Damping Torque Through Mechanical Torque Control
From Secondary Power System Stabilizer

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Abstract

This paper presents an alternative method to add damping torque to synchronous generators (e.g. hydro generators) through a secondary power system stabilizer (PSS). Traditionally, a single PSS is used to add damping torque through controlling the field excitation system to change the electrical torque. When the PSS provides a sufficient amount of compensation to produce an electrical torque in phase with speed deviation, rotor oscillations will damp.

There are two factors of speed deviation—electrical torque and mechanical torque. The traditional (primary) PSS acts on the electrical torque. In this paper, an alternative (secondary) PSS is designed to act on the mechanical torque. A power system study is conducted to evaluate the independent and combined use of the two PSS’s after introducing a disturbance. The results from comparing the independent use of the primary and secondary PSS show an improved damping of rotor oscillations compared to a system without any PSS. When operating two PSS’s in parallel (i.e. both primary and secondary PSS enabled), the damping of rotor oscillations are further reduced. However, with the parallel use of PSS’s, the speed deviation took longer before reaching a steady state compared to solely using the primary PSS.
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1. Introduction

Power system stability refers to the ability of the power system to maintain or return to a steady state operating point when subject to a disturbance. In order for power systems to maintain stability, the synchronous generators that generate the power for the grid (e.g. hydro generators) must be in steady state operation. Figure 1.1 shows the various subsystem controls in a synchronous generator that are used to meet the requirements of stability.

![Subsystem Controls in a Generator](image)

In normal operation, synchronous generators maintain a constant speed ($\omega$) and a constant relative angle between the stator and rotor windings ($\delta$). Upon the introduction of a disturbance to the system, the ability for synchronous generators to maintain stability is governed by the balance between mechanical power into the generator turbine and electrical power to the load. The following mathematical equation, known as the swing equation (or EOM), models the generator dynamics.

$$T_m - T_e = J \times \frac{d^2 \delta}{dt^2}$$

Equation: 1.1: Swing Equation

As observed from the above equation, an imbalance of $T_m$ and $T_e$ (i.e. $P_m$ and $P_e$) results in a change in velocity ($\Delta \omega$) of the turbine. Alternatively, it can be stated that this imbalance results in an acceleration of the rotor angle. If the rotor angle exceeds a relative angle of 90° between the stator and rotor windings, the synchronous generator is considered out of sync or unstable.
Power protection systems will trip and handle cases of synchronous generators falling out of sync.

Both the change in speed ($\Delta \omega$) and change in relative rotor angle ($\Delta \delta$) are fundamental elements that relate damping torque, synchronizing torque, and electrical torque. The equation for electrical torque is depicted by the following equation:

$$ Te = \Delta T_d + \Delta T_s = D \cdot \Delta \omega + K \cdot \Delta \delta; $$

where $D$ is the damping coefficient and $K$ is the synchronizing coefficient.

Equation 1.2: Damping and Synchronizing Torque Relationship

From Figure 1.2, it can be observed that $\Delta \omega$ and $\Delta \delta$ have a relative phase angle of 90° between one another due to the ($\frac{\omega}{\delta}$) transfer function (refer to Figure 1.4). In terms of a rectangular coordinate system, we can represent the relationship between $\Delta \omega$ and $\Delta \delta$ (refer to Figure 1.2). Essentially, damping torque ($T_d$) refers to the component of torque that is in phase with $\Delta \omega$, while synchronizing torque ($T_s$) refers to the component of torque that is in phase with $\Delta \delta$.

The mentioned torques above, damping and synchronizing torques, play a crucial role in the stability of the synchronous generator, and thus, the power system. An insufficient amount of either of the torques will cause the synchronous generator to go unstable. With an insufficient amount of synchronizing torque, the relative rotor angle will increase steadily [1]. Likewise, with an insufficient amount of damping torque, the relative rotor angle will oscillate with increasing amplitude [1].
Traditionally in the control of synchronous generators, a power system stabilizer (PSS) adds damping torque to lessen the rotor oscillations by controlling field excitation through an additional signal to the excitation system. A simple operation of the traditional PSS is illustrated in Figure 1.4 in a block diagram. As described previously, the purpose of the PSS is to introduce more damping torque; the input signal to the PSS is then $\Delta \omega$. The PSS outputs an auxiliary control signal to the excitation system to control the field excitation. By controlling the excitation, the electrical torque, $T_e$, will ultimately be controlled to be in phase with $\Delta \omega$. The dynamics from the input of the exciter to $T_e$ also introduces a phase shift to the original output signal from the PSS and thus, the PSS must compensate for the phase shift of the dynamics at the oscillating frequency.

