EFFECT OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE ON AUTOMATIC GENERATION CONTROL

CONSIDERING GOVERNOR DEADBAND AND BOILER DYNAMICS

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Keywords  - Automatic Generation Control, Superconducting Magnetic Energy Storage.

Abstract  - A comprehensive digital computer model of the two-area interconnected power system including the governor deadband non-linearity, steam reheat constraints and the boiler dynamics is developed. The improvement in AGC with the addition of a small capacity Superconducting Magnetic Energy Storage (SMES) unit is studied. Time domain simulations are used to study the performance of the power system and control logic. Optimization of gain parameters and the stability studies are carried out by the second method of Lyapunov. Suitable methods for the control of SMES units are described.

INTRODUCTION

The application of SMES to electric power systems can be grouped into two categories: (i) large scale energy storage like conventional pumped hydro plant storage meant for diurnal load leveling application and (ii) low capacity storage to improve the dynamic performance of the power system. In the first case, large sized (hundreds of meters in diameter) high capacity superconducting magnets capable of storing $10^6 - 10^7$ MJ are necessary [1,2,3]. For the second application, very small sized SMES units with storage capacity of the order of $10^2$ MJ or even less would be sufficient.

In most of the automatic generation control (AGC) studies, the effect of the boiler system and its controls and the governor deadband effects are neglected for simplicity. But for a realistic analysis of the performance of the system, these should be included as they have considerable effects on the amplitude and settling time of the oscillations as established in this paper. Even in the case of small load disturbances and with the optimized gain for the integral controller, the power frequency oscillations and the tie-line power deviations persist for a long duration. The addition of a small capacity SMES unit to the system significantly improves this situation and the oscillations are practically damped out.

Methods are described for the suitable control of SMES unit. Optimal values for the gain parameters of the existing power system and the SMES units are determined for a proper coordination to extract the maximum benefit out of the available capacity of the SMES units. The second method of Lyapunov for linearized system is used for parameter optimization which guarantees stability.

The power system model for AGC including the SMES is described in the form: $\dot{X} = [A]X$ which saves much computational efforts for time domain simulations, optimization and stability analysis.

CONFIGURATION OF THE SYSTEM

Fig.1 shows the basic configuration of a SMES unit in the power system. The superconducting coil can be charged to a set value (which is less than the full charge) from the utility grid during normal operation of the grid. The DC magnetic coil is connected to the AC grid through a Power Conversion System (PCS) which includes an invertor/rectifier. Once charged, the superconducting coil conducts current, which supports an electromagnetic field, with virtually no losses. The coil is maintained at extremely low temperature (below the critical temperature) by immersion in a bath of liquid helium.

When there is a sudden rise in the demand of load, the stored energy is almost immediately released through the PCS to the grid as line quality AC. As the governor and other control mechanisms start working to set the power system to the new equilibrium condition, the coil charges back to its initial value of current. Similar is the action during sudden release of loads. The coil immediately gets charged towards its full value, thus absorbing some portion of the excess energy in the system, and as the system returns to its steady state, the excess energy absorbed is released and the coil current attains its normal value.
DEVELOPMENT OF A COMPREHENSIVE MATHEMATICAL MODEL FOR AGC WITH SMES

A digital computer model for AGC of two-area power system with governor deadband, reheat steam turbines, boiler dynamics and the SMES unit is shown in Fig.2. Since the purpose is to study the control strategies, an incremental model is adequate.

Govener Deadband

Describing function approach [4] is used to incorporate the governor deadband non-linearity. An adequate description of the hysteresis type of non-linearities is expressed as:

\[ y = F(x, \gamma) \quad (1) \]

It is necessary to make the basic assumption that the variable \( x \) is sufficiently close to a sinusoidal oscillation, that is

\[ x = A \sin \omega_0 t \quad (2) \]

where the amplitude \( A \) and the frequency \( \omega_0 \) of the oscillation are constant. Such an assumption is quite realistic as the non-linear system may exhibit periodic oscillations arbitrarily close to pure sinusoid. It has been found that the backlash non-linearity tends to produce a continuous sinusoidal oscillation with a natural period of about 2 seconds [5]. Then,

\[ m_0 = 2n \omega_0 = 7, \text{ with } f_0 = 0.5 \text{ Hz}. \]

