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Power System Stabilizer Tuning with Presence of Torsional Oscillations

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SUMMARY

In this paper we present power system small signal stability and a methodology for optimally tuning Power System Stabilizer (PSS) parameters that meet the WECC/NERC PSS design criteria [1-3]. A PSS produces a supplementary control signal that acts through the automatic voltage regulator (AVR) to modulate the generator field. A properly tuned PSS will then produce positive damping torque to the electromechanical oscillations with frequencies typically in the range of 0.1 Hz to 3.0 Hz. A dual-input PSS model (IEEE PSS2B model, [1]), was considered in this work. A phase compensation approach was adopted and PSS parameters were determined for a thermal unit located within the AESO's (Alberta Electric System Operator) jurisdiction. During commissioning of the PSS, torsional oscillations were observed while performing a gain margin test. This oscillation impeded the completion of gain tuning. A notch filter was then designed and tuned to the frequency of torsional oscillations. Since the notch filter introduces additional phase lag, the PSS lead and lag were retuned. After implementing the notch filter and new PSS settings, the PSS was successfully commissioned.

KEYWORDS

Power system stabilizer, optimal tuning, phase compensation and gain margin, torsional oscillations.

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Introduction

A Power System Stabilizer (PSS) is designed to add damping torque to generator rotor oscillations by controlling its excitation using a stabilizing signal without jeopardizing synchronizing torque. The PSS should produce a component of electrical torque in phase with the rotor speed deviation and is designed to compensate for the phase lag that exists within the exciter and generator field circuit.

The input signal to the PSS needs to be filtered to attenuate any undesirable frequencies outside the frequency range of interest. A washout function having a time constant of 2.0-10.0 seconds is sufficient for DC and low-frequency filtering. Tuning of the low-pass and ramp-tracking filters is also required.

A torsional filter (if required) provides desired gain reduction at a specified frequency, and is used to attenuate torsional frequency components present in the input signal [4-5]. Phase compensation is provided through a few cascaded lead-lag functions, with each function practically compensating up to 60 degrees of overall phase angle.

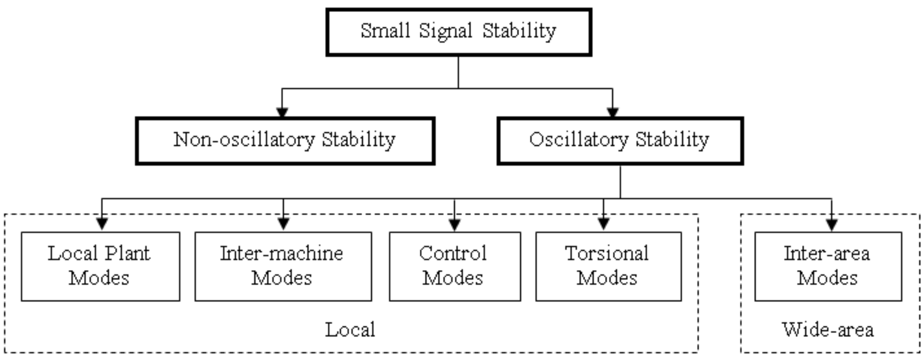
The PSS should be set for obtaining the desired damping without adverse effects.

Power System Stability

Small signal (or small disturbance) stability is the ability of a power system to maintain synchronism under small disturbances. Such disturbances occur continually on the power system due to variations in loads / generation. Stability is mainly determined by:

- Strength of transmission as seen by the plant (short circuit capability).
- Excitation control.
- Plant output and voltage.

Oscillatory instability, which results from a lack of damping torque, can be further classified into a number of modes of behaviour, namely, local plant, inter-machine, control, torsional, and inter-area modes. Typical frequencies of oscillation associated with either local plant mode oscillations or inter-machine oscillations are in the range of 0.7 to 2.0 Hz. Oscillations associated with control systems, commonly referred to as control modes, are mostly found at higher frequencies (>2.0 Hz), while generator shaft oscillations, commonly referred to as torsional modes, inherit mechanical modes of oscillation from the shaft system.



Two common oscillation patterns that can be readily solved using a PSS are: a) oscillation of a single generator or plant against rest of the power system, b) oscillation between a few generators close to each other. Considering a sufficiently small disturbance, linearization of the system of equations is permissible for analysis, and the classical K-constant method can be used to understand local mode stability problems (see Figure 1). Details of this method are described in Power System Stability and Control by Dr. P. Kundur [1].

