Load Frequency Control in an Interconnected Hydro Power System with SMES and SCES Units

V. Rajaguru1, R. Sathya2, Tesfaye Nafo Tefera3

1Lecturer, Department of Electrical & Computer Science Engg., Debre Berhan University, Debre Berhan, Ethiopia
2Assistant Professor, Department of EEE, Krishnasamy College of Engg & Tech., Cuddalore, India
3Scientific Director, Institute of Technology, Debre Berhan University, Debre Berhan, Ethiopia

Abstract—In the power system, any sudden changes in the load leads to frequency deviation. But the frequency should remain nearly constant for the satisfactory operation of a power system. So the Load Frequency Control (LFC) is an important issue in interconnected power systems. Energy storage units are very important for damping out the oscillations due to sudden changes in the power system. The addition of small capacity energy storage unit in each area of the power system can effectively restrain the system oscillations. Hence in this paper, the Superconducting Magnetic Energy Storage (SMES) Units and Super Capacitor Energy Storage (SCES) Units are incorporated in the Load Frequency Control model of two area interconnected hydro power system. The proposed work consist of two area interconnected hydro power system with SMES and SCES units has been designed to improve the dynamic performance of the system and also Integral Square Error (ISE) technique is used to obtain the optimal integral gain settings. The simulation result shows that the Load Frequency Control in an interconnected hydro power system with SCES units is considerably improved the system dynamics such as peak overshoot, settling time and frequency oscillations as compared to that of the system with SMES units and also the system without SMES and SCES units.

Keywords—Energy storage units, interconnected hydro power system, Integral Square Error technique, Load Frequency Control, Superconducting Magnetic Energy Storage Unit, Super Capacitor Energy Storage Unit.

I. INTRODUCTION

Load Frequency Control introduces as the most important term in power system so as to supply reliable and quality power supply to the consumers. Any change in the system loads, may be cause to abnormal operation of the system. In order to overcome from this problem, using the Load Frequency Control is essential. Maintaining frequency and power interchanges with interconnected control areas at the scheduled values are the main task of a Load Frequency Control. A lot of research work has been made in this area are as follows.

A dual mode two layer fuzzy logic controller were designed and implemented for two-area thermal reheat interconnected power system with super capacitor energy storage units [1]. Fast – acting energy storage devices can effectively damp electromechanical oscillations in a power system. A power system with a SMES unit of 4 – 6 MJ capacity would reduce the maximum deviation of frequency and tie-line power flow by about 40% in power areas of 1000 – 2000MW capacity is analyzed [2]. A fuzzy logic controller for Automatic Generation Control (AGC) in an interconnected thermal power system including SMES units has been studied [3]. Real time simulation of AGC for interconnected power system is presented and a new control strategy for digital controller is developed [4]. Proportional Integral (PI) controller design using Maximum Peak Resonance Specification (MPRS) has been implemented to maintain frequency and the power interchange and also proved that effective and efficient method to control the overshoot, settling time and maintain the stability of the system [5]. A simulation model for load frequency control in an interconnected hydro power systems using fuzzy - Proportional Integral Derivative (PID) controller is presented and proved that fuzzy logic controller yields better control performance [6]. Load frequency control in an interconnected two area hydro-hydro system has been studied [7]. AGC of an interconnected four area hydro-thermal system using Superconducting Magnetic Energy Storage (SMES) unit is examined [8]. Automatic generation control of a two area hydro thermal system under traditional scenario by considering the effect of Capacitive Energy Storage (CES) and Thyristor Controlled Phase Shifter (TCPS) is proposed and the simulation result shows that the dynamic performance of the system is greatly improved by using TCPS and CES unit in the system [9]. Implementation of load following in multi-area hydro thermal system under restructured environment is investigated [10].
A comprehensive digital computer model of a two area interconnected power system including the Governor Dead Band (GDB) non-linearity, steam reheat constraints and the boiler dynamics is developed. The improvement in AGC with the addition of a small capacity SMES unit is studied [11].

