APPLICATION OF SIMULTANEOUS ACTIVE AND REACTIVE POWER MODULATION OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE UNIT TO DAMP TURBINE-GENERATOR SUBSynchronous OSCILLATIONS

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ABSTRACT

An active and reactive power (P-Q) simultaneous control scheme which is based on a superconducting magnetic energy storage (SMES) unit is designed to damp out the subsynchronous resonant (SSR) oscillations of a turbine-generator unit. In order to suppress unstable torsional mode oscillations, a proportional-integral-derivative (PID) controller is employed to modulate the active and reactive power input/output of the SMES unit according to speed deviation of the generator shaft. The gains of the proposed PID controller are determined by pole assignment based on modal control theory. Eigenvalue analysis of the studied system shows that the PID controller is quite effective over a wide range of operating conditions. Dynamic simulations using the nonlinear system model are also performed to demonstrate the damping effect of the proposed control scheme under disturbance conditions.

1. INTRODUCTION

Subsynchronous resonance (SSR) problems have received great attention in the literature since the first two shaft failures in 1970 and 1971 [1–3]. SSR problems of the turbine-generator will occur in a power system with series capacitor compensated long AC transmission lines if damping of the torsional modes is not enough [4–6]. Many countermeasures for SSR problem have been suggested in the literature to increase torsional mode damping, such as block filter [2], excitation control [4–5], static VAR compensator [6–10], HVDC [11], static phase shifter [12], by pass filter [13], and the shunt reactor [14].

Owing to the substantial development of high temperature superconducting material, application of the superconductor becomes an important issue in the electrical engineering [15–22]. Since the successful commissioning test of the BPA 30 MJ superconducting magnetic energy storage (SMES) unit [15, 16], a new chapter of bulk electric energy storage is opened. The SMES unit is designed to store electric energy in the low loss superconducting magnetic coil [15–22]. With difference to the AC flow in the shunt reactor which provides only the reactive power modulation to the system, the flow in the SMES coil is DC. Both the active and reactive power modulations are given by the SMES unit. Active power and/or reactive power can be absorbed (charging mode) by or released (discharging mode) from the unit according to the system requirement [21, 22].

Although the original purpose of the SMES unit is to store electric energy at the off-peak load period, and release it at the peak load period, the unit can also be used as a stabilizer of power system, with a well designed control scheme. The stability improvement must be an additional benefit from the SMES unit but not the only one, since the unit must be primarily used for load leveling and load management. The SMES unit can be applied to be a transmission line stabilizer [15] and load frequency controller [18], or to damp out low frequency electromechanical oscillations and increase the stability of power system [19]. The use of an inductor converter unit (IC unit) to damp torsional oscillations was first proposed by Wasynczuk in [23]. The IC unit is similar to the SMES unit, and basically the DC current can be held at a relative constant value in a large inductor. But the Nyquist stability criterion design procedure in [23] is inefficient and complicated for damping torsional modes by the compensating filter of the IC unit. With the P-Q simultaneous control scheme [21, 22], damping effect of the SMES unit on the subsynchronous oscillations will be more effective.

In this paper, the SMES unit with an active and reactive power simultaneous control scheme and a proportional-integral-derivative (PID) controller is first proposed by the authors to increase the torsional mode damping of the turbine-generator. The PID controller is very simple in structure and has been successfully used as a VAR controller to damp out torsional mode oscillations [9, 10]. The gains of the PID controller are determined by pole assignment based on modal control theory [24], that shifts the torsional modes to the prespecified position. Eigenvalue analysis and nonlinear time domain simulations are performed on the IEEE first benchmark model in order to demonstrate the effectiveness of the proposed controller.

2. DESCRIPTION OF THE STUDIED SYSTEM

2.1 Series capacitor compensated power system

The studied system considered in this paper is the IEEE first benchmark model [3], which consists of a turbine-generator connected to a large power system through a capacitor compensated transmission line as shown in Fig. 1. A superconducting magnetic energy storage (SMES) unit is located at the generator bus terminal to increase the damping of the torsional modes. The dynamic behavior of the generator is described by a nonlinear full current model [2, 3]. The generator is equipped with a static excitation system which is illustrated by the s-domain block diagram shown in Fig. 2 [3]. Combining the mass-spring system, armature and field windings, damping windings, excitation system, governor system, and the capacitor compensated transmission line, a set of 27 order nonlinear differential equations for the system without the SMES unit can be obtained. At the initial operation condition, the nonlinear differential equations can be linearized to give the linear differential equations [24]. The system data are given in Appendix II.