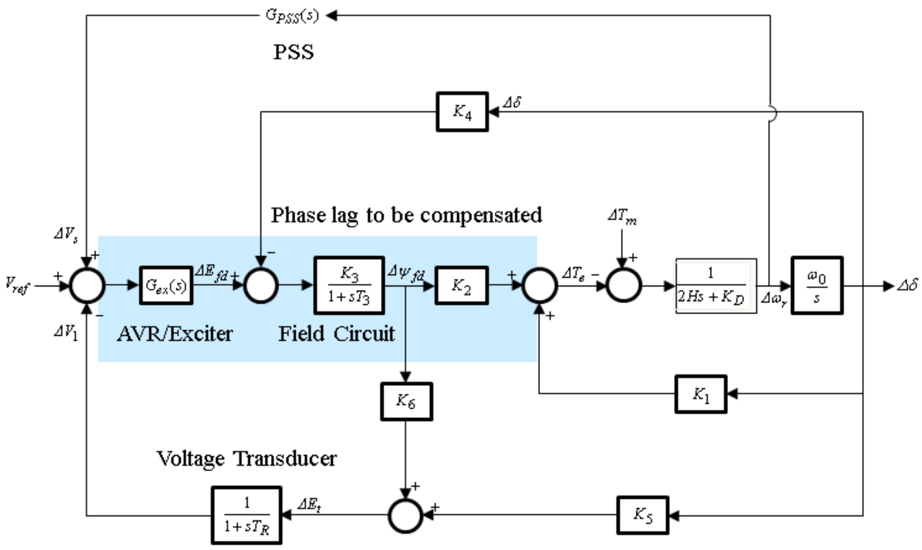


Figure 1: Linearized generator and excitation system

Negative K_5 is commonly encountered where high values of external system reactance and / or high generator output exists. With negative K_5, the AVR action introduces a positive synchronizing torque component and a negative damping torque component; an effect that is desirable for transient stability enhancement, while undesirable for small signal stability. The addition of a PSS can resolve this conflict, as it can enhance damping of inter-area modes, as well as that of local modes.

Large interconnected systems usually have two distinct forms of inter-area modes of oscillation:

1. A very low frequency mode involving all the generators in the system, where the system is essentially split into two parts such that generators in one part swing against generators in the other part with a frequency of oscillation on the order of 0.1 to 0.3 Hz (higher for smaller systems). On August 10, 1996, a 0.23 Hz unstable mode resulted from cascading outages triggered by a fault, and ultimately led to a wide-spread blackout in the Western United States, Canada and Northwest of Mexico.
2. Higher-frequency modes involving a sub-group of generators swinging against each other with a frequency of oscillation typically in the range of 0.4 to 1.0 Hz. Multiple groups of generators may be involved.

Inter-area modes of oscillation are complicated phenomena that are functions of network configuration / strength, load characteristics, and types of excitation systems and their locations. Analysis of such problems requires detailed representation of the system, and the development of mitigation methods requires consideration and comprehensive understanding of many factors. There is no universally applicable method available.

A PSS is one of the most practical and economical means of enhancing system stability as it improves both transient and small signal stability. Despite their relative simplicity, PSSs are perhaps one of the most misunderstood and misused power system controls. A PSS may be used with any type of exciter: fast or slow; static or rotating. They are most effective in enhancing overall system stability when used with high initial response exciters.

Power System Stabilizers

Damping generator rotor oscillations can be achieved by modulating excitation to develop a component of electrical torque in-phase with the speed deviations. The most logical signal to modulate excitation is speed deviation itself, $\Delta\omega_r$. Other signals including the integral of electrical power, or generator terminal frequency are also used.

If the transfer functions of the excitation system and generator were pure gains, direct feedback of $\Delta\omega_r$ would result in damping torque. In practice, however, both exhibit frequency dependent gain and phase characteristics. Phase compensation is therefore required to compensate for the phase lag between the AVR input and the electric torque of the generator. Exact phase compensation results in a pure damping torque component at all oscillating frequencies. Over-compensation introduces a negative synchronizing torque component, while under-compensation introduces a positive synchronizing torque component [4].

One of the main objectives of PSS design and tuning is to obtain an equivalent speed signal that is free of torsional modes and measurement noise. A delta-p omega PSS uses a ramp-tracking filter to condition the input signals. The resulting equivalent speed is then:

$$\Delta\omega_{eq} = G(s)\left[\Delta\omega(s) + \frac{\Delta P_e(s)}{2Hs}\right] - \frac{\Delta P_e(s)}{2Hs}$$

where G(s) is the ramp-tracking filter.