II. TRANSFER FUNCTION MODEL OF TWO – AREA INTERCONNECTED HYDRO POWER SYSTEM

A two area system consists of two single area systems, Connected through a power line called tie-line, is shown in the Fig.1. Each area feeds its user pool, and the tie line allows electric power to flow between the areas. Information about the local area is found in the tie line power fluctuations. It is conveniently assumed that each control area can be represented by and equivalent turbine, generator and governor system. Fig.1 shows the block diagram representing the two area interconnected hydro power system. This model includes the conventional integral controller gains (K_i1, K_i2). Each power area has a number of generators which are closely coupled together so as to form a coherent group. Such a coherent area is called a control area in which the frequency is assumed to be same.

III. INTEGRAL CONTROLLER

The integral control composed of a frequency sensor and an integrator. The frequency sensor measures the frequency error Δf and this error signal is fed into the integrator.

The input to the integrator is called Area Control Error (ACE). The ACE is the change in area frequency, which when used in an Integral-control loop, forces the steady-state frequency error to zero.

The integrator produces a real-power command signal ΔPc and is given by

\[ \Delta P_c = -K_i \Delta f \, dt \]  

\[ = -K_i \Delta \text{ACE} \, dt \]  

Where,

\[ \Delta P_c = \text{input of speed \_\_\_\_ changer} \]

\[ K_i = \text{integral gain constant} \]

The value of \( K_i \) is so selected that the response will be damped and non-oscillator. For conventional Integral controller, the gains \( K_i \) have to be determined by using Integral Square Error (ISE) criterion. The objective function used for this technique is

\[ J = \frac{1}{2} \int \left( \Delta \dot{f}^2 + \Delta P_{tie}^2 \right) dt \]  

Where,

\[ \Delta \dot{f} = \text{change in frequency in area 1} \]

\[ \Delta P_{tie} = \text{change in tie-line power} \]

The optimum values of \( K_i \) for the system with and without energy storage units are found to be 0.03, 0.04 & 0.02 respectively.

Fig.1 Transfer Function Model of two area interconnected hydro power system
IV. SMES Model

The Fig. 2 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 inverter/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. The operation of SMES units, that is, charging, discharging, the steady state mode and the power modulation during dynamic oscillatory period are controlled by the application of the proper positive or negative voltage to the inductor. This can be achieved by controlling the firing angle of the converter bridges.

Neglecting the transformer and the converter losses, the DC voltage is given by

\[ E_d = 2V_{do} \cos \alpha - 2I_d R_c \]  \hspace{1cm} (4)

Where,  
- \( E_d \) = DC voltage applied to the inductor (KV)
- \( \alpha \) = firing angle (degree)
- \( I_d \) = current through the inductor (KA)
- \( R_c \) = equivalent commutating resistance (Ω)
- \( V_{do} \) = maximum open circuit bridge voltage of each six pulse convertor at \( \alpha = 0 \) degree (KV).

The inductor is initially charged to its rated current, \( I_{do} \) 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, \( W_L \), is

\[ W_L = \frac{1}{2} (I_d^2) \text{MJ} \]  \hspace{1cm} (5)

Where,  
- \( L \) = inductance of SMES, in Henry
- \( I_d \) = current through the inductor (KA).

In LFC operation, the \( E_d \) is continuously controlled by the input signal to the SMES control logic. The inductor current must be restored to its nominal value quickly after a system disturbance so that it can respond to the next load disturbance immediately. Thus, in order to improve the current restoration to its steady state value the inductor current deviation is used as a negative feedback signal in the SMES control loop. Based on the above discussion, the converter voltage deviations applied to the inductor and the inductor current deviations are described as follows:

\[ \Delta E_{dl}(S) = \frac{K_{SMES}}{1 + S T_{dci}} U_{SMESi}(S) - \frac{K_{id}}{1 + S T_{dci}} \Delta I_{dl}(S) \]  \hspace{1cm} (6)

\[ \Delta I_{dl}(S) = \frac{1}{S L_i} \Delta E_{dl}(S) \]  \hspace{1cm} (7)

Where
- \( \Delta E_{dl} (s) \) = Converter voltage deviation applied to inductor in SMES unit
- \( K_{SMES} \) = gain of control loop SMES
- \( T_{dci} \) = converter time constant in SMES unit
- \( U_{SMESi} \) = control signal of SMES unit
- \( K_{id} \) = gain for feedback \( \Delta I_i \) in SMES unit
- \( \Delta I_{dl} (s) \) = inductor current deviation in SMES unit.
The ACE is defined as follows:

\[
ACE_i = B_i \Delta F_i + \Delta P_{\text{tie,i}}
\]  

(8)

Where

- \( B_i \) = Frequency bias in area i
- \( \Delta F_i \) = Frequency deviation in area i
- \( \Delta P_{\text{tie,i}} \) = Net tie line power flow deviation in area i.