The complete eigenvalues of the open loop system, that is without the SMES unit, are listed in the second column of Table I. The real part of the eigenvalues associated with the torsional modes...
versus the compensation degree is plotted in Fig. 5(a). It is indicated reasonable compensation degree and load condition.

It is desired to enhance the damping of these two modes without effecting damping of the other modes. Therefore, with the proposed control scheme, all the torsional modes must be stable under reasonable compensation degree and load condition.

2.2 The P-Q simultaneous control scheme of SMES unit

The fundamental configuration of a SMES unit is shown in Fig. 3. The unit contains an Y-Δ/Y-Y connected transformer, two sets of six-pulse cascaded bridge forced commutated converters in series, and a DC superconducting inductor. The control of the firing angles \( \alpha_1 \) and \( \alpha_2 \) of the cascaded converters makes the SMES have the ability to control active and reactive power independently and rapidly within a circular range containing four quadrants. A possible way to extend the controllable power regions is to use a forced commutated GTO converter [21]. The GTO circuit is efficient and has the ability of self-turning off. The commutation capacitors for ordinary thyristors are not needed, and the difficulty of commutation stability can be reduced. Usually the SMES is suggested to be placed as close as possible to the load center in order to provide instantaneous power modulation. For improvement of power system damping, the location is near the generator terminal.

In order to derive the independent control of active and reactive power, assume, for simplicity, the equivalent commutating resistance are neglected, and the converters are operating in equal firing angle mode, i.e., \( \alpha_1 = \alpha_2 = \alpha \) [20]. According to the circuit analysis of converter, the voltage \( V_{sm} \) in the DC side of the 12-pulse converter is expressed by

\[
V_{sm} = E_{d1} + E_{d2} = 2 V_{sm0} \cos \alpha
\]

where \( E_{d1} \) and \( E_{d2} \) denote the output DC voltage of each 6-pulse converter, and \( V_{sm0} \) is the ideal no-load maximum DC voltage of the 6-pulse bridges.

The active and reactive power transferred in the 12-pulse converter are given by

\[
P_{sm} = 2 V_{sm0} I_{sm} \sin \alpha \tag{2}
\]

\[
Q_{sm} = 2 V_{sm0} I_{sm} \cos \alpha \tag{3}
\]

The relation between the current and voltage of the superconducting inductor is

\[
\frac{dI_{sm}}{dt} = \frac{V_{sm} - R_{sm} I_{sm}}{L_{sm}} \tag{4}
\]

where \( L_{sm} \) and \( R_{sm} \) are the inductance and resistance of the superconducting inductor, respectively.

The converter currents referred to the generator bus reference frame are [25]

\[
I_{sm} = \sqrt{3} I_{smx} \sin \alpha \tag{5}
\]

\[
I_{sm} = \sqrt{3} I_{sym} \cos \alpha \tag{6}
\]

The amount of active power and reactive power drawn from or delivered to the power system can be obtained by controlling the firing angle \( \alpha \) of the converters in the full range between 0° and 180°. In order to use the SMES unit as a torsional mode stabilizer, the active power \( P_{sm} \) transferred in the converter is controlled continuously depending on the measured speed deviation of the turbine-generator rotor, that is

\[
\Delta P_{sm} = K_{cp} \frac{\Delta \omega}{1 + s T_{cp}} \tag{7}
\]

where \( T_{cp} \) and \( K_{cp} \) are the speed measurement device time constant and the control loop gain, respectively. The reactive power control is usually for the purpose of voltage stabilization. Then the reactive power \( Q_{sm} \) transferred in the converter is controlled continuously depending on the measured voltage deviation of the generator bus terminal as the SVC [22], that is

\[
\Delta Q_{sm} = \frac{K_{cp}}{1 + s T_{cp}} \Delta V_t \tag{8}
\]

![Table 1](image)

