PID-Fuzzy based AGC of Multi Area Power System in Deregulated Environment with SMES

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Abstract—In this paper, the conventional three-area AGC system is modified to take into account the effect of bilateral contracts on the dynamics of the system. In the considered power system, each area contains two Genose and Discos at three areas with thermal turbines. To describe bilateral contracts for three-area AGC, Disco participation matrix is used. The performance of system is studied for different operating cases. A PID controlled fuzzy logic controller (FLC) is used for load frequency control. Super conducting magnetic energy storage device (SMES) is incorporated in the model to see the impact on the load-frequency control. SMES is controlled through PID controlled Fuzzy Logic Controller. A comparative study has been provided between PID-FLC controlled system and PID-FLC-SMES controlled system including the study with conventional integral controller.

Keywords—frequency, Automatic Generation control, Deregulated power system, conventional integral controller, FLC., SMES.

I. NOMENCLATURE

$\Delta P_{d1}$ Change in the load demand for thermal area 1.

$\Delta P_{d2}$ Change in the load demand for thermal area 2.

$\Delta P_{d3}$ Change in the load demand for thermal area 3.

$\Delta f_1$ Incremental Frequency of thermal area 1.

$\Delta f_2$ Incremental Frequency of thermal area 2.

$\Delta f_3$ Incremental Frequency of thermal area 3.

$T_{p1}$, $T_{p2}$, $T_{p3}$ Power system time constant of area 1, area 2 and area 3 respectively.

$K_{p1}$, $K_{p2}$, $K_{p3}$ Power system gains of area 1, area 2 and area 3 respectively.

$T_{i1}$, $T_{i2}$, $T_{i3}$ Turbine time constants of area 1, area 2 and area 3 respectively.

$T_{g1}$, $T_{g2}$, $T_{g3}$ Governor time constants of area 1, area 2 and area 3 respectively.

$R_{g1}$, $R_{g2}$ Governor speed regulation parameter of area 1.

$R_{g3}$, $R_{g4}$ Governor speed regulation parameter of area 2.

$R_{g5}$, $R_{g6}$ Governor speed regulation parameter of area 3.

$T_{d1}$, $T_{d2}$, $T_{d3}$ Synchronizing coefficients of area1, area2 and area3 respectively.

$K_{i1}$, $K_{i2}$, $K_{i3}$ integral gains of area1, area 2 and area 3, respectively.

$K_{p1}$, $K_{p2}$, $K_{p3}$ proportional gains of area1, area 2 and area 3, respectively.

$K_{d1}$, $K_{d2}$, $K_{d3}$ differetial gains of area1, area 2 and area 3, respectively.

II. INTRODUCTION

The successful operation of interconnected power systems requires the matching of total generation with total load demand and associated system losses. With time, the operating point of a power system changes, and hence, these systems may experience deviations in nominal system frequency and scheduled power exchanges to other areas, which may yield undesirable effects as in [1-2]. The need for satisfactory operation of power stations running in parallel needs area control error to be zero. Many authors have worked in the area of AGC with the initial work on the LFC is proposed in [3-5].

Many authors have proposed different types of controllers to maintain the power system in a normal state of operation. These controllers for AGC are categorized as: Proportional and Integral (PI), Proportional-Integral-Derivative (PID), and optimal controllers. To maintain the system at a normal operation, different types of controllers based on optimal control theory [6-8] and variable structure control theory have been used [9-11]. The gain of the controllers can be set to control fast transient recovery and low overshoot in the dynamic response of the system. Many authors have used gain setting of PI controllers based on integral squared error [6,7,8,9]. PI controllers improve steady state error with little or no overshoot. Using control theory, author introduces a new method to obtain the parameters of the PI (or PID) controllers based on an optimization technique using the constant-M circles in Nichols chart [12]. A new robust PID controller design for hydro power system is presented in [13].

With the operation of the power system in new competitive environment, the new strategies have been adopted for load frequency control with the addition of new elements. AGC in a deregulated power system environment has been well presented in [14-21]. Besides addressing the operational
structures likely to result from deregulation, the possible approaches to LFC, and associated technical issues, i.e., standards and algorithms were described by Christie and Bose [14]. A comprehensive study on simulation and optimization of AGC system after deregulation has been carried out [15]. A robust decentralized approach for LFC in deregulated environment was presented in [16]. In recent years, several control scenarios based on robust and optimal approaches have been proposed for the AGC system in deregulated power systems [17-20]. Authors presented LFC with conventional integral technique in hybrid electricity market model [21].

Even in the case of small load disturbances and with the optimized 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. Thus, to compensate for the sudden load changes, an active power source with fast response such as superconducting magnetic energy storage (SMES) unit is expected to be the most effective countermeasure. Various studies have been done with SMES [22-25].

This paper gives a model of interconnected three area thermal power system in deregulated environment with PID-Fuzzy approach using impact of SMES for load frequency control. A comparison of PID-FLC and PID-FLC with SMES has been presented for load frequency control. The study with conventional integral controller is also included. Simulation of three area system with thermal turbines has been carried out using MATLAB SIMULINK 7.0.6 version.

III. MATHEMATICAL MODEL

In this section a general diagram of interconnected bilateral thermal-thermal-thermal power plant is given in Fig. 1. A change in demand in three areas is taken as $\Delta P_{d1}$, $\Delta P_{d2}$ & $\Delta P_{d3}$ with the sign of $\Delta P_{d}$ such that $\Delta P_{d} > 0$, for a sudden increase in generation, $\Delta P_{d} < 0$, for a sudden increase in load.