The deviation in the inductor real power of SMES unit is expressed in time domain as follows:

\[
\Delta P_{\text{SMES,i}} = \Delta E_{di} I_{di} + \Delta I_{di} \Delta E_{di}
\]  

(9)

Where,

- \( \Delta P_{\text{SMES,i}} \) = Deviation in the inductor real power of SMES unit in area i.
  
This value is assumed to be positive for transfer from AC grid to DC. Fig. 3 shows the block diagram of SMES unit.

V. SCES MODEL

The block diagram of Super Capacitor Energy Storage (SCES) Unit is shown in Fig. 4. Either frequency deviation or Area Control Error (ACE) can be used as the control signal to the SCES unit (\( \Delta \text{error}_i = \Delta F_i \) or \( \Delta \text{ACE}_i \)). \( E_{di} \) is then continuously controlled in accordance with this control signal. For the ith area, if the frequency deviation \( \Delta F_i \) (i.e., \( \Delta \text{error}_i = \Delta F_i \)).

Of the power system is used as the control signal to SCES, then the deviation in the current, \( \Delta I_{di} \) is given by

\[
\Delta I_{di} = \frac{1}{1 + S T_{di}} [K_{\text{SCES,i}} \Delta F_i - K_{\text{vd1,i}} \Delta E_{di}]
\]  

(10)

If the tie-line power flow deviations can be sensed, then the Area Control Error (ACE) can be fed to the SCES as the control signal (i.e., \( \Delta \text{error}_i = \Delta \text{ACE}_i \)). Being a function of tie-line power deviations, ACE as the control signal to SCES, may further improve the tie-power oscillations. Thus, ACE of the two areas are given by

\[
\Delta I_{di} = \frac{1}{1 + S T_{DCl}} [K_{\text{SCES,i}} \Delta F_i - K_{\text{vd1,i}} \Delta E_{di}]
\]  

(11)

Where, \( \Delta P_{\text{tie,ij}} \) is the change in tie-line power flow out of area i to j.

Thus, if \( \Delta F_i \) is the control signal to the SCES, then the deviation in the current \( \Delta I_{di} \) would be

\[
\Delta I_{di} = \frac{1}{1 + S T_{DCl}} [K_{\text{SCES,i}} \Delta F_i - K_{\text{vd1,i}} \Delta E_{di}]
\]  

(12)

The control actions of Super Capacitor Energy Storage units are found to be superior to the action of the governor system in terms of the response speed against, the frequency fluctuations.
The following table shows the comparison of various parameter of SMES & SCES unit.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Parameters</th>
<th>SMES</th>
<th>SCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Typical Range</td>
<td>1-100 MW</td>
<td>1-250KW</td>
</tr>
<tr>
<td>2</td>
<td>Power Density (kW/M$^3$)</td>
<td>&gt;530</td>
<td>&gt;176678</td>
</tr>
<tr>
<td>3</td>
<td>Energy Density (kW-h/M$^3$)</td>
<td>&gt;7.07</td>
<td>&gt;53</td>
</tr>
<tr>
<td>4</td>
<td>Emission</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>Life time</td>
<td>~30 Years</td>
<td>~30 Years</td>
</tr>
<tr>
<td>6</td>
<td>Losses/W</td>
<td>17mW</td>
<td>0.004mW</td>
</tr>
<tr>
<td>7</td>
<td>Electrical Efficiency</td>
<td>90%</td>
<td>&gt;95%</td>
</tr>
<tr>
<td>8</td>
<td>Levelized annual cost ($/kW-h)</td>
<td>200</td>
<td>85</td>
</tr>
<tr>
<td>9</td>
<td>Response Time</td>
<td>Milliseconds</td>
<td>Milliseconds</td>
</tr>
<tr>
<td>10</td>
<td>Backup Time</td>
<td>Seconds</td>
<td>Seconds</td>
</tr>
<tr>
<td>11</td>
<td>Applications</td>
<td>Peak saving, Power quality</td>
<td>Emergency power sources, Power quality, Defence</td>
</tr>
<tr>
<td>12</td>
<td>Advantages</td>
<td>Storage time is very high, Independent of the number of charges &amp; discharges</td>
<td>High charge and discharge current, Maintenance free, Very high power &amp; energy density</td>
</tr>
</tbody>
</table>
VII. SIMULATION MODEL AND RESULTS

Fig. 5 (a) Load frequency control in an interconnected hydro power system without SMES & SCES units.
Fig. 5 (b) Load frequency control in an interconnected hydro power system with SMES units
Fig. 5 (c) Load frequency control in an interconnected hydro power system with SCES units
The fig.5 (a, b & c) shows the simulation diagram of Load Frequency Control in an interconnected hydro power system without & with SMES and SCES unit.