<table>
<thead>
<tr>
<th>Mode</th>
<th>without SMES</th>
<th>with SMES but without PID controller</th>
<th>with SMES and PID controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 5</td>
<td>-0.1817</td>
<td>-0.1817</td>
<td>-0.1824</td>
</tr>
<tr>
<td>Mode 4</td>
<td>0.1599</td>
<td>0.1908</td>
<td>-1.12</td>
</tr>
<tr>
<td>Mode 3</td>
<td>1.0806</td>
<td>-0.0183</td>
<td>-2.9</td>
</tr>
<tr>
<td>Mode 2</td>
<td>-0.6773</td>
<td>-0.6774</td>
<td>-1.0945</td>
</tr>
<tr>
<td>Mode 1</td>
<td>-0.3453</td>
<td>-0.3466</td>
<td>-1.0945</td>
</tr>
<tr>
<td>Mode 0</td>
<td>-0.5647</td>
<td>-0.5674</td>
<td>-1.0945</td>
</tr>
<tr>
<td>Other modes</td>
<td>-7.0654</td>
<td>8.0799</td>
<td>-6.9908</td>
</tr>
<tr>
<td></td>
<td>-6.0266</td>
<td>9.4584</td>
<td>-1.9423</td>
</tr>
<tr>
<td></td>
<td>-4.6268</td>
<td>-8.4940</td>
<td>-6.0266</td>
</tr>
<tr>
<td></td>
<td>-0.1819</td>
<td>-3.1648</td>
<td>8.0799</td>
</tr>
<tr>
<td></td>
<td>-0.0719</td>
<td>-3.1648</td>
<td>-8.0799</td>
</tr>
<tr>
<td></td>
<td>-2.3383</td>
<td>2.3383</td>
<td>-4.7072</td>
</tr>
<tr>
<td></td>
<td>-0.1421</td>
<td>0.1421</td>
<td>-2.3383</td>
</tr>
<tr>
<td></td>
<td>-0.0822</td>
<td>0.0822</td>
<td>-0.1421</td>
</tr>
</tbody>
</table>

* assigned eigenvalues

![Diagram](image)
where \( T_{CO} \) and \( K_{CO} \) are the voltage measurement device time constant and the control loop gain, respectively.

The P-Q simultaneous control scheme of SMES unit is shown in Fig. 4. \( T_p \) and \( K_p \) are the firing circuit delay time constant and the converter loop gain, respectively. Because of the constraint of hardware implementation, the current of the inductor has upper and lower limits. Since the converter operates in continuous mode, the upper limit of the inductor is set at 1.38 \( I_{SMO} \), and the lower limit 0.31 \( I_{SMO} \), where \( I_{SMO} \) is the initial current.

When the SMES unit is incorporated into the power system, all the system eigenvalues are listed in the third column of Table 1, and the real part of torsional modes versus compensation degree is plotted in Fig. 5(b). From Table 1 and Fig. 5(b), it is shown that the system with the SMES unit alone still has insufficient damping for modes 3 and 4. As a result, some additional control signal must be employed in order to damp out the torsional oscillations resulted from the negative damping modes. In this paper, a PID controller, which is widely used in the process industry, is proposed to increase the damping of modes 3 and 4.

3. EIGENVALUES ANALYSIS

In the design and analysis of the PID controller for the SMES unit, nonlinear differential equations are used to describe the dynamic behavior of the system. All the nonlinear differential equations can be linearized at the initial operation point to obtain the linear differential equations which describe the small signal characteristics of the system around the operation point. The gains of the PID controller can be determined from the linear differential equations.

3.1 Controller design

All the linear differential equations can be represented in a compact form.

\[
X(t) = AX(t) + BU(t) \tag{9}
\]

\[
Y(t) = C X(t) \tag{10}
\]

where \( X(t) = [\Delta \omega_1, \Delta \omega_2, \Delta \theta_1, \Delta \theta_2, \Delta \omega_3, \Delta \omega_4, \Delta \omega_5, \Delta \theta_3, \Delta \theta_4] \) is the state vector, \( Y(t) = [\Delta \omega] \) is the output vector, and \( U(t) = U_{SMES}(s) \) is the supplementary control signal from the PID controller. \( A, B, \) and \( C \) are constant matrices. The PID controller is described by the transfer function

\[
H(s) = \frac{U_{SMES}(s)}{\Delta \omega(s)} = \frac{1}{1 + s T_w} \left( K_p + \frac{K_i}{s} + K_d s \right) \tag{11}
\]

Since the four parameters, \( K_p, K_i, K_d, \) and \( T_w, \) of the PID controller provide four degrees of freedom, two pairs of torsional modes, that is four eigenvalues, can be controlled by the PID controller. The pole assignment method based on modal control theory [24] as described in Appendix I is used in this paper to determine the parameters of the PID controller by shifting the eigenvalues of mode 3 and mode 4 to the prespecified position.

