Accelerating-Power Based Power System Stabilizers

G.R. Bérubé, L.M. Hajagos, Members
Kestrel Power Engineering Ltd.
Mississauga, Ontario, Canada

Abstract: This paper provides an overview of the key features of the accelerating power-based power system stabilizer (PSS). This design of PSS has been adopted by most major manufacturers and is integrated as an option in many digital excitation systems. The structure has been the topic of numerous published papers discussing the choice of input signals, parameter selection and advantages over other conventional PSS structures. This paper reviews the key design principles and application issues.

Keywords: Excitation Control, Power System Stability, Stabilizers, Ramp-Tracking Filters.

I. INTRODUCTION

Despite their relative simplicity, power system stabilizers may be one of the most misunderstood and misused pieces of generator control equipment. The ability to control synchronous machine angular stability through the excitation system was identified with the advent of high-speed exciters and continuously acting voltage regulators. By the mid-1960's several authors had reported successful experience with the addition of supplementary feedback to enhance damping of rotor oscillations [1].

The function of a PSS is to add damping to the unit's characteristic electromechanical oscillations. This is achieved by modulating the generator excitation so as to develop components of electrical torque in phase with rotor speed deviations. The PSS thus contributes to the enhancement of small-signal stability of power systems. Many excellent references are available with guidance on the selection of PSS settings once the required speed signal is provided as an input to the PSS [2,3,4,5].

Early PSS installations were based on a variety of methods to derive an input signal that was proportional to the small speed deviations characteristic of electromechanical oscillations [1,6,7]. After years of experimentation the first practical integral-of-accelerating-power based PSS units were placed in service [8,9,10]. This design provided numerous advantages over earlier speed-based units and forms the basis for the PSS implementation that is used in most units installed in North America. This design is now a requirement in many Reliability Regions within North America and has been modelled in the IEEE standards as the PSS2A and PSS2B structures [11]. For simplicity, the term PSS2A stabilizer will be used to refer to the integral-of-accelerating power based design in general throughout this paper.

This paper briefly describes some of the earlier structures in order to explain the advantages of the accelerating-power design. This design is then described along with a detailed review of the role of the "ramp-tracking" mechanical filter and the basis for the present structure that is in wide use by many manufacturers.

II. OVERVIEW OF PSS STRUCTURES

Shaft speed, electrical power and terminal frequency are among the commonly used input signals to the PSS. Alternative forms of PSS have been developed using these signals. This section describes the practical considerations that have influenced the development of each type of PSS as well as its advantages and limitations.

A. *Speed-Based ($\Delta\omega$) Stabilizer*

Stabilizers employing a direct measurement of shaft speed have been used successfully on hydraulic units since the mid-1960s. Reference [1] describes the techniques developed to derive a stabilizing signal from measurement of shaft speed of a hydraulic unit.

In early designs on vertical units, the stabilizer's input signal was obtained using a transducer consisting of a toothed-wheel and magnetic speed probe supplying a frequency-to-voltage converter. Among the important considerations in the design of equipment for the measurement of speed deviation is the minimization of noise caused by shaft run-out (lateral movement) and other causes [1,6]. Conventional filters could not remove such low-frequency noise without affecting the electromechanical components that were being measured. Run-out compensation must be inherent to the method of measuring the speed signal. In some early applications, this was achieved by summing the outputs from several pick-ups around the shaft, a technique that was expensive and lacking in long-term reliability.

The original application of speed-based stabilizers to horizontal shaft units (e.g. multi-stage 1800 RPM and 3600 RPM turbo-generators) required a careful consideration of the impact on torsional oscillations. The stabilizer, while damping the rotor oscillations, could reduce the damping of the lower-frequency torsional modes if adequate filtering measures were not taken. In addition to careful pickup placement at a location along the shaft where low-frequency shaft torsionals were at a minimum, electronic filters were also required in the early applications [7].

While stabilizers based on direct measurement of shaft speed have been used on many thermal units, this type of stabilizer has several limitations. The primary disadvantage is the need to use a torsional filter. In attenuating the torsional components of the stabilizing signal, the filter also introduces a phase lag at lower frequencies. This has a destabilizing effect on the "exciter mode", thus imposing a maximum limit on the allowable stabilizer gain [3]. In many cases, this is too restrictive and limits the overall effectiveness of the stabilizer in damping system oscillations. In addition, the stabilizer has to be custom-designed for each type of generating unit depending on its torsional characteristics. The integral-of-accelerating power-based stabilizer, referred to as the Delta-*P*-Omega (ΔPω) stabilizer throughout this section, was developed to overcome these limitations.

B. *Frequency-Based (Δf) Stabilizer*

Historically terminal frequency was used as the input signal for PSS applications at many locations in North America. Normally, the terminal frequency signal was used directly. In some cases, terminal voltage and current inputs were combined to generate a signal that approximates the machine's rotor speed, often referred to as "compensated" frequency.

One of the advantages of the frequency signal is that it is more sensitive to modes of oscillation between large areas than to modes involving only individual units, including those between units within a power plant. Thus it seems possible to obtain greater damping contributions to these "interarea" modes of oscillation than would be obtainable with the speed input signal [4].