![Block Diagram with PSS](image)

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Figure 1.4: Typical Generator Block Diagram with PSS [4]

## 2. Mechanical Torque Approach

A different approach that is explored in this paper is a secondary PSS that takes in the same input ($\Delta \omega$), but instead of a signal to control the field excitation, an auxiliary signal is used to control the gate position of the generator turbine. With this signal, the mechanical torque, and thus the mechanical power, can be controlled in a similar manner as electrical torque. Figure 2.1 shows the adjustment to Figure 1.4 to include a secondary PSS (PSS controlling $T_m$) that works in parallel with the primary PSS (PSS controlling $T_e$).

In Figure 2.1, the block representation for the primary PSS is truncated to be represented by a single block, $G_{PPSS}(s)$. 
The principle of the secondary PSS is similar to that of the primary PSS. Figure 2.2 depicts the secondary PSS in a block diagram representation. In general, the primary components of the secondary PSS are: washout filters, low pass filters, lead-lag compensators, gain, and saturation limits. The washout filters serve the purpose of a high pass filter, where the time constant is high enough to allow the rotor oscillation frequency to pass through and reject frequencies close to 0Hz. The time constant for the washout filters shall be chosen to allow for the design of a range of frequencies as opposed to designing for a specific frequency. On the other end, a low pass filter sets an upper bound for a range of oscillating frequencies.

As mentioned above, the purpose of the secondary PSS is to control the mechanical torque to produce a damping torque. Similarly to the phase shift between the input of the excitation system to Te, there is also a phase shift between the input of the governor to Tm. In order for the mechanical torque to be in phase with \(\Delta \omega\), the PSS must compensate for this phase shift (between governor input and Tm). The cascade of lead-lag compensators allows for the phase shift of the entire PSS system (i.e. washout filters, low pass filter, lead-lag compensators) to be adjusted in order to compensate for the phase shift between the input of the governor to Tm (see Equation 2.1). A gain is also included to adjust the PSS output magnitude to be adequate enough to introduce damping torque.
3. Models

In MATLAB, a hydro generator is modeled with its associated subsystems to control the generator operations. Figure 3.1 illustrates the MATLAB model being used. The primary PSS model is based on the IEEE recommended practice dual-input stabilizer, PSS2C [2]. The excitation system is also based on the IEEE recommended practice static excitation system, ST1 [2]. The model for the hydro generator is a GENTPF based from network equations and block diagrams presented in [3]. The governor and turbine dynamics are modeled based on the swing equation [1] and the associated PID controllers to control the turbine gate position; any non-linear components for the governor (e.g. deadtime) are not considered in the model.

The secondary PSS responsible for introducing damping torque through Tm is as modeled as described in Section 2.
The below list describes the progression of events that the model undergoes before reaching steady state:

I. \( t < 0 \text{s} \): All systems are off (i.e. the generator is not on, turbines are not spinning, and the electrical load is not loading the generator)

II. \( t = 0 \text{s} \): The turbine starts to spin and ramps up to a steady state of 1pu. The electrical load is not loading the generator yet.

III. \( t = 200 \text{s} \): The mechanical speed has reached a speed that corresponds to an electrical frequency of 1pu. At this point, the generator is loaded with the electrical system and the PSS(s) is/are enabled (depending on the Test Case described in Section 4)

IV. \( t = 500 \text{s} \): A disturbance is introduced into the system

V. \( t = 700 \text{s} \): End of simulation

4. Experiment

In order to simulate the effectiveness of implementing the secondary PSS, a Single Generator Single Load network is shown in Figure 4.1. Table 4.1 and 4.2 also shows the network parameters and the steady state operating conditions.

