In this paper, Automatic Generation Control (AGC) of an interconnected power system with a Capacitive Energy Storage unit (CES) is studied. The system transfer function model comprises hydro and thermal power generations with governor models and system load for studying the dynamic response for small load perturbations. Integral controllers have been considered in both the areas whose optimal values are obtained by minimising the Integral Squared Error (ISE) technique. The dynamic responses without and with CES unit are compared. Simulation studies reveal that with the application of the CES unit, there is an improvement in AGC in terms of peak amplitudes and deviations in frequencies of both the areas.

Keywords: Automatic Generation Control, Capacitive Energy Storage, Integral Squared Error.

1. INTRODUCTION

Increasing demand for electrical power and the complexity of load patterns has necessitated interconnected power systems. An interconnected power system consists of different control areas which are inter-linked through tie-lines. Each control area strives to meet its own demand in addition to the scheduled interchanges with other areas so that the entire power system can supply consumer demands at nominal frequency and voltage levels and be in an equilibrium state. But in practice, the loads are random and continuously changing with time. Further, due to physical/technical limitations, the ability of generation to track the varying loads is limited. Thus, Automatic Generation Control (AGC) of an interconnected power system is concerned with controlling the real power output of electric generators within a control area in response to changes in system frequency and tie-line loading in an economical way so that the scheduled system frequency and established interchange with other areas are maintained [1].

Literature survey shows that, most of the studies concerned with AGC of interconnected power systems pertain to tie-line bias control strategy [2-5]. Supplementary controllers are designed to regulate the area control errors to zero effectively. Even in the case of small load disturbances and with the optimised gain for the supplementary controllers, the power frequency and the tie-line power deviations persist for a long duration. In these situations, the governor system may no longer be able to absorb the frequency fluctuations due to its slow response [2]. On the other hand, the electromechanical oscillations can be effectively damped by fast acting energy storage devices such as flywheel energy storage, Battery Energy Storage, Fuel cells, Superconducting Magnetic Energy Storage etc since additional energy storage capacity is provided as a supplement to the kinetic energy storage in the moving mass of the generator rotor. The energy storage devices share the sudden changes in load power requirement and hence, the instantaneous mismatch between the real power supply and demand for sudden load perturbations can be reduced [6-11].
Recent advances in energy storage and power electronics technology has made Capacitive Energy Storage (CES) as a better option for damping power system oscillations [6,12-16]. The advantages of CES are that they are relatively cheap, high energy efficiency which is close to 100%, maintenance free, relatively higher energy density and environment friendly as opposed to other systems. The capacity of a CES unit can be upgraded by simply adding capacitors in parallel.

A study of literature [4,5] further shows that, most of the AGC studies are carried out for thermal-thermal power systems and very few or practically no hydrothermal power systems have been subjected for AGC analysis. An interconnected hydrothermal system involves widely different characteristics for the hydro and thermal subsystems. The characteristics of hydro turbines differ from steam turbines in that the relatively large water inertia used as a source of energy causes a considerably greater time lag in the response of the change in the prime mover torque to a change in gate position, and also a non-minimum phase behaviour, that is, an initial tendency for the torque to change in a direction opposite to that finally produced. The speed governor characteristics of the hydro unit are widely different from that of the turbo governor. Moreover, the maximum permissible generation rate constraint for the hydro units is relatively much higher than that for the thermal units. In [14], the AGC analysis of an interconnected thermal-thermal power system has been carried out with a CES unit whereas in [16], for a standalone power system, the AGC analysis with CES unit is done.

Hence, this paper aims to study the AGC of an interconnected hydrothermal power system with CES unit in to improve the system performance. A small rating CES unit of 3.8MJ storage capacity is fitted to the thermal area to examine its effect on the hydrothermal power system performance. The optimum values of the controller parameters are obtained by Integral Squared Error (ISE) performance indices. Finally, the different dynamic responses are plotted with 1% step load perturbation in either of the areas.