Frequency signals measured at the terminals of thermal units contain torsional components. Hence, it is necessary to filter torsional modes when used with steam turbine units. In this respect frequency-based stabilizers have the same limitations as the speed-based units. Phase shifts in the ac voltage, resulting from changes in power system configuration, produce large frequency transients that are then transferred to the generator's field voltage and output quantities. In addition, the frequency signal often contains power system noise caused by large industrial loads such as arc furnaces [12].

C. *Power-Based* (ΔP) *Stabilizer*

Due to the simplicity of measuring electrical power and its relationship to shaft speed, it was considered to be a natural candidate as an input signal to early stabilizers. The equation of motion for the rotor can be written as follows:

$$\frac{\partial}{\partial t}\Delta\omega = \frac{1}{2H}(\Delta P_m - \Delta P_e) \qquad (1)$$

where

H = inertia constant
ΔP_m = change in mechanical power input
ΔP_e = change in electric power output
$\Delta\omega$ = speed deviation

If mechanical power variations are ignored, this equation implies that a signal proportional to shaft acceleration (i.e. one that leads speed changes by 90°) is available from a scaled measurement of electrical power. This principle was used as the basis for may early stabilizer designs. In combination with both high-pass and low-pass filtering, the stabilizing signal derived in this manner could provide pure damping torque at exactly one electromechanical frequency.

This design suffers from two major disadvantages. First, it cannot be set to provide a pure damping contribution at more than one frequency and therefore for units affected by both local and inter-area modes a compromise is required. The second limitation is that an un-wanted stabilizer output is produced whenever mechanical power changes occur. This severely limits the gain and output limits that can be used with these units. Even modest loading and unloading rates produce large terminal voltage and reactive power variations unless stabilizer gain is severely limited.

Many power-based stabilizers are still in operation although they are rapidly being replaced by units based on the integral-of-accelerating power design.

D. *Integral-of-Accelerating Power* (ΔPω) *Stabilizer*

The limitations inherent in the other stabilizer designs led to the development of stabilizers that measure the accelerating power of the generator [11,8,9]. The earliest systems combined an electrical power measurement with a derived mechanical power measurement to produce the required quantity. On hydroelectric units this involved processing a gate position measurement through a simulator that represented turbine and water column dynamics [6]. For thermal units a complex system that measured the contribution of the various turbine sections was necessary [10].

Due to the complexity of the design, and the need for customization at each location, a new method of indirectly deriving the accelerating power was developed. The operation of this design of stabilizer is described in references [9,8]. The IEEE standard PSS2A model used to represent this design is shown as Figure 1 [11].

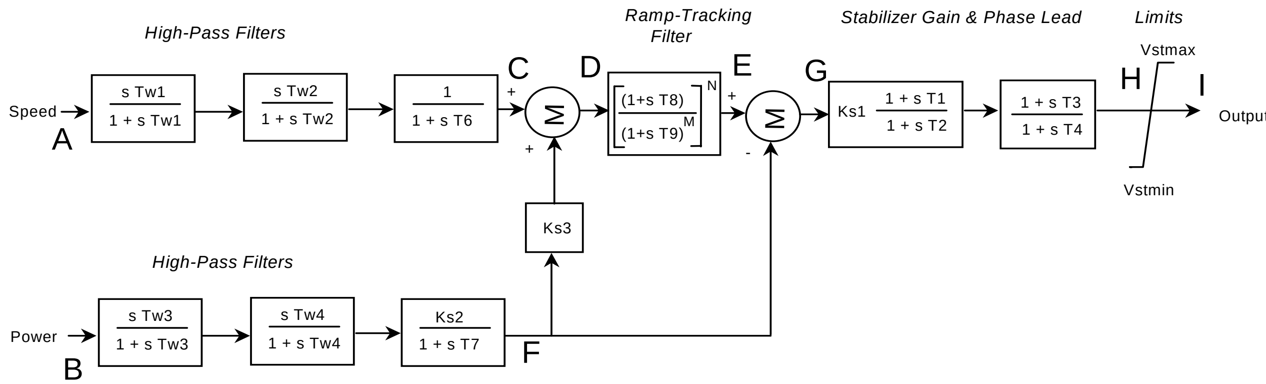


Fig 1. Accelerating Power PSS Model (PSS2A)

The principle of this stabilizer is illustrated by re-writing equation (1) in terms of the integral of power.

$$\Delta\omega = \frac{1}{2H}\int\left(\Delta P_m - \Delta P_e\right)\,\partial t \qquad (2)$$

The integral of mechanical power is related to shaft speed and electrical power as follows:

$$\int \Delta P_m \partial t = 2H\Delta\omega + \int \Delta P_e \partial t \quad (3)$$

The ΔPω stabilizer makes use of the above relationship to simulate a signal proportional to the integral of mechanical power change by adding signals proportional to shaft-speed change and integral of electrical power change. On horizontal-shaft units, this signal will contain torsional oscillations unless a filter is used. Because mechanical power changes are relatively slow, the derived integral of mechanical power signal can be conditioned with a low-pass filter to attenuate torsional frequencies.

The overall transfer function for deriving the integral-of-accelerating power signal from shaft speed and electrical power measurements is given by:

$$\int \frac{\Delta P_a}{2H}\partial t \rightarrow -\frac{\Delta P_e(s)}{2Hs} + G(s)\left[\frac{\Delta P_e(s)}{2Hs} + \Delta\omega \quad (s)\right] \quad (4)$$

where G(s) is the transfer function of the low-pass filter.