Fig.6 (a, b, & c) shows the simulation results of two area interconnected hydro power system with SCES & SMES unit and also for without SCES & SMES unit, considering Integral controller. Fig.6 (a & b) shows the frequency response of area-1 (i.e. $\Delta f_1$) and area-2 (i.e. $\Delta f_2$) for the system with SCES and SMES unit and also for the system without energy storage units. And the fig.6 (c) shows the tie line power deviation ($\Delta p_{tie,1,2}$) for the system with and without energy storage units. Thus, from the Simulation Results, We say that the dynamic performance (such as frequency oscillation, peak overshoot and settling time) of the hydro power system is significantly improved when the SCES units are incorporated in a system.

VIII. Conclusion

Load Frequency Control provides a relatively simple, yet extremely effective method of adjusting generation to minimize frequency deviation and regulate the tie – line power flow. In this paper, Load Frequency Control in an interconnected hydro power system with SMES and SCES units has been presented.
The simulation model consists of identical hydro units (two units per area) with and without energy storage units (SMES & SCES units) are considered for this study. And also the system performance is observed for 1% step load disturbance. In addition to this, Integral Square Error technique is used to obtain the conventional integral controller gains. The simulation results show that the dynamic performance of the system is significantly improved in terms of frequency oscillations, peak overshoot and settling time when the SCES units are incorporated in a two area interconnected hydro power system rather than the system with SMES units and without SMES & SCES units.

Appendix

A.1 Data for the two-area interconnected hydro power system

\[ P_f = P_o = 2000\text{MW}, \quad T_1 = 41.6\text{sec}, \quad T_2 = 0.513\text{sec}, \]

\[ T_R = 5\text{sec}, \quad T_{ci} = 1\text{sec}, \quad H = 5\text{sec}, \quad D = 8.33\times10^{-3}\text{Pu. MW/Hz}, \]

\[ B = 0.425\text{Pu.MW/Hz}, \quad R = 2.4\text{Hz/Pu.MW}. \]

A.2 Data for SMES block

\[ L = 2.65\text{H}, \quad T_L = 0.03\text{sec}, \quad K_{SMES} = 50\text{KV/unit MW}, \]

\[ K_a = 0.2\text{ KV/KA}, \quad I_{SMES} = 4.5\text{ KA}. \]

A.3 Data for SCES block

\[ K_{dc} = 0.1\text{ KV/KA}, \quad K_{d} = 70\text{ KV/Hz}, \]

\[ K_{SCES} = 0.7\text{ Hz/Pu. MW}, \quad T_{SCES} = 0.01\text{sec}, \]

\[ C = 1\text{ F}, \quad R = 100\Omega. \]

REFERENCES


BIOGRAPHIES

V.Rajaguru received B. E. degree in Electrical and Electronics Engineering in 2006 from Annamalai University and M.E degree in Power Systems Engineering in 2009 from Annamalai University, India. He is currently working as a Lecturer in Electrical and Computer Science Engineering Department at Debreh Berhan University, Debere Berhan, Ethiopia.

R.Sathya received B. E. degree in Electrical and Electronics Engineering in 2007 from Annamalai University and M.E degree in Power Systems Engineering in 2009 from Annamalai University, India. She is currently working as a Assistant Professor in Krishnasamy College of Engineering & Technology, Cuddalore,TamilNadu, India.

Tesfaye Nafo Tefera received B. E. degree in Electrical & Electronics Technology in 2005 from Addama Science & Technology University and M.Tech degree in Power & Energy Systems in 2010 from National Institute of Technology, Karnataka Surthakal, India. He is currently working as Director, Institute of Technology at Debere Berhan University, Debere Berhan, Ethiopia.