2. HYDROTHERMAL POWER SYSTEM MODEL

The AGC system under analysis is composed of an interconnection of thermal system and a hydro system. All the thermal power generating units are lumped together and are represented by a single thermal plant dynamics. Similarly, the hydro power generating units are represented by the respective single plant dynamics [1,17,18]. The transfer function models used for analysis are developed in [19,20]. Figure1 shows the linear time invariant (LTI) transfer function block diagram of the two area hydrothermal power system with CES unit in the thermal area. All the system parameters are defined as in Appendix 1. The CES unit is fitted in thermal area and the performance of the system is studied for unit step load disturbance in either of the areas. The values of the constants in block diagram for both areas and CES unit are given in Appendix 2.

3. MATHEMATICAL MODELLING

The linear time invariant model of the power system with CES unit under consideration can be modelled using standard state space technique as

\[
\dot{X} = AX + BU + \Gamma p
\]  

(1)

Where \(X\), \(U\) and \(p\) are state, input and disturbance vectors as given below

\[
X = [\Delta f, \Delta E, \Delta P_{i,1}, \Delta P_{i,2}, \Delta P_{l}, \Delta I_{l}, \Delta I_{di}, \Delta E_{di}]^T
\]  

(2)
While $A$, $B$, and $\Gamma$ are the corresponding real constant coefficient matrices as given in Appendix 3.

Figure 1: LTI model of the interconnected hydrothermal power system with CES in thermal area

4. CAPACITIVE ENERGY STORAGE UNIT

A capacitor stores the energy in its electrostatic field created between its plates in response to applied potential across it. A Capacitive Energy Storage (CES) unit consists of, from a circuit point of view, a super capacitor or a cryogenic hyper capacitor, a power conversion system and the associated protective circuitry [14]. The dimensions of the capacitor are determined by the energy storage capacity required. Initially, the capacitor is charged to its set value of voltage from the utility grid during its normal operation. Once the voltage reaches its rated value, it is kept floating at this value and the CES is now ready to be put into service. When there is a sudden rise in load demand, the stored energy is almost immediately released to the grid. As the governor and other control mechanisms start working to set the power system to the new equilibrium condition, the capacitor charges to...
its initial voltage value. The action during sudden releases of load is similar. The capacitor immediately gets charged to its full voltage value, thus absorbing some portion of the excess energy in the system. As the system returns to its steady state, the excess energy absorbed is released and the capacitor voltage attains its normal value.

The set value of the CES voltage has to be restored at the earliest after a load perturbation so that the CES unit is ready to act for the next load perturbation. For this, the capacitor voltage deviation can be sensed and used as a negative feedback signal in the CES control loop so that fast restoration of the voltage is achieved. Figure 2 depicts the functional block diagram of the CES unit with the negative voltage feedback.

The area control error (ACE) is a linear combination of weighted frequency perturbation in an area and tie-line power perturbation. The ACE of the thermal area is fed as control signal to the CES unit.

\[
ACE_i = B_i \Delta f_i + \Delta P_{tie_{i,j}}; \ i, j=1, 2
\]  

Figure 2: Functional block diagram of CES unit

5. OPTIMAL VALUES OF INTEGRAL GAIN SETTINGS

The transient performance of the system depends upon the type and value of the AGC controllers. The integral squared error (ISE) technique is used to obtain optimal gain settings of the integral controller in either of the areas since the ISE criterion weighs heavily on the large fluctuations as compared to the smaller ones [1]. The performance index used for optimizing the gain settings is given by

\[
J = \int_0^1 \left( \Delta f_1^2 + \Delta f_2^2 + \Delta P_{tie_12}^2 \right) dt
\]  

The performance index is minimized for a unit step load disturbance in either of the areas to obtain optimal gain settings. Since a two area system with different units is investigated, the optimum gain settings are obtained separately by considering the other area uncontrolled. Figure 3 shows the variation of the performance index with respect to \(K_{i1}\) with 1% step load perturbation in the thermal area and hydro area kept uncontrolled. It is seen that, the optimum values of the integral gain settings without and with CES unit are
0.754 and 1.008 respectively. Similar plots were also obtained for 1% step load perturbation in hydro area by keeping the thermal area uncontrolled.