Some benefits of a dual-input PSS are that torsional oscillations are naturally attenuated, and the control is relatively insensitive to measurement noise and mechanical power variations. The typical structure of a dual-input PSS (IEEE PSS2B) is shown in Figure 2:

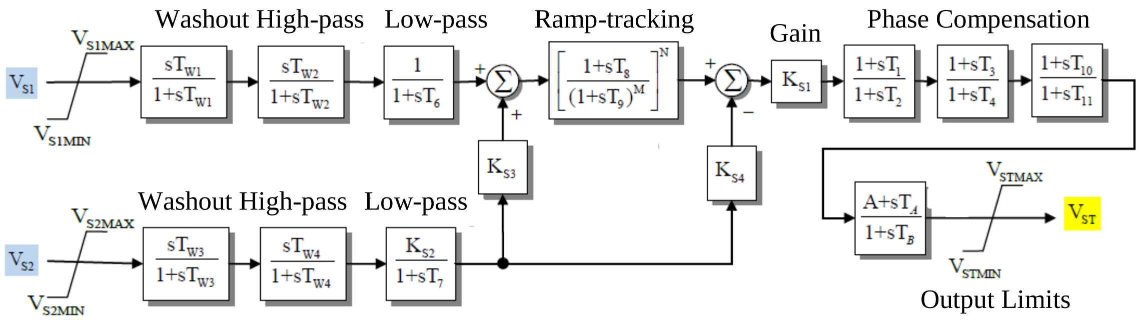


Figure 2: Functional block diagram of a general dual-input PSS

Suitability for PSS Installation

The uncompensated frequency response can be calculated or measured in a field test. This phase lag should be checked against the frequency response of the WECC suggested fitness function for PSS suitability [2]:

$$T(s) = \frac{1}{(1+1.59s)(1+0.159s)(1+0.0159s)}$$

If the measured phase lag exceeds the phase lag of the third-order fitness function in the frequency range of interest (0.1 to 1.0 Hz), the unit can be considered too slow for a PSS to prove to be effective.

PSS Tuning Methodology

The principal objectives of PSS tuning are:

- To ensure that the PSS provides maximum damping for the frequency range of interest, without adverse impact on the generator or system. This requires consideration of control modes, local modes, inter-area modes and the structure of the PSS.

- Enhance transient stability.
- Prevent adverse effects on system performance during major upsets (i.e. large frequency and voltage excursions).
- Minimize consequences of component failure.

To accomplish these objectives, certain criteria should be followed:

- Inputs should be in phase with generator speed and free of noise as much as possible.
- Washouts should react only to speed deviations.
- Phase compensators should provide required phase lead in the frequency range of interest.
- Gain should maximize the damping torque PSS can provide.
- Limit the PSS output during transients.

PSS parameters that are normally not be tuned are gain K_{S2} for electric power in a delta-p omega PSS and gain K_{S3} – this is set to 1. Parameters for which typical data may be used are washout and ramp-tracking filter time constants, and output limits. Parameters that are required to be carefully tuned are lead/lag time constants in the phase compensator and PSS gain.

The K_{S2}/T_7 block is a combined washout/integrator block. To ensure signal $\Delta\omega_{eq}$ adequately represents generator speed, K_{S2} should be set to $T_7/2H$.

In the PSS2B model, there are four washout and two lag time constants: T_{W1}, T_{W2}, T_{W3}, T_{W4}, T_6, and T_7. Both T_{W1} and T_{W2} are normally set for input speed, with T_6 = 0. Only one of T_{W3} and T_{W4} (the other set to zero), as well as T_7, should be set equal to T_{W1} and T_{W2} for input power. A washout is a high pass filter that prevents steady changes in the input signal from impacting excitation. The washout time constants should be high enough to allow signals associated with oscillations to pass unchanged and low enough to reduce noise. A lower value is used for higher frequencies, and vice versa. Typically, a value 2.0-10.0 seconds is sufficient for DC and low frequency filtering.

The ramp-tracking filter is basically a low-pass filter, such that within the low frequency range, $\Delta\omega_{eq}$ contains mostly speed and within the high frequency range, $\Delta\omega_{eq}$ contains mostly the integral of electric power. This helps overcome two basic problems found in single-input PSS, namely, torsional noise in generator speed in a delta-omega PSS and output deviation when the generator output is ramped in an electric power based PSS.

