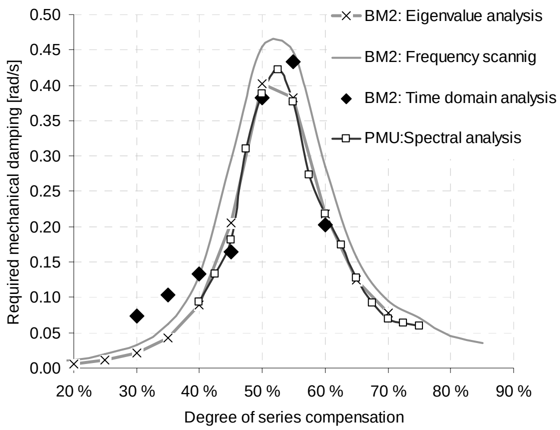

Fig 10. Comparison of PMU based results with results given in [8]

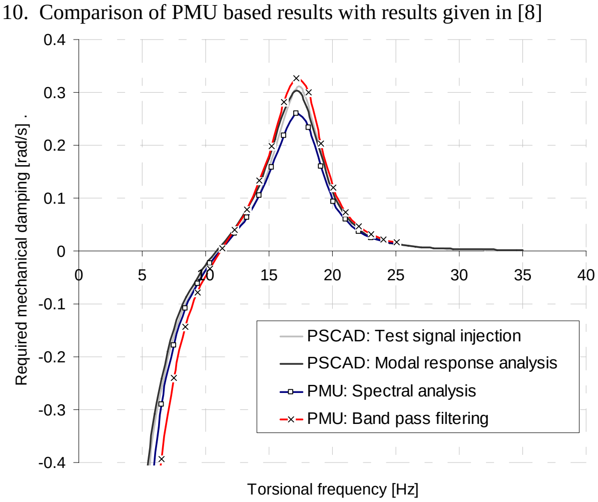

Fig 11. Comparison of PMU based results with simulation results obtained using PSCAD for System-1 with 75 % degree of series compensation

C. Detection and analysis of several different subsynchronous torsional frequencies

In the first and the second part of the tests capability of PMU to detect subsynchronous oscillations were studied only on one single subsynchronous frequency. Therefore, the performance of the proposed approach was finally analyzed under conditions, where two different turbine-generator structures with different torsional modes were connected into the AC-DC-network shown in Fig 3. In Fig. 12 the subsynchronous components obtained using standard deviation calculation for band-pass filtered rate-of-change of frequency signal are shown. The shape of the subsynchronous components illustrate clearly the damping of each below 20 Hz torsional mode given in table I. Thus, its obvious that the damping of the modes can be estimated also while several subsynchronous components due to torsional oscillations are superposed on the measured system frequency or rate-of-change of frequency.

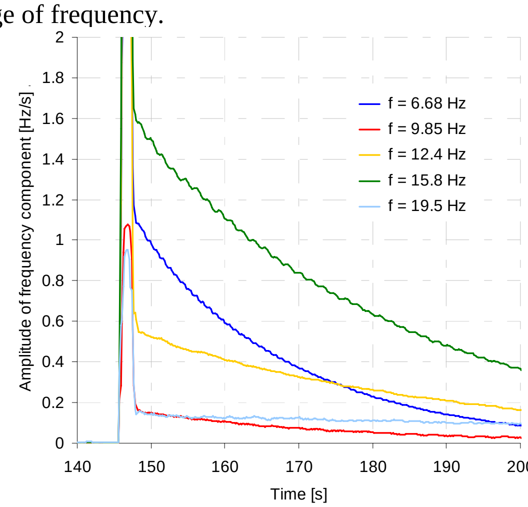

Fig 12. Attenuation of torsional components determined using standard deviation of the band-pass filtered rate-of-change of frequency

In Fig. 13 the logarithmical damping calculated based on subsynchronous components of PMU output frequency spectrum are shown after 30 % voltage dip at the rectifier bus. The strength of the AC system in parallel with the rectifier was in this case 2500 MVA and the spectrum is calculated using Hanning window with 2^8 samples. Damping in Fig. 13 is given as logarithmical decrement over period of 0.16 s. In Fig. 4 similar spectrum on two separate moments of time was shown while the strength of the AC network was set to 10 000 MVA.