The major advantage of a ΔPω stabilizer is that there is no need for a torsional filter in the main stabilizing path involving the ΔP_e signal. This alleviates the exciter mode stability problem, thereby permitting a higher stabilizer gain that results in better damping of system oscillations. A conventional end-of-shaft speed measurement or compensated frequency signal can be used with this design.

III Practical Application Issues

Many excellent papers have been written dealing with the tuning of PSS [4,5]. These authors dealt with the selection of phase compensation, gain and output limit settings and their effect on the overall performance of the PSS. This will not be repeated here. Instead, this section will focus on the derivation of the accelerating-power signal and its use in deriving an equivalent speed signal. Specifically, this section will describe the impact of speed measurement issues and mechanical power variations on the operation of units equipped with this style of PSS and how this has influenced the design of PSS2A stabilizers.

With a large base of installed units, and long history of usage, experience has been acquired with many different vintages of hardware. Early designs suffered from failures due to mechanical components such as speed pickups. Replacement of the measured speed signal with a derived frequency signal has greatly improved reliability at many facilities. The early analog-electronic designs also suffered from reliability problems due to failures of components used to implement the adjustable settings (e.g. switches, potentiometers). Digital designs have eliminated these components and improved reliability and ease of use. Further gains in reliability are achieved when the PSS is implemented as additional software code in a complete digital excitation system, since this eliminates any additional hardware.

A. Signal Mixing

Referring to the block diagram of Figure 1, the two input signals to the ΔPω stabilizer are speed (A) and active power (B). Although the ΔPω design has many advantages over stabilizers that employ only one of these inputs it is sensitive to the relationship between these two inputs. For optimum performance it is critical that the two signal paths (A-C and B-F) are matched in terms of gain and filter time constants.

The power path employs two high-pass filter stages and an integration to derive the integral-of-electrical power change signal, ΔP_e:

$$\int \frac{\Delta P_e}{2H} \rightarrow \left(\frac{sT_W}{1+sT_W} \right)^2 \frac{1}{s2H} P_e \quad (5)$$
$$\rightarrow \left(\frac{sT_{W3}}{1+sT_{W3}} \right) \left(\frac{K_{S2}}{1+sT_7} \right) P_e$$

The second part of Equation 5 is based on the notation of Figure 1 and the following settings:

$T_{W3} = T_7 = T_W$
$T_{W4} = 0$ (i.e. this block is bypassed)
$K_{S2} = T_W / (2H)$
$K_{S3} = 1$

In order for the speed signal path to match the power path it must employ two stages of high-pass filtering as well, and its equivalent filter time constant must be kept as small as possible:

$T_{W1} = T_{W2} = T_W$
$T_6 \approx 0$

With these settings the signal appearing at point D is proportional to changes in the integral-of-mechanical power, ΔP_m. When re-combined with the ΔP_e signal at point G, the integral-of-accelerating power, ΔP_a, is formed. This signal is then treated as equivalent speed and the phase lead blocks that follow are set to compensate in order to maximize the contribution of the stabilizer to damping torque.

B. Mechanical Power Variations

Although the original requirement for the PSS units was based on a need to provide damping for the local plant modes of oscillation, many new installations and retrofits have been applied to improve damping of inter-area modes of oscillation [5] as is common in western U.S. utilities. In order to be effective at damping these modes of oscillation, the high-pass filters, parameters Tw1 to Tw4 in Figure 1, must be set to admit frequencies as low as 0.1 Hz without significant attenuation or the addition of excessive phase lead.

Early attempts at re-tuning PSS for these frequencies identified some side effects related to mechanical power variations on the units. Tests on the original $\Delta P\omega$ design on thermal units included fast intercept valve closures that produced a step change in power of approximately 5%, followed by a ramp of 0.55%/s [7]. The maximum generator terminal voltage change produced by a PSS configured with short washout time constants was below 2%, for the normal in-service gain. On the first tests of this design on hydraulic units, mechanical power ramp-rates in excess of 10%/s were achieved under gate limit control.

The introduction of long high-pass filter time constants produced excessive terminal voltage and reactive power deviations. In response to this problem, researchers identified the root cause of the variations and modified the designs accordingly.

When mechanical power is changed rapidly, electrical power follows quickly but there is a limited change in the rotor speed. Although this depends on the strength of the system interconnection, the speed changes will always be relatively small and are considered to be negligible in the following analysis.

Referring to Figure 1, when electrical power (B) is ramped, the integral-of-electrical power signal (F) will change with a rate and magnitude determined by the selected washout time constants and unit inertia. From this point forward, the signal follows two paths to the output. The lower path is a direct connection to the derivation of the equivalent speed signal at point G. The signal produced at point F also travels through the mechanical power low-pass filter (E) before appearing at the output. Ideally these signals would exactly cancel each other, since the PSS was not intended to produce an output for this condition. With long washouts and high ramp rates, this is not the case and a large error signal can propagate to the PSS output, thereby changing terminal voltage and reactive power on the unit. This problem forced the selection of low PSS gains or output limits, severely limiting the effectiveness of the PSS.