Although the filter characteristics are important for the overall PSS performance, its parameters generally do not depend on system conditions. The commonly used ramp-tracking filter coefficients are N=1 and M=5. To obtain 40 dB of attenuation at low torsional frequency (approximately 7 Hz), T_9 should be set to 0.1 seconds which results in T_8 being set to 0.5 seconds [4].

Theoretically, each lead / lag function can provide up to 90° of phase leading compensation. Practically, the maximum should not exceed about 60°. A two-block phase compensator can therefore provide up to 120° of phase compensation. The values of the time constants may be in a wide range from 0.01 seconds to 0.5 seconds, however, the ratios of the time constant (T_1/T_2, T_3/T_4, etc.) should typically not exceed 15.

Many approaches can be used to determine the phase lag to be compensated. A simple method, the "large inertia method", has been used effectively in many PSS applications. In this method, the inertia constant of the generator is set to large number. This effectively holds the generator speed and angle constant. Under this condition, the phase lag between the AVR reference point and the electric torque is the required phase to be compensated.

This phase characteristic can be easily computed using commercial software or preferably measured in the field. When it is calculated by software, it is best to make the phase characteristics smooth for compensator design by representing other generators in the system by infinite buses (behind reactance). The first author developed an educational tool in Microsoft Excel to determine the required compensation such that the compensated phase in the frequency of interest is within ±30°.

The main considerations during tuning are noise level in the input signals, impact on other modes (including control modes), magnitude of damping improvement and degree of PSS output saturation (limits) following system faults. The PSS overall gain may be set at the lowest of the following:

- 1/3 of the value that starts causing unacceptable output noises (from field testing), or that starts making the damping of any other modes unacceptable (from modal analysis).
- The value beyond which no significant damping improvement can be made.
- The value at which the PSS output becomes over-saturated even after the transients are settled following faults.
- The value that meets, with sufficient margin, the required performance criterion.

The PSS gain should be set for obtaining the desired damping without unacceptable adverse effects on other electromechanical or control modes. The WECC PSS design criteria requires the PSS gain margin of 6 to 10 dB (i.e. approximate factor of 2 to 3).

The WECC PSS design criteria requires that the stabilizer output limits be set to at least 5% of the generator terminal voltage. Setting the limits higher than 10% is normally not recommended since the stabilizer might lead to excessively high or low generator voltages, resulting in inadvertent protective relay or limiter operations that may trip the unit. A field test should be conducted to determine the adequate power level at which the tuned PSS is enabled. In general the PSS is not needed at low unit output. It is recommend to enable the PSS when the unit output is greater than 10%, and to have certain hysteresis included in the control logic to avoid inadvertent PSS switching operations at the enabling power level.

Commissioning of a Dual Input PSS

In this section, PSS tuning and commissioning of a unit connected to the Alberta Interconnected Electric System (AIES) at 144 kV is presented. The unit is equipped with a generator rated 58.59 MVA at 13.8 kV and 0.85 pf, and is powered by a gas-fired combustion turbine. The generator is equipped with brushless rotating excitation system and Basler DECS 250N AVR that features a built-in dual-input PSS.

To effectively commission the PSS, a PSS tuning study was carried out to determine the optimal settings for the stabilizer in order to achieve the best damping performance under various system conditions. The study was carried out by adhering to WECC PSS design and performance criteria [2].

In the study, the frequency response method was used to calculate the stabilizer phase compensation, root-locus techniques were used to determine the stabilizer gain, and network fault simulations were performed to check the dynamic performance. The performance of the tuned PSS with recommended parameter settings was evaluated by frequency-domain eigenvalue analysis, and further confirmed in time-domain simulations on the entire AIES.

Using the methodology described above, a Microsoft Excel based tool was developed to obtain the required phase compensation. A screen capture of the tool is shown in Figure 3.