The results are listed as follows.

\[ \text{prespecified eigenvalues}: \]

\[ -2.9 \pm 1.55j (\text{mode } 3) \]
\[ -1.2 \pm 2.08j (\text{mode } 4) \]

\[ \text{parameters of PID controller:} \]

\[ T_w = 0.0085 \]
\[ K_p = 4.96 \]
\[ K_i = 334 \]
\[ K_d = 0.0066 \]

It must be noted that the prespecified position for the assigned torsional modes is chosen arbitrarily with the condition that all the parameters are within the suitable ranges being satisfied. From modal control theory, a PID controller can shift two pairs of torsional modes to the prespecified position. If more torsional modes have to be controlled, another PID controller with a different feedback signal such as current or electrical torque is needed.

3.2 Eigenvalues analysis

The eigenvalues of the system with P-Q simultaneous modulation SMES unit and the proposed PID controller are given in the fourth column of Table 1. Also the real part of torsional modes versus compensation degree is plotted in Fig. 5(c). It can be observed that mode 3 and mode 4 are exactly at the assigned position. Although primarily it is required to enhance the damping of these two modes, the other torsional modes also benefit from the damping effect of the PID controller. It is valuable to note that the damping of the electro-mechanical mode (mode 0 or low frequency oscillation mode) is simultaneously greatly improved. The most widely used power system stabilizer (PSS) isn’t needed to damp the low frequency oscillation since the SMES can provide enough damping torque. Fig. 5(c) also shows that the torsional modes are always stable at any degree of compensation.

The choice of the initial firing angle of the converter bridge will be explained. An examination of torsional modes for the system with SMES but without PID controller at different firing angles is given in Table 2. There is no significant difference between the eigenvalues of the torsional modes. The initial firing angle \( \alpha \) is arbitrarily chosen to be \( 7^\circ \). The determination of the parameters of the PID controller is based on this firing condition.

Eigenvalue sensitivity analysis of the system with SMES and PID controller will be carried out in order to observe and survey the robustness of the proposed controller under various operating conditions. Table 3 shows the eigenvalues at different converter firing angles. The damping of modes 3 and 4 are more sensitive to variation in firing angle than other modes. The eigenvalues under several values of terminal voltage are listed in Table 4. Table 5 gives the effect of generator loading condition. The eigenvalues at loading condition \( P_g = 0.9, P_o = 1.2, \) and \( P_o = 0.6 \) are listed in each column.

![Fig. 4 P-Q simultaneous control scheme of SMES unit.](image-url)
part of torsional mode versus active power is plotted in Fig. 6. It is observed that the system is always stable for any load condition. Also the sensitivity with respect to the transmission line resistance to reactance ratio \((R/I_x)\) is shown in Fig. 7, where mode 3 and mode 4 are also more sensitive.

4. DYNAMIC SIMULATIONS

Dynamic simulations based on nonlinear differential equations are performed in order to demonstrate the damping effect of the SMES unit with the PID controller. All the nonlinearities such as the exciter ceiling voltage limit and the current limit of the superconducting inductor must be included. The dynamic responses for an 100 ms, 0.2 p.u. step change in mechanical torque input, a large disturbance, are plotted in Figs. 8-12.

The dynamic responses of the system without SMES unit are shown in Fig. 8, while the responses of the system with SMES unit but without the PID controller are given in Fig. 9. In both control

Table 2. Torsional modes versus firing angle \(\alpha\) for system with SMES but without PID controller.