The function, \( F(x, \gamma) \) can be developed in a Fourier series as follows:

\[ F(x, \gamma) = F_0 + N_{1} x + \frac{N_{2}}{\omega_0} \gamma \quad (3) \]

A resonable approximation of this solution is to consider the first three terms only. As the backlash non-linearity is symmetrical about the origin, \( F_0 = 0 \).

\[ F(x, \gamma) = N_{1} x + \frac{N_{2}}{\omega_0} \gamma \quad (4) \]

where \( DB \) is the deadband.

Refering to the discussion of [6], a backlash of approximately 0.05% is chosen for the analysis. As described in [5], the Fourier coefficients are obtained as:

\[ N_1 = 0.8 \quad \text{and} \quad N_2 = -0.2. \]

Boiler System

Fig.3 shows the model to represent the boiler dynamics [7]. This includes the long-term dynamics of fuel and steam flow on boiler drum pressure. Representations for combustion controls are also incorporated. Eventhough the model is basically for a drum type boiler, similar responses have been observed for once-through boilers and pressurized water reactors [71]. The model can be used to study the responses of coal fired units with poorly tuned (oscillatory) combustion controls, coal fired units with well tuned controls and well tuned oil or gas fired units. In conventional steam units, changes in generation are initiated by turbine control valves and the boiler controls respond with necessary immediate control action upon sensing changes in steam flow and deviations in pressure [87].

DISCRETE-DATA CONTROL MODEL

The two-area power system shwon in Fig.2 is a linear continuous-time dynamic system and it can be represented by a set of linear differential equations of the form:

\[ \dot{x} = [A] x + [B] u + [r] p \quad (5) \]

where \( x, u \) and \( p \) are state, control and disturbance vectors and \([A], [B] \) and \([r]\) are constant matrices associated with them respectively. However, if \( p \) represents known load disturbances and since the control forces are derived from the system itself (for example, frequency error or area control error), (5) can be conveniently brought to the form:

\[ \dot{x} = [A] x (t) \quad (6) \]
where \( \frac{x}{3} \) is a 23rd order state vector obtained:

\[
\begin{align*}
X &= \begin{bmatrix}
\Delta F_1 & \Delta F_2 & \Delta F_3 & \Delta F_4 & \Delta F_5 & \Delta F_6 \\
\Delta F_1 & \Delta F_2 & \Delta F_3 & \Delta F_4 & \Delta F_5 & \Delta F_6 \\
\Delta F_1 & \Delta F_2 & \Delta F_3 & \Delta F_4 & \Delta F_5 & \Delta F_6 \\
\end{bmatrix}
\end{align*}
\]

The inductor is initially charged to its rated current \( I_{dc} \) by applying a small positive voltage. Once the current has attained the rated value, it is held constant by reducing voltage ideally to zero since the coil is superconducting. A very small voltage may be required to overcome the commutating resistance.

The energy stored at any instant,

\[
E = \frac{1}{2} L I^2
\]

where \( L \) is inductance of SMES, \( H \).

**Frequency Deviation as Control Signal**

The frequency deviation \( AF \) of the power system is sensed and used to control the SMES voltage, \( E_d \). When power is to be pumped back into the grid in the case of a fall in frequency due to sudden loading in the area, the control voltage \( E_d \) is to be negative since the current through the inductor and the thyristors cannot change its direction. The incremental change in the voltage applied to the inductor is expressed as:

\[
AE = KF \cdot AF
\]

where \( KF \) is the gain of the control loop and \( S \) is the Laplace operator \( d/dt \).

**Area Control Error (ACE) as Control Signal**

In cases where tie-line power deviation signals are available, it may be desirable to use area control error as input to SMES control logic. Here, has certain advantages, which are described later, compared to frequency deviation derived controls.