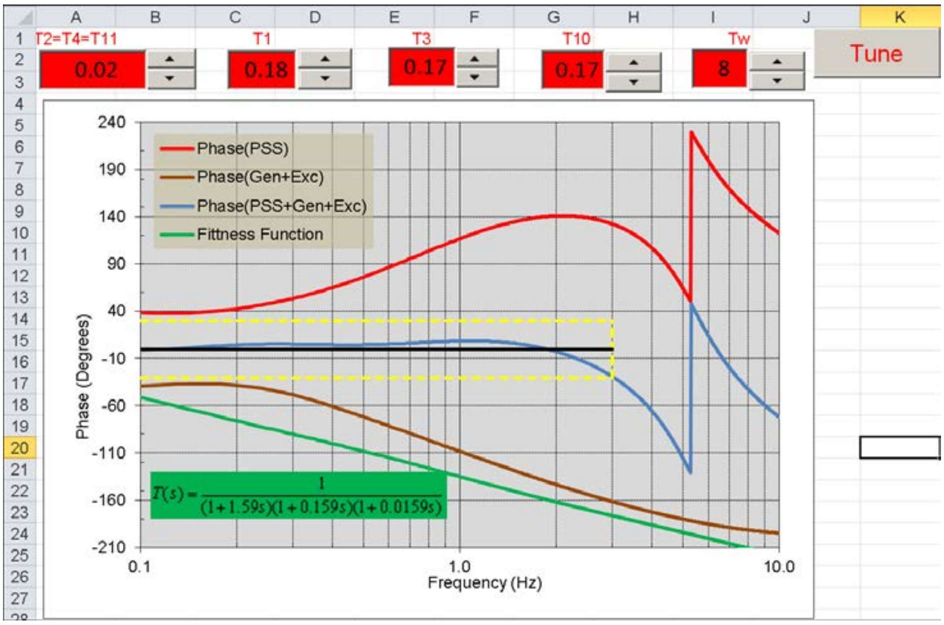


Figure 3: Main screen of PSS design tool

During commissioning of the PSS parameters, the frequency response of the exciter and generator was measured (see Figure 4). As commissioning continued, a 5.3 Hz oscillation was observed during the gain margin test. The oscillation was observed to progressively increase in magnitude as the PSS gain was increased from 0 to 3 (see Figure 5).

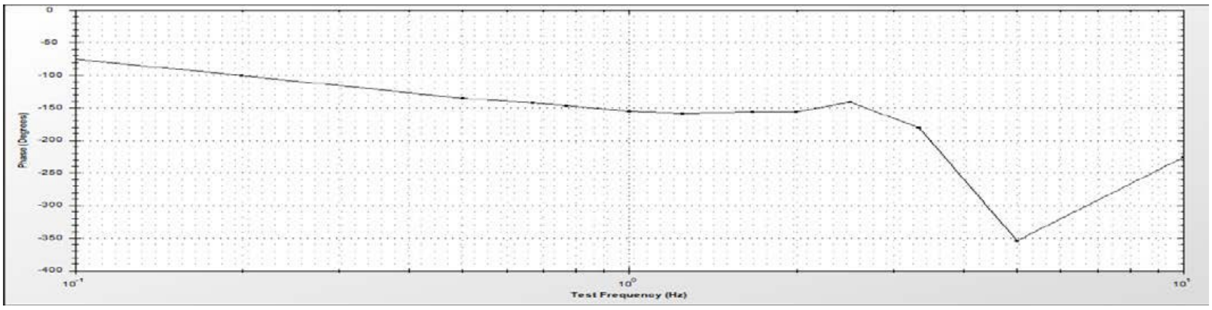


Figure 4: Frequency Response obtained from DECS250N – Phase Angle (Vt/Vref)

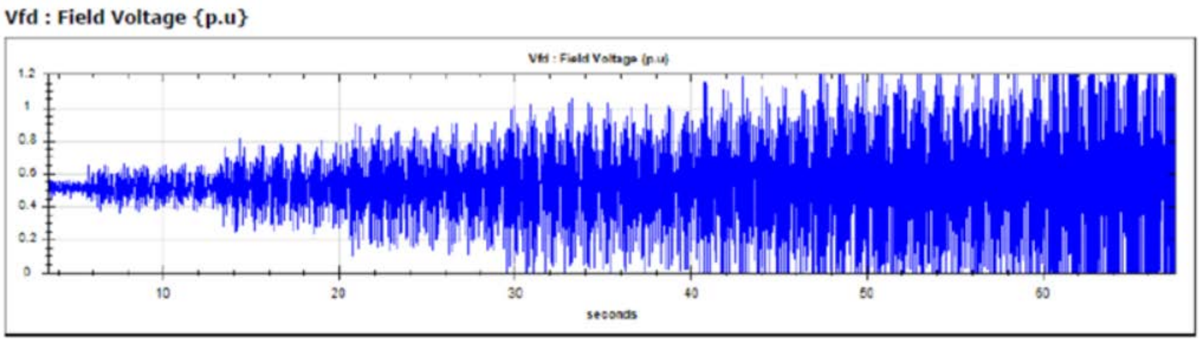


Figure 5: PSS gain margin test with existing PSS settings

Since the torsional oscillations hampered satisfactory operation of the PSS, the torsional filter within the Basler DECS 250N PSS was enabled. The torsional filter is implemented as a notch filter, and was tuned to 5.3 Hz with a bandwidth of 3 Hz in this particular case. The frequency response of the torsional filter alone is shown in Figure 6.