<table>
<thead>
<tr>
<th>(\alpha)</th>
<th>0°</th>
<th>7°*</th>
<th>15°</th>
<th>20°</th>
<th>-15°</th>
<th>-20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>mode 5</td>
<td>-0.1817</td>
<td>-0.1817</td>
<td>-0.1817</td>
<td>-0.1817</td>
<td>-0.1817</td>
<td>-0.1817</td>
</tr>
<tr>
<td>mode 4</td>
<td>0.19010</td>
<td>0.19010</td>
<td>0.19010</td>
<td>0.19010</td>
<td>0.19010</td>
<td>0.19010</td>
</tr>
<tr>
<td>mode 3</td>
<td>0.0334</td>
<td>0.0334</td>
<td>0.0334</td>
<td>0.0334</td>
<td>0.0334</td>
<td>0.0334</td>
</tr>
<tr>
<td>mode 2</td>
<td>-0.6754</td>
<td>-0.6754</td>
<td>-0.6754</td>
<td>-0.6754</td>
<td>-0.6754</td>
<td>-0.6754</td>
</tr>
<tr>
<td>mode 1</td>
<td>-0.3353</td>
<td>-0.3353</td>
<td>-0.3353</td>
<td>-0.3353</td>
<td>-0.3353</td>
<td>-0.3353</td>
</tr>
<tr>
<td>mode 0</td>
<td>-0.5276</td>
<td>-0.5276</td>
<td>-0.5276</td>
<td>-0.5276</td>
<td>-0.5276</td>
<td>-0.5276</td>
</tr>
</tbody>
</table>

*: Operating point

Table 3. Torsional modes versus firing angle \(\alpha\) for system with SMES and PID controller.

<table>
<thead>
<tr>
<th>(\alpha)</th>
<th>0°</th>
<th>7°*</th>
<th>15°</th>
<th>20°</th>
<th>-15°</th>
<th>-20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>mode 5</td>
<td>-0.1823</td>
<td>-0.1823</td>
<td>-0.1823</td>
<td>-0.1823</td>
<td>-0.1823</td>
<td>-0.1823</td>
</tr>
<tr>
<td>mode 4</td>
<td>-1.4842</td>
<td>-1.4842</td>
<td>-1.4842</td>
<td>-1.4842</td>
<td>-1.4842</td>
<td>-1.4842</td>
</tr>
<tr>
<td>mode 3</td>
<td>-2.7227</td>
<td>-2.7227</td>
<td>-2.7227</td>
<td>-2.7227</td>
<td>-2.7227</td>
<td>-2.7227</td>
</tr>
<tr>
<td>mode 2</td>
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<td>-1.0459</td>
<td>-1.0459</td>
<td>-1.0459</td>
<td>-1.0459</td>
<td>-1.0459</td>
</tr>
</tbody>
</table>

*: Operating point

Table 4. Torsional modes versus terminal voltage

<table>
<thead>
<tr>
<th>(V_t)</th>
<th>0.9 (p.u.)</th>
<th>1.0 (p.u.)</th>
<th>1.05 (p.u.)*</th>
<th>1.1 (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mode 5</td>
<td>-0.1823</td>
<td>-0.1823</td>
<td>-0.1823</td>
<td>-0.1823</td>
</tr>
<tr>
<td>mode 4</td>
<td>-1.0137</td>
<td>-1.0137</td>
<td>-1.0137</td>
<td>-1.0137</td>
</tr>
<tr>
<td>mode 3</td>
<td>-2.8963</td>
<td>-2.8963</td>
<td>-2.8963</td>
<td>-2.8963</td>
</tr>
<tr>
<td>mode 2</td>
<td>-1.0815</td>
<td>-1.0815</td>
<td>-1.0815</td>
<td>-1.0815</td>
</tr>
<tr>
<td>mode 1</td>
<td>-4.0704</td>
<td>-4.0704</td>
<td>-4.0704</td>
<td>-4.0704</td>
</tr>
<tr>
<td>mode 0</td>
<td>-3.2136</td>
<td>-3.2136</td>
<td>-3.2136</td>
<td>-3.2136</td>
</tr>
</tbody>
</table>

*: Operating point

Fig. 5 The real part of torsional modes versus compensation degree.
schemes, the system is unstable. This agrees with the results given in Table 1.

The responses of the system with P-Q simultaneous modulation SMES unit and the PID controller are shown in Figs. 10-12 for three different load conditions. It is shown that torsional mode oscillations can be effectively suppressed by the proposed control scheme.