![Figure 4.1: Power System Single Generator Single Load Network](image)

Table 4.1: Single Generator Single Load Network Per Unit

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Per Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator (X''d)</td>
<td>j0.251</td>
</tr>
<tr>
<td>Generator (Xd)</td>
<td>j1.2</td>
</tr>
<tr>
<td>Transformer (T1)</td>
<td>j0.1</td>
</tr>
<tr>
<td>Transformer (T2)</td>
<td>j0.1</td>
</tr>
</tbody>
</table>
For the same power system, a series of tests (see Table 4.3) are conducted to simulate the effects the PSS’s have on the generator. The simulation undergoes the same simulation events as described in Section 3. At \( t = 500 \) s, a disturbance is applied to the system. For the purpose of observing the full effects of the secondary PSS, two types of disturbances are used as described below:

A. A short circuit fault that is cleared after 8 cycles: This exhibits a realistic case for power system studies. A short circuit is introduced at bus V4 which is cleared by the circuit breaker (CB) after 8 cycles.

B. A signal that creates an artificial increase in the mechanical power that the turbine observes. Figure 4.2 depicts this disturbance. The purpose of this disturbance is to observe the effects of the PSS on a larger scale. In this disturbance, a 0.3pu signal is used to artificially increase the mechanical power signal.
Table 4.3: Test Case Scenarios

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>No PSS</th>
<th>Primary PSS (Te)</th>
<th>Secondary PSS (Tm)</th>
<th>Both PSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disturbance A</td>
<td>Test Case 1</td>
<td>Test Case 2</td>
<td>Test Case 3</td>
<td>Test Case 4</td>
</tr>
<tr>
<td>Disturbance B</td>
<td>Test Case 5</td>
<td>Test Case 6</td>
<td>Test Case 7</td>
<td>Test Case 8</td>
</tr>
</tbody>
</table>

5. Results

The purpose of the primary and secondary PSS is to introduce damping torque to counteract the change in speed ($\Delta \omega$). Logically, the results from the test cases described in Section 4, can be observed through analyzing the transient speed of the generator. Figures 5.1 - 5.16 illustrate the speed response; two figures were captured for each test case. The first figure of each test case shows the overall speed of the generator from the moment of the fault until steady state, while the second figure shows a magnified capture of the same speed waveform.
Test Case 1: Short-Circuit Fault With No PSS Enabled

Figure 5.1: Short-Circuit Fault With No PSS Enabled (Overall)

Figure 5.2: Short-Circuit Fault With No PSS Enabled (Magnified)
Test Case 2: Short-Circuit Fault with Primary PSS Enabled

Figure 5.3: Short-Circuit Fault with Primary PSS Enabled (Overall)

Figure 5.4: Short-Circuit Fault with Primary PSS Enabled (Magnified)
Test Case 3: Short-Circuit Fault With Secondary PSS Enabled

Figure 5.5: Short-Circuit Fault With Secondary PSS Enabled (Overall)

Figure 5.6: Short-Circuit Fault With Secondary PSS Enabled (Magnified)
Test Case 4: Short-Circuit Fault with Both PSS’s Enabled

Figure 5.7: Short-Circuit Fault with Both PSS’s Enabled (Overall)

Figure 5.8: Short-Circuit Fault with Both PSS’s Enabled (Magnified)
Test Case 5: Artificial Fault With No PSS Enabled

Figure 5.9: Artificial Fault With No PSS Enabled (Overall)

Figure 5.10: Artificial Fault With No PSS Enabled (Magnified)
Test Case 6: Artificial Fault With Primary PSS Enabled

Figure 5.11: Artificial Fault With Primary PSS Enabled (Overall)

Figure 5.12: Artificial Fault With Primary PSS Enabled (Magnified)
Test Case 7: Artificial Fault With Secondary PSS Enabled

Figure 5.13: Artificial Fault With Secondary PSS Enabled (Overall)

Figure 5.14: Artificial Fault With Secondary PSS Enabled (Magnified)
Test Case 8: Artificial Fault With Both PSS’s Enabled

Figure 5.15: Artificial Fault With Both PSS’s Enabled (Overall)

Figure 5.16: Artificial Fault With Both PSS’s Enabled (Magnified)
6. Discussion

As observed in Test Case 1 and 5, an introduction of a disturbance causes the rotor speed to oscillate at a certain frequency. Both the primary and secondary PSS are designed to adequately compensate for the phase shift around this specific frequency range. In the short circuit test cases, the effects of enabling the primary and secondary PSS individually (Test Case 2 and 3) had a positive effect on the damping. By enabling both PSS’s (Test Case 4), it can be observed that the speed oscillations greatly damped after the first cycle compared to Test Case 1, 2, and 3. This response can be explained by both the PSS’s acting on Δω (i.e. Te and Tm are in phase to counter Δω).