The transfer function between the power input, P_E, and the integral-of-accelerating power signal, P_A, (points B and G in Figure 1) may be written as follows:

$$\frac{P_A(s)}{P_E(s)} = \left(\frac{sT_{W3}}{1+sT_{W3}} \right) \frac{K_{S2}}{1+sT_7} \left(G(s) - 1 \right) \quad (6)$$

The original design of mechanical power low-pass filter consisted of a simple multi-pole filter of the form:

$$G(s) = \frac{1}{(1+sT_9)^M} \quad (7)$$

which is achieved in the model by setting the following values:

$T_8 = 0$
$N = 1$

The filter order, M, and time constant, T_9, can be selected to provide adequate attenuation of the lowest torsional frequency for horizontal-shaft applications.

Researchers [13] discovered that they could reduce the sensitivity to mechanical power variations by re-designing the mechanical power low-pass filter to utilize a transfer function of the form:

$$G(s) = \left(\frac{1 + \frac{2\xi}{\omega_o} s}{\frac{s^2}{\omega_o^2} + \frac{2\xi}{\omega_o} s + 1} \right)^M \quad (8)$$

Further analysis and tests on actual hardware implementations confirmed that the complex-pole implementation was not optimal and that the following transfer function could be used to reduce mechanical power effects on the PSS output.

$$G(s) = \left[\frac{(1 + sT_8)}{(1 + sT_9)^M} \right]^N \quad (9)$$

The filter of equation 9 is frequently identified as a "ramp-tracking" filter based on its properties when the coefficients, T_8, T_9, M and N are selected correctly.

The criteria used to analyze the merits of different mechanical power filter designs are the following:

- Attenuate high-frequency components in the input signal.
- Allow low-frequency mechanical power changes to pass through with negligible attenuation.
- Minimize the PSS output deviation that occurs when the mechanical power is changing rapidly.

Based on torsional frequencies as low as 7 Hz, the first two criteria dictated the selection of filters with four poles (M=4) and time constants (T_9) of 0.08 seconds. These filters were used on numerous large horizontal units but did not meet the third criteria, especially when applied to hydroelectric units with their rapid ramp rates.

To understand the advantages of the "ramp-tracking" filter and the required selection of coefficients it is instructive to compute the accelerating power signal that is generated when mechanical power changes rapidly. For this purpose, the integral-of mechanical power changes are characterized as combinations of the following time-domain inputs:

- step, A*u(t)
- ramp, B*t
- parabola, C*t^2

where t is time in units of seconds and A, B and C are the magnitudes of the associated components in per unit.

The steady-state P_A signal for each of these inputs can be calculated using the final value theorem by evaluating the following:

$$\lim_{t\to\infty} p_A(t) = \lim_{s\to 0}(s * \text{Input} * (G(s) - 1)) \quad (10)$$

Appendix A provides details of the evaluation of equation (10) for a conventional low-pass filter (eqn.7) and the ramp-tracking filter (eqn.9). The result for each type of input is summarized in Table 1.

Table 1: Steady State Response to Power Variations

Input	Steady-State Output	
	Low-Pass	Ramp-Tracking
step input	0	0
ramp input	-B*M*T_9	0
parabolic input	infinite	-C*F(M,T_9)

The key result in this table is that the ramp-tracking filter produces a zero steady-state output for a ramp input and a bounded output for a parabolic input. This is only true if the coefficients are selected to satisfy

$$T_8 = M * T_9 \quad (11)$$

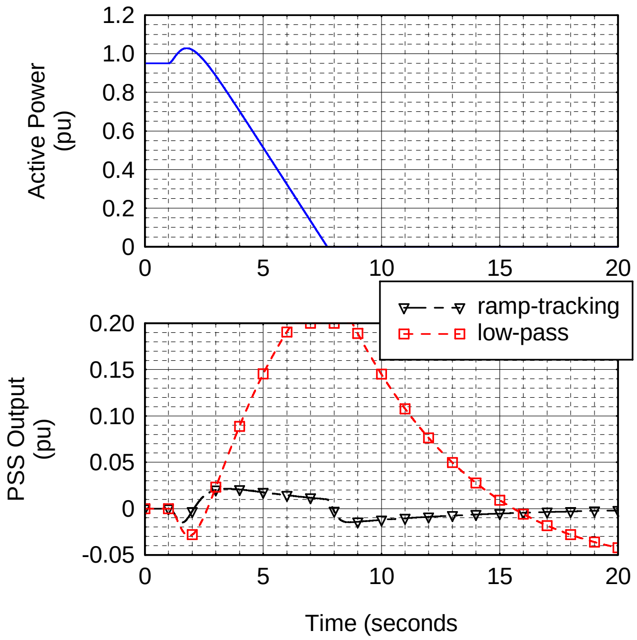
The derivation of the results provided in Table 1, including the relationship of Eqn(11) is included as Appendix A.

The most commonly used ramp-tracking filter coefficients are N=1 and M=5 since this provides four net poles with the minimum number of numerator and denominator terms. To obtain 40 dB of attenuation at 7 Hz, the denominator time constants are set to 0.1 s, resulting a numerator time constant of 0.5 s.

With this design, the filtered integral-of-mechanical power signal can track rapid rates-of-change in the measured electrical power signal, greatly reducing the terminal voltage modulation produced by the PSS. Figure 2 displays the simulated output of stabilizers equipped with a conventional and ramp-tracking low-pass filter to a power ramp on a hydraulic turbine. Clearly the ramp-tracking filter greatly reduces the PSS output deviation for this condition.