The area control error of two areas are defined as:

\[
ACE = \frac{\Delta F_i + \Delta P_{ij}}{B_i}
\]

where \( \Delta F_i \) is the area control error of area \( i \), and \( \Delta P_{ij} \) is the power flow from area \( i \) to area \( j \).

**Inductor Current Deviation Feedback**

Neglecting the transformer and the converter losses, the D.C. voltage is given by [91]:

\[
E_d = 2 V_{dc} \cos a - 2 I_d R_c
\]

where \( V_d \) is the DC voltage applied to the inductor, \( a \) is the firing angle (degree), \( I_d \) is the current through the inductor (kA), \( R_c \) is the equivalent commutating reactance (ohm), \( V_{dc} \) is the maximum open circuit bridge voltage of each 6-pulse converter at \( a = 0^\circ \).

The energy stored at any instant,

\[
E = \frac{1}{2} L I^2
\]

where \( L \) is the inductance of SMES, \( H \).
where \( K_{Id} \) (kV/kA) is the gain corresponding to the load increase of 0.01 Pu. in area 1. It shows that the current is \( I_{ref} \), limited to its normal value (4.5kA) only very slowly. The inductor current deviation can be sensed and used as a negative feedback signal in the SMES control loop to achieve quick restoration of current. Then, with frequency deviation as control signal, the weightings are obtained from the solution of:

\[
A_{I} = \frac{1}{1 + S T_{dci}} \begin{bmatrix} \kappa_{F} & -I_{Id} \Delta T_{dci} \\
\end{bmatrix}
\]

(15)

where \( K_{Id} \) (kV/kA) is the gain corresponding to the \( A_{I d} \) feedback. The block diagram representation of such a control scheme is shown in Fig. 5.

\[\text{Fig. 4. Current deviations in SMES units without inductor current deviation feedback.}\]

The process of evaluating \( n \) is repeated by varying one parameter at a time, checking the convergence of (18). Equation (18) is solved for \( [P_I] \) using the iterative technique described in [12]. The performance index curve is calculated as:

\[
\text{P.I.} = \int_{0}^{\tau} \left( W_{\alpha} (\Delta P_{\alpha})^2 + W_{\beta} (\Delta P_{\beta})^2 \right) dt + \int_{0}^{\tau} W_{m} \left( \frac{d}{dt} \Delta t \right) dt
\]

(19)

where \( W_{\alpha}, W_{\beta}, \) and \( W_{m} \) are weight factors of 1.0, 15.0 and 75.0 respectively. The integration was performed over a period of 40 seconds by which time the excursions of these errors die down. The stability with the optimal gains thus obtained is ensured by checking the convergence of (18).
Fig. 1. Performance with SMES units in operation.

Fig. 2. Performance without SMES units in operation.

Fig. 3. Transient Response with and without deadband when SMES is not in operation.

Fig. 4. Transient Response with SMES when frequency deviation is used to control SMES.

Fig. 5. Transient Response with SMES when ACU is used to control SMES.

Fig. 6. Transient Response with SMES when frequency deviation is used to control SMES.

Fig. 7. Transient Response with and without deadband when SMES is not in operation.

Fig. 8. Transient Response with and without deadband when SMES is not in operation.

Fig. 9. Transient Response with and without deadband when SMES is not in operation.

Fig. 10. Effect of optimization on performance.

Fig. 11. Throttle pressure deviations with and without SMES.
The transient responses for frequency deviation in area 1 and tie-line power deviation out of area 1, with and without governor deadband effects (and having SMES in the model but not in use), are shown in Fig.7 (a) and (b) for a step load increase of 0.01 Pu in area-1. It shows that the governor deadband is having a considerable effect on the amplitude of oscillations and its settling time. Without deadband, the oscillations settle around 40 seconds, whereas, with the deadband, the settling time is around 120 seconds with their respective optimized integrator gains.

The oil/gas-fired boiler is having the fastest response among boilers (data are given in the Appendix) and provides the maximum participation for the improvement of AGC. For the analysis in this paper with the SMES, such type of boiler is considered so that the effect of SMES in the improvement of AGC can be appreciated.