![Performance index (J)](image)

**Figure 3:** Variation of performance index against integral controller gain settings for thermal area for 0.01 pu step load perturbation in thermal area

Table 1 shows the values of optimal gain settings for both the thermal area as well as hydro area without and with CES unit in the thermal area. From the table, it is seen that, the optimum values of the integral gain settings with CES unit in the thermal area are higher than that without CES unit.

<table>
<thead>
<tr>
<th>Step load perturbation</th>
<th>Optimum integral gain settings for thermal area</th>
<th>Optimum integral gain settings for hydro area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without CES unit</td>
<td>With CES unit</td>
</tr>
<tr>
<td>0.01 pu</td>
<td>$K_{I1} = 0.7540$</td>
<td>$K_{I1} = 1.0080$</td>
</tr>
</tbody>
</table>

6. **DYNAMIC RESPONSES AND DISCUSSIONS**

Simulation studies are performed with the optimal values of the integral gain settings, to investigate the performance of the two-area hydrothermal power system without and with CES unit in the thermal area. It has been observed that, a CES in either or both the areas yields more or less the same performance. Hence, a CES unit in the thermal area is considered. The values of the different parameters of the system are given in Appendix 3. A step load disturbance of 1% of nominal loading is considered in either of the areas.
Figure 4: Dynamic responses for $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie12}$ with 1% step load perturbation in thermal area.
Figures 4 and 5 depict the different dynamic responses for the hydrothermal area with 1% step load perturbation in the thermal area, without and with CES unit. As evident from figure 4, with the CES unit, the dynamic responses for frequency deviations $\Delta f_1$ and $\Delta f_2$ have improved and further, it can be observed that, the oscillations in area frequencies and tie-line power deviations have been damped out by the CES unit. The generation responses for both thermal and hydro areas (i.e., $\Delta P_{g1}$ and $\Delta P_{g2}$) without and with CES unit in thermal area are plotted in figure 5. It may be noted that, as the step load disturbance has occurred in the thermal area, the thermal unit should adjust its output at the earliest, so as to take up the local load perturbation in its area as per its obligation. Further, as per the approved practices of interconnected operations, the hydro area need not contribute to the local load fluctuation in the thermal area and hence should settle down to steady state value of zero as early as possible and this is reflected in figure 5. It may be noted that the initial negative deflection of the transient response of the output of the hydro unit is attributed to water hammer effect.

Figure 5: Generation responses for thermal and hydro area ($\Delta P_{g1}$ and $\Delta P_{g2}$) with 1% step load perturbation in thermal area
Figure 6: Dynamic responses for $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie12}$ with 1% step load perturbation in hydro area

Similar findings were also observed with a step load perturbation of 1% in the hydro area as shown in figures 6 and 7.
7. CONCLUSIONS

A comprehensive mathematical model for the AGC of a two area interconnected hydrothermal power system fitted with CES unit in thermal area has been presented in this paper. The system frequency and tie-line power oscillations due to small load disturbances were found to persist for a longer duration even with optimal gain settings of integral controllers. It has been shown that these oscillations can be effectively damped out with the use of a small capacity CES unit. From the studies it is evident that the AGC of the hydrothermal system is much better by adding a CES unit into the system.