Different coefficients and time constants can be used to improve the tracking of power ramps or to provide greater attenuation of low-frequency torsional components. Increasing the denominator order or the denominator time constant is a viable alternative to introducing notch filters at torsional frequencies since it does not interfere with the selected phase compensation of the resulting accelerating power signal. This will increase the sensitivity of the stabilizer to power changes however this is normally acceptable on large horizontal shaft units with their slow loading rates.

Figure 2 Simulated Ramp Response



The performance of this filter may also be critical to the behaviour of the unit, in the event of inadvertent islanded operation resulting in large frequency and mechanical power variations.

C. Input Signals

Electrical power is readily available as an input. In analog implementations it can be measured using a three-phase Hall-effect watt transducer or equivalent device that produces an instantaneous output proportional to the generator active power. Selective filtering is required to remove the characteristic harmonics present in the output measurement. In digital implementations a variety of techniques are available to calculate power from the sampled ac voltage and current measurements. In either case the key is to not add unnecessary filtering and phase lag that will affect the phase compensation in this signal path. This has been achieved with good success in various manufacturers' implementations for many years.

The original $\Delta P\omega$ stabilizers employed a physical measurement of shaft speed using magnetic speed pickups as the source. A frequency-to-voltage converter was then used to generate the required direct measurement of speed. This necessitated the use of filtering and as a result, the input speed probe signals had to be relatively high frequency, necessitating multiple probes and toothed wheel or milled slot. Once again careful selection of the filtering was necessary to avoid the introduction of phase lag in this path. In applications where excessive filtering is used, the time constant, T_6, can be used in the model of Figure 1 to simulate the effect on overall stabilizer performance.

Although there is a long history of speed measurement in excitation control, it introduces several complications to the application of the stabilizer. Since it requires the only moving parts in the entire device, it is the least reliable element of the design. Numerous stabilizers have been temporarily disabled or have failed during operation due to improper gapping of speed measurement probes or failure of physical or electrical connections. On vertical shaft hydraulic units, there was the significant additional complication of dealing with shaft runout. On these units there can be a significant lateral movement of the shaft that varies with load level. Regardless of the location of the pickups, once-per-revolution noise appears at some level. On units with speed in the range of 100 rpm this is very significant since the noise component may coincide with the local mode electromechanical frequency of the unit. Early speed based stabilizers coped with this problem through an ingenious mechanical arrangement that made use of up to 5 speed probes mounted equidistant around the circumference of the shaft to eliminate the runout component [5]. Although this worked and formed the basis for many successful stabilizer installations it was costly due to the need for customization at each location. It was also relatively unreliable due to the requirement to have all probes in operation for the cancellation effect to function properly.

For these reasons, direct speed measurement was gradually phased out in favour of compensated frequency, which can be measured using the same PT and CT inputs that are already available for measurement of electrical power.

C.1 Compensated Frequency

Direct terminal frequency, measured from the generator PTs, has been used as an input signal in many stabilizers in the past. Its advantages and disadvantages were discussed earlier. It cannot be used directly in a $\Delta P\omega$ stabilizer configuration. Referring to the signal nomenclature of Figure 1, it is a requirement that the "speed" signal at point A match the power signal at point B so that the derived integral-of-mechanical power signal at point D represents equation 3 accurately. Any error in the derivation of the signal at point D due to signal mismatch will pass through the filter to point E and will result in an error in the stabilizer output.

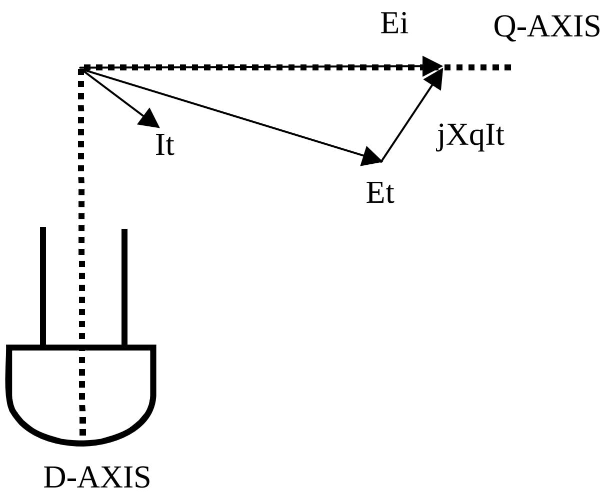
The extent to which the electromechanical components appear in terminal frequency is dependent on the component and the system strength. For example inter-machine modes between two units connected together at their low-voltage bus will be completely absent in a frequency signal measured from the generator PTs. Inter-area modes involving large groups of units will be visible in the terminal frequency but local machine modes will be greatly attenuated in for strong system connections.

Based on the above, frequency measurement can only be used if the ac source can simulate a voltage that is coupled directly to shaft position changes. Both the generator terminal voltage and a voltage proportional to the generator's terminal current are used in deriving the “internal voltage”. A voltage behind quadrature axis reactance is used for this purpose:

$$\overline{E_i} = \overline{E_t} + jX_q \overline{I_t} \quad (12)$$

where Xq has been used to denote an impedance proportional to the generator’s quadrature axis impedance.