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\[ K_{1L} \cdot K_{2L} = 35 \text{kV} / \text{Hz} \]

\[ K_{1H} \cdot K_{2H} = 0.20 \text{kV/kA} \]

(b) when ACE is used as the SMES control signal:

\[ K_{1L} = K_{2L} = 0.70 \]

\[ K_{1H} = K_{2H} = 50 \text{kV/unit ACE} \]

\[ K_{1D} \cdot K_{2D} = 0.20 \text{kV/kA} \]

**The Prime-Mover Data**  \( [7, 13, 17] \)

<table>
<thead>
<tr>
<th>Type of Boiler</th>
<th>( T_0 )</th>
<th>( I_0 )</th>
<th>( I_d )</th>
<th>( I_c )</th>
<th>( B )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas or oil fired</td>
<td>0.10</td>
<td>0.20</td>
<td>0.095</td>
<td>0.92</td>
<td>200</td>
</tr>
<tr>
<td>Coal fired, well tuned</td>
<td>40</td>
<td>25</td>
<td>0.020</td>
<td>90</td>
<td>69</td>
</tr>
<tr>
<td>Coal fired, poorly tuned</td>
<td>45</td>
<td>25</td>
<td>0.019</td>
<td>90</td>
<td>69</td>
</tr>
</tbody>
</table>

**REFERENCES**


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Discussion

D. Das (Tata Energy Research Institute, New Delhi, India) and D. P. Kothari (Indian Institute of Technology, Delhi, India): We wish to commend the authors for their valuable contribution in providing a comprehensive digital computer model of the two-area interconnected power system including the governor deadband nonlinearity, steam reheate constraints and the boiler dynamics. However, we would like to seek the authors’ clarification on the following points.

1. From Eq. (9) of the paper it appears that the authors have carried out their analysis in the discrete-mode of the AGC and therefore the value of the sampling period may please be mentioned.

2. The authors have optimized the performance index (Eq. 17) by obtaining a positive definite Hermitian matrix $[P]$ (Eq. 18) using system matrix $[A]$. The authors may please comment on desirability of using $[B]$ matrix (Eq. 9) rather than matrix $A$.

3. The authors may please mention the maximum value of the generation rate constraint (GRC) that might have been used in the computer simulation since modern reheat type steam units have a value of GRC of the order of 3% per minute.

Once again we congratulate the authors for their very useful and interesting paper.

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S. C. Tiopathy, R. Balasubramanian and P. S. Chandramohan Nair: The authors would like to express their appreciation to Mr. Das and Prof. D. P. Kothari for the interest they have shown on the paper and their discussion.

Concerning the first equation it is clarified that the performance of AGC presented in the paper is only for continuous analog control and not for digital AGC. For the simulation purpose, the system is brought to a discrete data control model. So $T$ in equation (9) represents actually the solution interval. However, this discrete-data model has the advantage that it can be straight away used for studies of discrete mode of AGC. In such a case, the modification needed in the algorithm may be that updating of the area control error signal is done only at intervals limited by the speed of the data acquisition and control system installed for the purpose. Values of $T$ selected for the study presented in this paper are 0.05 s for cases without SMES and 0.01 s for cases with SMES, considering the values of smallest time constants appearing in the system respectively.

Convergence of eqn. (18) ensures stability as described in [10, 11, 12]. Optimal values for different gain parameters are obtained by observing performance index by varying the value for one particular gain parameter at a time, in successive steps. Eqn. (181 has the advantage that in each step, only the new elements of $[A]$ matrix are to be obtained to start the iterative technique for solution $[P]$. This involves very simple computations rather than solution of equation of the form:

$$\begin{bmatrix} \mathbf{A} \\ \mathbf{B} \end{bmatrix} \begin{bmatrix} \mathbf{P} \\ \mathbf{Q} \end{bmatrix} = \begin{bmatrix} \mathbf{F} \\ \mathbf{G} \end{bmatrix}$$

Once again we congratulate the authors for their very useful and interesting paper.

References


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