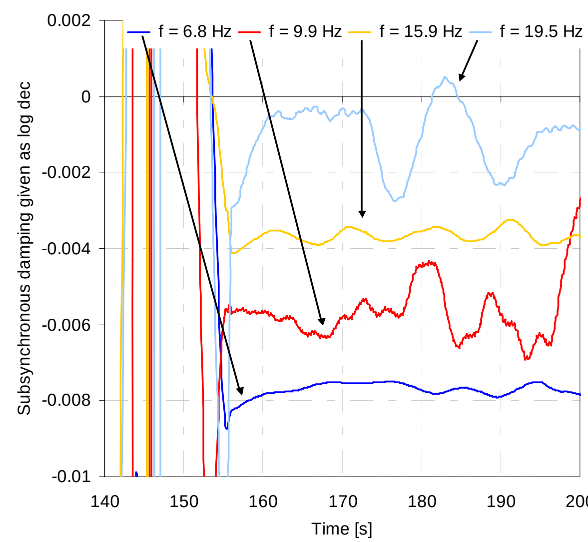

Fig 13. Subsynchronous damping calculated using results of spectral analysis performed for rate of change of frequency

Fig. 13 illustrates well the quality of damping estimation based on subsynchronous components determined using spectral analysis. Unlike in connection of high amplitude increasing oscillations, no highly accurate values for damping can be obtained using proposed methods. However, as shown in Fig. 13, good estimations of the amount of the total damping can be obtained. This was later verified by measurements performed in Finnish 400 kV transmission network, where both approaches were used in estimation of subsynchronous damping seen by a 950 MVA unit [13].

VII. Summary

In this paper an approach on subsynchronous damping analysis using PMU measurement data was presented. The methods to extract subsynchronous signals from PMU output data were tested in real-time simulation environment. Also, the verification of the methods used for subsynchronous damping analysis based on the PMU based signals was presented. Based on the results shown in this paper, it is evident that PMU output data can be used to observe the behavior of subsynchronous oscillations at least up to 20 Hz. Frequency and rate-of-change of frequency provided by PMU proved to be the most suitable measurement signals for subsynchronous damping analysis.

It's worth emphasizing, that the quality of measured oscillations is certainly lower than those based on generator speed measurements. Therefore, the presented approach shall not be considered as an alternative for torsional measurement systems. However, the presented approach allow observation of subsynchronous oscillations and evaluation of subsynchronous damping at the locations, where torsional measurement systems haven't been installed. The proposed approach can be for example used to evaluate the need for torsional measuring system after significant changes in transmission network structure, that may have potential decreasing effect on subsynchronous damping or increasing effect on level of post-disturbance torsional stresses.

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X. Biographies

Tuomas Rauhala was born in Rovaniemi, Finland, on September 11, 1979. He received his Master's degree in electrical engineering from Helsinki University of Technology, Finland, in January 2004. Since he has been working as research engineer and post-graduate student in Tampere University of Technology. His main research subjects are phenomena causing high amplitude subsynchronous oscillations and analysis of subsynchronous damping.

Pertti Järventausta was born in Urjala, Finland, on May 28, 1965. He received the Diploma Engineer and the Licenciate of Technology degrees in electrical engineering from Tampere University of Technology in 1990 and 1992, respectively, and the Dr. Tech. Degree in electrical engineering from Lappeenranta University of Technology in 1995. At present he is a professor at the Institute of Power Engineering of Tampere University of Technology. His research activities focus on electricity distribution (e.g. distribution automation, power quality and new business models), distributed generation, transmission systems, and electricity market.