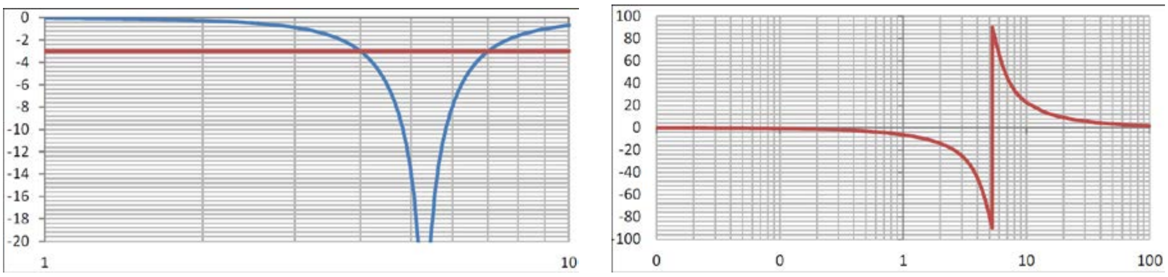


Figure 6: Frequency Scan of Torsional Filter – Magnitude (dB, left) and Phase Angle (degrees, right)

The PSS parameters were re-optimized considering the additional delay introduced by the torsional filter in the frequency range of interest (0.1-3 Hz). The oscillation of field voltage was observed (see Figure 7) to start at higher gain (10) compared with the previous PSS setting.

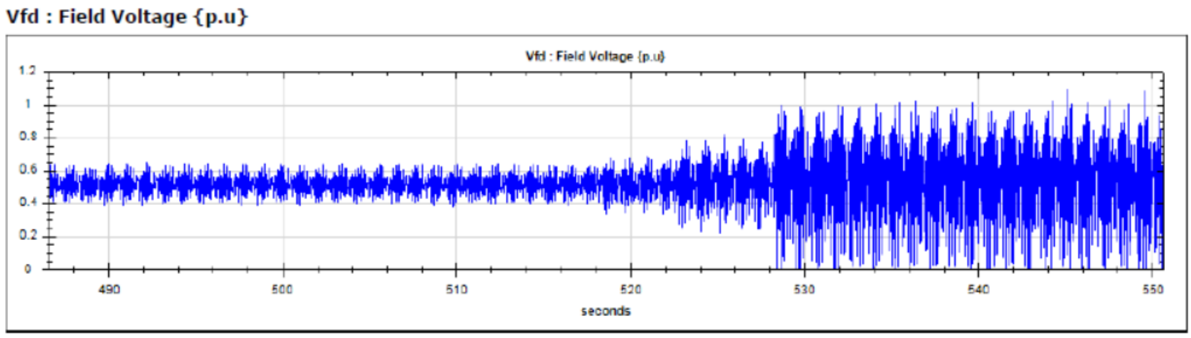


Figure 7: PSS gain margin test with new PSS settings

The PSS was successfully tested and commissioned, the PSS gain was increased from 0.5 to 5 pu.

Conclusion

In this paper we discussed power system small signal stability, power system stabilizer tuning methodology, and presented a case where torsional oscillations were observed while tuning a PSS in the field. A tuning study determined the optimal PSS settings according to WECC design criteria. Small signal analysis and fault simulations indicated that the tuned PSS significantly increased the damping of electromechanical oscillations associated with the unit. In addition, a torsional filter was designed to mitigate a 5.3 Hz torsional oscillation that was observed during field tests.

BIBLIOGRAPHY

[1]. IEEE Standard 421.5-2005, IEEE Recommended Practice for Excitation System Models for Power System Stability Studies.
[2]. WECC, “WECC Power System Stabilizer Design and Performance Criteria,” April 23, 2004.
[3]. VAR-501-WECC-3.1 – Power System Stabilizer, NERC Reliability Standard, 2017.
[4]. P.Kundur. "Power System Stability and Control", Mc. Graw Hill 1994.
[5]. A. Heniche, I. Kamwa, Torsional-mode identification for turbogenerators with application to PSS tuning. International Conference on Power Systems Transients (IPST’05) in Montreal, Canada on June 19-23, 2005, Paper No. IPST05 – 222.