In the artificial disturbance, Test Case 5 showed a similar waveform compared with Test Case 1. With individually testing the primary and secondary PSS’s effect on the system (Test Case 6 and 7), it can be observed that the damping was improved compared to Test Case 5. The magnitudes of the cycles in Test Case 6 and 7 have a lower magnitude compared to Test Case 5. When we enabled both PSS’s (Test Case 8), it can be observed that the magnitude of the oscillations are lower compared to Test Case 5, 6, and 7. However, from comparing Test Case 6 and Test Case 8, the speed oscillation waveform settles at a steady state faster in Test Case 6. This phenomenon could be explained by the introduction of the secondary PSS. By comparing Test Case 5 and Test Case 6, the secondary PSS also takes longer to reach a steady state value of Δω = 0.

It can also be noted that the first swing of oscillations (speed minima) is most reduced when using both PSS’s. This finding may indicate that with both PSS’s enabled, the combined effects may improve transient stability. In Test Case 1, a short circuit disturbance resulted in the speed dropping to 0.997756pu on the first swing after clearing the fault. In Test Case 4, where both PSS’s are enabled, the speed drops to 0.9983pu—lower drop compared to all Test Cases 1-3. With a larger disturbance in Test Cases 5-8, the speed dropped to 0.929214pu without any PSS’s enabled. With both PSS’s enabled (Test Case 8), the speed only dropped to 0.971069pu—lower drop compared to all Test Cases 5-7.

The findings from the experiment is consistent to the theories presented in Section 1 and Section 2. With both the primary and secondary PSS acting on damping the rotor oscillation, the magnitude of the oscillations are greatly reduced. For the short circuit disturbance (Test Cases 1-4), the magnitude of the oscillation succeeding the initial disturbance was about 1.00123pu without the PSS, and about 1.00022pu with both PSS’s. For the artificial disturbance (Test Cases 5-8), the magnitude of the oscillation was about 1.03901pu without the PSS, and about 1.00825pu with both PSS’s. The impact of having two PSS adding damping torque via Te and Tm shows a net positive effect on the rotor oscillation damping.
7. Conclusion

The effects of introducing a secondary PSS that adds damping torque to help damp the rotor oscillations after a disturbance was explored in this paper. Traditionally, a single PSS (i.e. primary PSS as referred to in this paper) is used to damp rotor oscillations by sending an auxiliary signal from the primary PSS to the excitation system to control the field excitation. By controlling the field excitation, an electrical torque must be in phase with the speed deviation ($\Delta\omega$). Fundamentally, the primary PSS must compensate for the phase shift between the input of the excitation system to the electrical torque.

The same principle of the primary PSS was applied to the design of the secondary PSS. Instead of adding damping torque through an electrical torque, mechanical torque is used. An auxiliary signal from secondary PSS is sent to the governor system to control the gate position. By controlling the gate position to be in phase with the speed deviation ($\Delta\omega$), damping torque is added via mechanical torque. Similarly to the primary PSS, the secondary PSS must compensate for the phase shift between the input of the governor to the mechanical torque.

From the results of the experiment, the two PSS’s can operate independently to damp the rotor oscillations. Alternatively, the two PSS's can work in parallel to further damp the rotor oscillations. However, it was also observed that with both PSS's working in parallel, the speed deviation reached steady state later compared to just using the primary PSS.

In this paper, the test case of a Single Generator and Single Load was explored. In this test case, the generator will not go unstable due to the the grid frequency being the single generator’s frequency (i.e. the frequency is not necessarily at a constant 60Hz [or 1pu]). In a case where a generator is connected to an infinite bus, the frequency can be thought as close to 60Hz (1pu). In this case, we can explore what impact the secondary PSS has in terms of both how speed ($\omega$) and angle ($\delta$) of the generator compares to the infinite bus after a disturbance. In other words, testing a Single Generator Infinite Bus case will give more details on the transient stability by observing the effects on the rotor angle ($\delta$) when implementing the secondary PSS.

Further research can be conducted to determine if the net effect of the primary and secondary PSS is a form of superposition of their isolated effects on the system (i.e. explore if the combination of the primary and secondary PSS is linear). Additionally, in the model and experiment used in this paper, the secondary PSS fully compensated for the phase shift of the governor and turbine dynamics. However, it can be noted from past literature [1], that some undercompensation is also desired. By undercompensating, there will be both an increase in damping torque, as well as a slight increase in synchronizing torque.
Bibliography