Observations are as follows.
(a) The damping of torsional modes can be greatly improved by the SMES unit with simultaneous P-Q control and the PID controller. The damping of the electromechanical mode can also be enhanced.
(b) Although the PID controller is designed for a special loading condition, it also can provide good damping at other operating conditions. The controller is robust to the system load.
(c) During the dynamic period, the SMES can draw active power and reactive power from the power system or release active and reactive power according to system requirement. As that shown in Figs. 10-12, the P-Q locus of the SMES unit is close to a circle diagram.

Table 5. The Torsional modes at different loading conditions

<table>
<thead>
<tr>
<th>Mode</th>
<th>P.O. (p.u.)</th>
<th>1.2 (p.u.)</th>
<th>0.6 (p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 5</td>
<td>-0.1824e+298.177</td>
<td>-0.1824e+298.177</td>
<td>-0.1824e+298.177</td>
</tr>
<tr>
<td>Mode 4</td>
<td>-1.2 +j208.4°</td>
<td>-1.0988 +j208.621</td>
<td>-1.3949 +j208.238</td>
</tr>
<tr>
<td>Mode 3</td>
<td>-2.9 +j155.7°</td>
<td>-2.9046 +j155.641</td>
<td>-2.7183 +j155.698</td>
</tr>
<tr>
<td>Mode 2</td>
<td>-1.1218 +j126.573</td>
<td>-1.0446 +j126.596</td>
<td></td>
</tr>
<tr>
<td>Mode 1</td>
<td>-4.2448 +j96.363</td>
<td>-4.5498 +j96.161</td>
<td>-3.7225 +j96.587</td>
</tr>
<tr>
<td>Mode 0</td>
<td>-3.6431 +j79.994</td>
<td>-3.5293 +j8.049</td>
<td>-3.7270 +j8.308</td>
</tr>
</tbody>
</table>

Fig. 6 The real part of torsional modes versus active power loading.

Fig. 7 The real part of torsional modes versus transmission line resistance to reactance ratio.

Fig. 8 Dynamic responses for the system without SMES at P.O. = 0.9 p.u.

Fig. 9 Dynamic responses for the system with SMES but without PID controller at P.O. = 0.9 p.u.
Fig. 10 Dynamic responses for the system with SMES and PID controller at $P_o = 0.9$ p.u..

Fig. 11 Dynamic responses for the system with SMES and PID controller at $P_o = 1.2$ p.u.
In this paper, an active and reactive power simultaneous modulation SMES unit with a PID controller is proposed to enhance torsional mode damping of the turbine-generator. A systematic approach based on modal control theory has been presented to determine the parameters of the PID controller by shifting the mode 3 and mode 4 to the prespecified locations. The procedure of pole assignment is simple since the solutions of the linear algebra equations can be easily obtained. If other torsional modes have to be controlled, additional feedback signal with incorporated controller is needed. Eigenvalue analysis and dynamic response simulations show that the additional feedback signal with incorporated controller is needed. Dynamic performance of the generator is greatly improved. Although the PID controller is designed for a special operating point, it can also provide good damping at other loading conditions.

Although the BPA has successfully built a 30 MJ SMES unit, commercial devices currently are not available. Cost of a practical unit is unknown but would be more expensive than other damping devices such as shunt reactor and SVC. Since the original purpose of the SMES is load leveling, damping improvement is an additional, but not the only, benefit.

6. NOMENCLATURE

general
\( \omega \) rotor speed
\( \delta, \theta \) torque angle
\( V, i \) voltage and current
\( R, X \) resistance and reactance
\( T \) torque
\( E_{FD} \) per unit output voltage of exciter
\( U_{SMES} \) stabilizing transformer output voltage
\( K_{SM} \) SMES controller output signal
\( K_{CP}, K_{CQ} \) gain of measurement devices
\( T_{CP}, T_{CQ} \) time constant of measurement devices
\( P, W \) power and energy
\( L \) inductance
\( K_{R} \) gain of converter
\( \tau_{R} \) delay time constant of converter

subscripts
\( d, q \) d-axis and q-axis
\( f \) field
\( k_d \) d-axis damper
\( k_q, k_{q\dot{\theta}} \) q-axis damper
\( C \) series compensated capacitor
\( SM \) superconducting compensated inductor
\( HP \) high pressure turbine
\( IP \) medium pressure turbine
\( LPA, LPB \) low pressure turbine
\( X \) exciter