APPENDIX 1

List of Symbols
T_{P1}, T_{P2} \quad \text{POWER SYSTEM TIME CONSTANTS}

K_{P1}, K_{P2} \quad \text{POWER SYSTEM GAINS}

T_{T} \quad \text{THERMAL TURBINE TIME CONSTANT}

T_{G} \quad \text{THERMAL GOVERNOR TIME CONSTANT}

T_{W} \quad \text{WATER TIME CONSTANT}

T_{R1}, T_{T1}, T_{T2} \quad \text{TIME CONSTANTS OF THE HYDRO GOVERNOR}

R_{1}, R_{2} \quad \text{GOVERNOR SPEED REGULATION PARAMETER OF THERMAL AND HYDRO AREAS, RESPECTIVELY}

P_{R1}, P_{R2} \quad \text{RATED AREA CAPACITIES (A_{12} = P_{R1}/P_{R2})}

T_{12} \quad \text{SYNCHRONISING COEFFICIENT}

B_{1}, B_{2} \quad \text{FREQUENCY BIAS CONSTANT OF THERMAL AND HYDRO AREAS, RESPECTIVELY}

K_{I1}, K_{I2} \quad \text{INTEGRAL GAINS OF THERMAL AND HYDRO AREAS, RESPECTIVELY}

APPENDIX 2

SYSTEM DATA

K_{P1} = K_{P2} = 120 \text{ HZ/P.U. MW}

T_{P1} = T_{P2} = 20 \text{ S}

R_{1} = R_{2} = 2.4 \text{ HZ/P.U. MW}

B_{1} = B_{2} = 0.4249

T_{G} = 0.08 \text{ S}, \quad T_{T} = 0.3 \text{ S},

T_{12} = 0.0866, \quad T_{1} = 41.6 \text{ S},

T_{2} = 0.513 \text{ S}, \quad T_{R} = 5 \text{ S}, \quad T_{W} = 1 \text{ S}

D_{1} = D_{2} = 8.333 \times 10^{-3} \text{ P.U. MW/Hz}

P_{R1} = P_{R2} = 1200 \text{ MW}

CAPACITIVE ENERGY STORAGE DATA

K_{VD} = 0.1 \text{ KV/KA}, \quad K_{d} = 70 \text{ KV/Hz},

T_{DC} = 0.05 \text{ S}, \quad C = 1 \text{ F}, \quad R = 100 \Omega, \quad E_{D0} = 2 \text{ KV}
APPENDIX 3

\[
A = \begin{bmatrix}
\frac{-1}{T_{p1}} & 0 & \frac{-K_{p1}}{T_{p1}} & \frac{K_{p1}}{T_{p1}} & 0 & 0 & 0 & 0 \\
0 & \frac{-1}{T_{p2}} & \frac{-K_{p2}}{T_{p2}} & 0 & \frac{K_{p2}}{T_{p2}} & 0 & 0 & 0 \\
2\Pi T_{12} & -2\Pi T_{12} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{-1}{T_T} & 0 & 0 & 0 & \frac{1}{T_T} \\
0 & \frac{2* T_T}{R_2 * T_1 * T_2} & 0 & 0 & -\frac{2}{T_T} & \frac{2(T_T + T_T)}{T_T} & 0 & \frac{2(T_T - T_T)}{T_T} \\
0 & \frac{-T_T}{R_2 * T_1 * T_2} & 0 & 0 & 0 & \frac{-1}{T_T} & 0 & \frac{(T_T - T_T)}{T_T} \\
\frac{-1}{T_G * R_1} & 0 & 0 & 0 & 0 & \frac{-1}{T_T} & 0 & 0 \\
0 & \frac{-1}{R_2 * T_1} & 0 & 0 & 0 & 0 & \frac{-1}{T_G} & 0 \\
\end{bmatrix}
\]

\[
B = \begin{bmatrix}
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & \frac{-2* T_T}{T_1 * T_2} \\
0 & \frac{T_T}{T_1 * T_2} \\
\frac{1}{T_G} \\
\frac{0}{T_G} \\
\end{bmatrix}
\]

\[
\Gamma = \begin{bmatrix}
\frac{-K_{p1}}{T_{p1}} & 0 \\
0 & \frac{-K_{p2}}{T_{p2}} \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
\end{bmatrix}
\]

REFERENCES