Figure 3 Compensated Phasor



For steady-state conditions the phasor derived from the synchronous q-axis reactance will be aligned with the quadrature axis is depicted in Figure 3. As the rotor moves, the phasor derived in this manner will maintain its position where the frequency derived from the compensated phasor will contain the desired electromechanical components. Since the rotor is in motion, the compensating reactance should represent the quadrature reactance that applies to the frequency range of interest. For round-rotor machines this normally requires an impedance value close to the transient quadrature reactance. Each generator will be somewhat different, and the compensating reactance should be selected based on knowledge of the machine reactances and time constants.

IV. Hardware Considerations

The hardware should be designed so as to allow setting of the PSS parameters over a sufficiently wide range. The design should also ensure a high degree of functional reliability and allow sufficient flexibility for maintenance. These requirements are often overlooked, resulting in unreliable and unsatisfactory performance of the PSS, much to the frustration of operators. There have been many instances of operators turning off the PSS because of poor performance resulting from inadequate hardware design and improper selection of control parameters.

The requirement for high reliability and maintainability of PSS and other elements of the excitation system may be in part satisfied by component redundancy. Duplicate voltage regulators and PSS [3,9] have been used on critical generating units. One voltage regulator with its PSS would be in service at any one time with the other tracking it. In the event of a PSS malfunction, various protective features would initiate transfer to the alternate regulator and PSS. In addition to improving the detection of PSS failures, this feature limits the adverse consequences of such failures. The improved reliability and reduced parts count of newer digital exciters, with built-in PSS, have mitigated the need for such complex systems.

Another feature worth incorporating in a PSS is built-in facility for dynamic tests. This allows routine testing of PSS periodically by station personnel in order to detect latent failures [9]. A convenient way to test the performance of a PSS is to inject a small (1 to 2%) change in the PSS output (AVR terminal voltage reference) signal and monitor the responses of key variables such as generator terminal voltage, field voltage, power output, frequency, and PSS output. Such a test facility is also very useful during PSS commissioning.

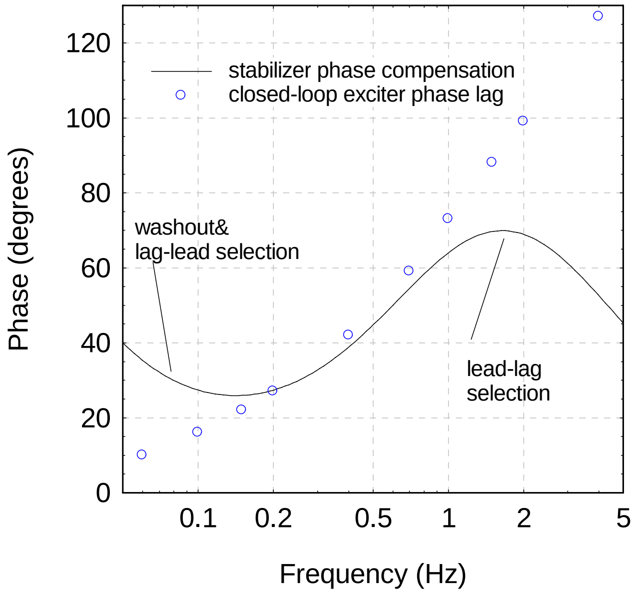
V. PSS Commissioning and Field Verification

During field commissioning, the actual response of the generating unit with the PSS is measured and used to verify some of the analytical results. Typical tests performed during commissioning include:

- measurement of the on-line closed-loop excitation system phase compensation requirements (Fig. 4),
- step response tests to measure damping improvement at local mode frequencies (Fig. 5),
- load-ramping tests to ensure that the PSS does not produce undesirable modulation of the unit’s terminal voltage under normal or emergency operating conditions (Fig. 6)

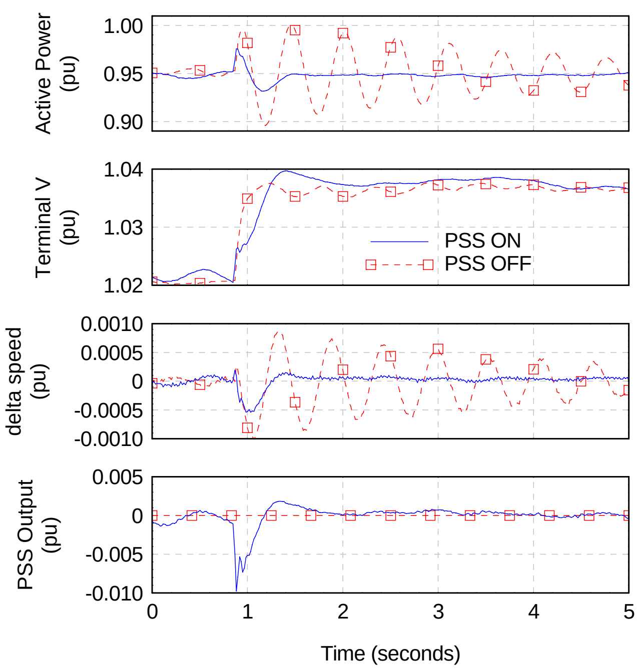
As noted in the previous section, the tests usually consist of injecting small step changes to the voltage regulator terminal voltage reference and monitoring a number of generator variables. If there are discrepancies between computed and measured responses, the models are appropriately modified; if necessary, revised PSS settings are determined and implemented. This "closed loop" design and commissioning process is very effective [14].