7. REFERENCES

APPENDIX I: Pole assignment approach using model control theory

Consider a controllable and observable single-input single-output (SISO) system, which is described by the linear state equations

\[ X(t) = A X(t) + B U(t) \quad (A.1) \]
\[ Y(t) = C X(t) \quad (A.2) \]

where \( X(t) \) is the n×1 state vector, \( U(t) \) is the 1×1 input vector, and \( Y(t) \) is the 1×1 output vector. \( A, B, \) and \( C \) are the constant matrices of the SISO system. Taking the Laplace transform of equs. (A.1) and (A.2), we obtain

\[ sX(s) = AX(s) + BU(s) \quad (A.3) \]
\[ Y(s) = CX(s) \quad (A.4) \]

where \( G(s) = C(sI - A)^{-1}B \) is the open loop transfer function. If the transfer function of the output feedback controller is \( H(s) \), the control signal can be represented by

\[ U(s) = H(s)Y(s) = \frac{s}{1+sT_W} (K_P + \frac{K_I}{s} + sK_D) Y(s) \quad (A.5) \]

It is easy to see that the characteristic equation of the closed loop control system is

\[ 1 - C(sI - A)^{-1}B H(s) = 0 \quad (A.6) \]

For any closed loop system, the eigenvalues \( \lambda_i, i = 1, 2, 3, 4 \) are the precised eigenvalues for the torsional modes, we can obtain a set of four linear algebra equations with four unknowns \( T_W, K_P, K_I, \) and \( K_D \). By solving this set of linear algebra equations, we can easily get the desired parameters for the proposed feedback controller.

APPENDIX II: System data and initial condition

The system data used are as follows [3,21,18]

Mass-spring system

- \( M_H = 0.1855794 \) sec.
- \( D_H = 0.1 \) p.u.
- \( K_{HI} = 19.303 \)

- \( M_I = 0.311178 \) sec.
- \( D_I = 0.1 \) p.u.
- \( K_{IA} = 34.929 \)

- \( M_A = 1.717340 \) sec.
- \( D_A = 0.1 \) p.u.
- \( K_{AB} = 52.038 \)

- \( M_B = 1.768430 \) sec.
- \( D_B = 0.1 \) p.u.
- \( K_{BO} = 70.858 \)

- \( M_C = 1.736990 \) sec.
- \( D_C = 0.1 \) p.u.
- \( K_{GC} = 2.8220 \)

- \( M_S = 0.068433 \) sec.
- \( D_S = 0.1 \) p.u.

- \( K_{GC} = 2.8220 \)

- \( T_{SR} = 0.2 \) sec.

- \( F_R = 0.3 \) sec.
- \( T_{CH} = 0.3 \) sec.
- \( K_G = 25 \)

- \( F_I = 0.26 \) sec.
- \( T_{RH} = 7.0 \) sec.
- \( T_{SM} = 0.3 \) sec.

- \( F_A = 0.22 \) sec.
- \( T_{CO} = 0.2 \) sec.

- \( F_B = 0.22 \) sec.
- \( T_{SM} = 0.3 \) sec.

Transformer and transmission line

- \( R_T = 0.01 \) p.u.
- \( X_T = 0.14 \) p.u.

- \( X_T = 0.14 \) p.u.

- \( X_T = 0.14 \) p.u.

- \( X_T = 0.14 \) p.u.

Exciter and voltage regulator

- \( K_{KA} = 50 \)
- \( T_A = 0.01 \) sec.

- \( K_P = 0.5 \) sec.
- \( T_Y = 0.5 \) sec.

SMES unit

- \( V_{SMO} = 0.2018 \) p.u.

- \( \alpha_0 = 7 \) deg.

- \( \omega_{SM} = 0.5 \) H

- \( K_{CF} = 1.06 \)

- \( T_{CP} = 0.026 \) sec.

- \( K_{CF} = 1.06 \)

- \( T_{CP} = 0.026 \) sec.

- \( K_G = 0.0182 \)

- \( T_R = 0.001 \) sec.

The initial operating conditions

- \( P_0 = 0.9 \) p.u.

- \( V_I = 1.05 \) p.u.

- \( P.F. = 0.9 \) lag

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