Figure 4 Closed-Loop Exciter Phase Compensation



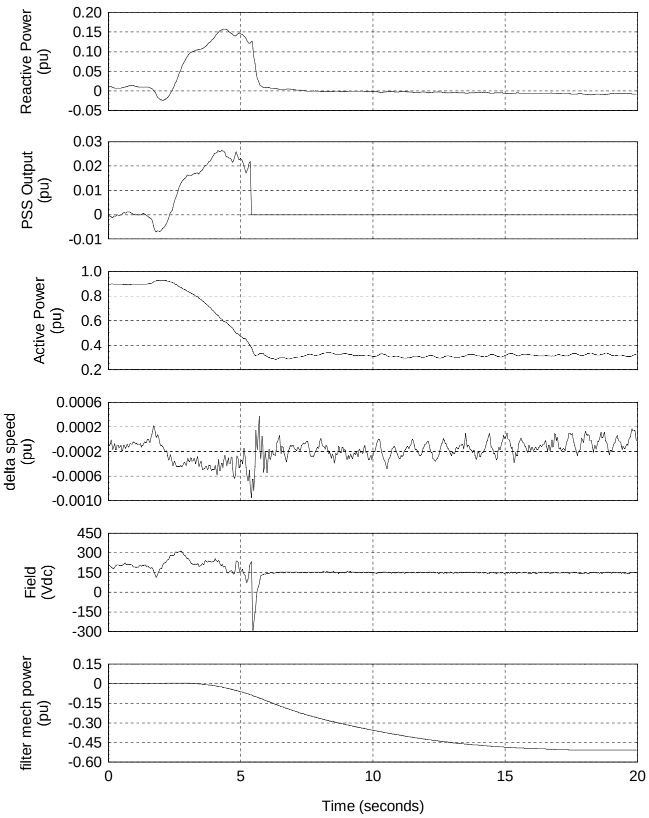
Initially, the PSS gain should be increased slowly, with transient testing at each setting. To insure sufficient stability margin, a good practice is to check the performance of the PSS with the gain increased up to twice the normal in-service setting. The objective is to ensure that the PSS gain is set at a value well below the limit at which either the exciter mode is unstable or there is excessive amplification of input signal noise.

Figure 5. Stabilizer On-Line Step Response



Tests and simulations performed on all types of utility-scale generators, including large and small hydro, large fossil-fired and nuclear units and combustion turbines, have consistently demonstrated that a conventional PSS tuned and tested in this manner, will improve stability for any reasonable operating scenario.

Figure 6. Fast Load Ramp



Appendix A - Derivation of Filter Responses

A.1 Background

The conventional low-pass filter and ramp-tracking filter are both based on the general form of a filter:

$$G(s) = \frac{(1+sT_8)}{(1+sT_9)^M} \quad \text{(A.1)}$$

The steady-state response of the output, y, to various inputs, u, is calculated from the final value theorem.

$$\lim_{t\to\infty} y(t) = \lim_{s\to 0}(s * U(s) * (G(s)-1)) \quad \text{(A.2)}$$

A.2 Conventional Low Pass Filter

The conventional low-pass filter is obtained from A.1 by setting T_8 = 0. The denominator of A.1 can be expanded as follows:

$$(1+sT_9)^M = \sum_{i=0}^{M} a_i (sT_9)^i \quad \text{(A.3)}$$

Some of the coefficients may be written by inspection as follows:

$a_0 = a_M = 1$
$a_1 = a_{M-1} = M$

The other coefficients are not critical to the analysis of the steady-state response. Substituting A.3 into A.1 yields:

$$G(s)-1 = \frac{1}{\sum_{i=0}^{M} a_i (sT_9)^i} - 1 = -\frac{sT_9 \sum_{i=1}^{M} a_i (sT_9)^{i-1}}{1+\sum_{i=1}^{M} a_i (sT_9)^i} \quad \text{(A.4)}$$

where the fact that a_0=1 has been used to reduce the numerator and expand the denominator.

Step input: U(s) = A/s

$$\lim_{t\to\infty} y(t) = \lim_{s\to 0} s\left(-\frac{A}{s}\frac{sT_9 \sum_{i=1}^{M} a_i (sT_9)^{i-1}}{1+\sum_{i=1}^{M} a_i (sT_9)^i}\right) = 0 \quad \text{(A.5)}$$

Ramp input: $U(s)=B/s^2$

$$\lim_{t\to\infty} y(t) = \lim_{s\to 0} s\left(-\frac{B}{s^2}\frac{sT_9 \sum_{i=1}^{M} a_i (sT_9)^{i-1}}{1+\sum_{i=1}^{M} a_i (sT_9)^i}\right) = \lim_{s\to 0}\left(-\frac{BT_9\left(a_1 + \sum_{i=2}^{M} a_i (sT_9)^{i-1}\right)}{1+\sum_{i=1}^{M} a_i (sT_9)^i}\right) = -B * T_9 * M \quad \text{(A.6)}$$

Parabolic input: C/s^3

$$\lim_{t\to\infty} y(t) = \infty$$

A.3 Ramp-Tracking Filter

$$G(s)-1 = \frac{1+sT_8}{\sum_{i=0}^{M} a_i (sT_9)^i} - 1 = \frac{s(T_8 - MT_9) - \sum_{i=2}^{M} a_i (sT_9)^i}{\sum_{i=0}^{M} a_i (sT_9)^i} \quad \text{(A.7)}$$

Step input: U(s) = A/s (A.8)

$$\lim_{t\to\infty} y(t) = \lim_{s\to 0} s\left(-\frac{A}{s}\frac{s(T_8 - MT_9) - \sum_{i=2}^{M} a_i (sT_9)^i}{\sum_{i=0}^{M} a_i (sT_9)^i}\right) = 0$$

Ramp input: $U(s) = B/s^2$ (A.9)

$$\lim_{t\to\infty} y(t) = \lim_{s\to 0} s\left(-\frac{B}{s^2}\frac{s(T_8 - MT_9) - \sum_{i=2}^{M} a_i (sT_9)^i}{\sum_{i=0}^{M} a_i (sT_9)^i} \right)$$
$$= T_8 - MT_9$$

A.9 equates to zero as long as $T_8 = M*T_9$

Ramp input: $U(s) = C/s^3$ (A.10)

$$\lim_{t\to\infty} y(t) = \lim_{s\to 0} s\left(-\frac{C}{s^3}\frac{\sum_{i=2}^{M} a_i (sT_9)^i}{\sum_{i=0}^{M} a_i (sT_9)^i} \right)$$
$$= \lim_{s\to 0}\left(-C\frac{a_2 T_9 + \sum_{i=3}^{M} a_i s^{i-2} T_9^{\,i}}{1 + \sum_{i=1}^{M} a_i (sT_9)^i} \right)$$
$$= -CT_9 \sum_{i=0}^{M-1} i$$

The reduction is based on the assumption that the coefficient relationship, $T_8 = M*T_9$, has been used. In this case the response to a parabolic input will be bounded and will increase with the number of poles and time constant as expected.

References

[1] P.L. Dandeno, A.N. Karas, K.R. McClymont, and W. Watson, "Effect of High-Speed Rectifier Excitation Systems on Generator Stability Limits," *IEEE Trans*., Vol. PAS-87, pp. 190-201, January 1968.

[2] P. Kundur, M. Klein, G.J. Rogers, and M.S. Zywno, "Application of Power System Stabilizers for Enhancement of Overall System Stability," *IEEE Trans.*, Vol. PWRS-4, pp. 614-626, May 1989.

[3] P. Kundur, D.C. Lee, and H.M. Zein El-Din, "Power System Stabilizers for Thermal Units: Analytical Techniques and On-site Validation," *IEEE Trans*., Vol. PAS-100, pp. 81-95, January 1981.

[4] E.V. Larsen and D.A. Swann, "Applying Power System Stabilizers, Parts I, II, and III," *IEEE Trans*., Vol. PAS-100, pp. 3017-3046, June 1981.

[5] M. Klein, G.J. Rogers, S. Moorty, and P. Kundur, "Analytical Investigation of Factors Influencing Power System Stabilizers Performance," *IEEE Trans. on Energy Conversion*, Vol. 7, pp. 382-390, September 1992.

[6] W. Watson and G. Manchur, "Experience with Supplementary Damping Signals for Generator Static Excitation Systems," *IEEE Trans*., Vol. PAS-92, pp. 199-203, January/February 1973.

[7] W. Watson and M.E. Coultes, "Static Exciter Stabilizing Signals on Large Generators – Mechanical Problems," *IEEE Trans*., PAS-92, pp. 204-211, January/ February 1973.

[8] F.P. deMello, L.N. Hannett, and J.M. Undrill, Practical Approaches to Supplementary Stabilizing from Accelerating Power," *IEEE Trans*., Vol. PAS-97, pp. 1515-1522, September/October 1978.

[9] D.C. Lee, R.E., Beaulieu, and J.R.R. Service, "A Power System Stabilizer Using Speed and Electrical Power Inputs – Design and Field Experience," *IEEE Trans*., Vol. PAS-100, pp. 4151-4167, September 1981.

[10] J.P. Bayne, D.C. Lee, W. Watson, "A Power System Stabilizer for Thermal Units Based on Derivation of Accelerating Power", *IEEE Trans*., Vol. PAS-96, Nov/Dec 1977, pp 1777-1783.

[11] *IEEE Recommended Practice for Excitation System Models for Power System Stability Studies*, IEEE Standard 421.5-2005, April 2006.

[12] F.W. Keay, W.H. South, "Design of a Power System Stabilizer Sensing Frequency Deviation", *IEEE Trans*., Vol. PAS-90, Mar/Apr 1971, pp 707-713.

[13] J.M.C. Soares, F.H. Pons, F.Reichert, D.O. Reis, Modelling and Field Tests of a Supplementary Stabilizing Signal for General Use, National Seminar on the Generation and Transmission of Electrical Energy, Brazil, 1987.

[14] P. Kundur, G.R. Berube, L.M. Hajagos, R.E. Beaulieu, "Practical Utility Experience with and Effective Use of Power System Stabilizers," *IEEE PES Meeting July 2003*, Vol 3, pp 1777- 1785.