A. Restructured system for AGC with three areas

The power system is assumed to have two GENCOs and two DISCOs in each three area system as shown in Fig. 1. In the system any Genco in any area may supply both Discos in its user pool and Discos in other areas through tie-line allowing electric power to flow between areas. In another words, for restructured system having several Gencos and Discos, any Disco may contract with any Genco in another control area independently. This case is called as “bilateral transactions”. The transactions have to be Disco implemented through an independent system operator (ISO). The independent system operator (ISO) provides many ancillary services, one of which is AGC. In deregulated environment, any Disco has the liberty to buy power at competitive prices from different Gencos, which may or may not have contract in the same area as the Disco. For practice, Genco-Disco contract is proposed with ‘Disco participation matrix’ (DPM) [16]. Essentially, DPM gives the participation of a Disco in contract with a Genco. In DPM, the number of rows has to be equal to the number of Gencos and the number of columns has to be equal to the number of Discos in the system. Any entry of this matrix is a fraction of total load power contracted by a Disco toward a Genco. As a result, total of entries of column belong to Disco of DPM $\sum cp_{ij} = 1$. the corresponding DPM to the considered power system having three areas and each of them including two Discos and two Gencos is given as follows[16].

![Diagram](image326x586 to 553x686)

**Fig. 1 The configuration of the deregulated power system**

$$\begin{vmatrix}
    cp_{11} & cp_{12} & cp_{13} & cp_{14} & cp_{15} & cp_{16} \\
    cp_{21} & cp_{22} & cp_{23} & cp_{24} & cp_{25} & cp_{26} \\
    cp_{31} & cp_{32} & cp_{33} & cp_{34} & cp_{35} & cp_{36} \\
    cp_{41} & cp_{42} & cp_{43} & cp_{44} & cp_{45} & cp_{46} \\
    cp_{51} & cp_{52} & cp_{53} & cp_{54} & cp_{55} & cp_{56} \\
    cp_{61} & cp_{62} & cp_{63} & cp_{64} & cp_{65} & cp_{66}
\end{vmatrix}$$

(1)

Where, $cp$ represents “contract participation factor”. For example, the fraction of the total load power contracted by Disco1 from Genco2 is represented by (2,1) entry. Off diagonal blocks correspond to demands of the Discos in one area to the Gencos in another area. In the deregulated case, when the load demanded by a Disco changes, a local change is observed in the area of the Disco. In the equations of the system given, such a load changes $P_{Lij}$ ($i=1,2…6$), are contained. Since there are a lot of Gencos in each area, area control error (ACE) signal must be shared by these Gencos in proportion to their contributions. The coefficients, which represent this sharing are called as “ACE participation factor (aps)” and $\sum_{j=1}^{m} apj = 1$ where $m$ is the number of Gencos in each area.

Compared to any conventional AGC systems, any Disco can demand power from all of the Gencos. These demands are determined by cps, which are contract participation factors, as load of the Disco.

In basic case, all of the ACE participation factors are the same as 0.5, so contribution of each area to AGC is assumed as equal. Moreover, DPM is formed only taking $cp_{11}$, $cp_{12}$, $cp_{21}$, $cp_{22}$ are equal to 0.5 as in [16]. In the steady state, any Genco generation must match the demand of the Discos in contract with it, as expressed as follows:

$$\Delta P_{Mi} = \sum cp_{i} \Delta P_{Lij}$$
When power is to be charging, converter acts in the converter mode (charging). If

\[ DPM = \begin{bmatrix}
0.5 & 0.5 & 0 & 0 & 0 & 0 \\
0.5 & 0.5 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 
\end{bmatrix} \] (2)

Where, \( \Delta P_{1j} \) is the total demand of Disco. In this operating case, Gencos belonging to area 2 and area 3 are not contracted by any Disco in other areas for transaction of power, so changes in generated power by them are zero in steady state.

**B. Design of fuzzy logic controller**

The basic definitions and mathematical operations of the fuzzy sets theory are given in [26]. Many authors have utilized fuzzy logic controller for load frequency control [27-29]. The input signal for the fuzzy logic controller is the output of PID controller and its derivative, where ACE is its input, which consists of the summation of the frequency deviation of each area multiplied by the frequency bias setting of the area plus deviation of the tie line power as \( B \Delta f + \Delta P_{mg} \). The fuzzy logic controller has three stages, which are fuzzification, rules evaluation and defuzzification. Each fuzzy variable is a member of the subsets with a degree of membership \( \mu \) varying between universe of discourse.

![Fig. 2 Fuzzy membership functions](Image)

The inputs are converted into fuzzy variables of the triangular membership function as given in Fig. 2. The universe of discourse of the input signals are (-0.2,0.2) rad/s, and (-0.04,0.04) rad/s. The universe of discourse of the output signals are (-1,1) rad/s. The universe of discourse is unevenly divided in order to obtain better accuracy near the steady state operating conditions. The decisions rules are given in Table 1.

![Table 1 Decision Rules for fuzzy logic controller](Image)

<table>
<thead>
<tr>
<th>I/P</th>
<th>d(l(I/P))</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>-1</td>
</tr>
<tr>
<td>NS</td>
<td>-1</td>
</tr>
<tr>
<td>Z</td>
<td>-1/2</td>
</tr>
<tr>
<td>PS</td>
<td>1/2</td>
</tr>
<tr>
<td>PB</td>
<td>1</td>
</tr>
</tbody>
</table>

**C. PID-FLC controller design**

By tuning the three constants in the PID controller algorithm, the controller can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the set point and the degree of system oscillation. For improving the overall dynamic response of the system FLC is used with proportional gain block as shown in Fig. 3.

![Fig. 3 Implementation of FLC within PID controller](Image)

**D. Configuration of the SMES in the power system**

The schematic diagram in Fig. 4 shows the thyristor controlled SMES unit configuration. The detailed model of SMES has been well documented in [22-24]. The energy exchange between the superconducting coil and the electric power system is controlled by a line commutated converter. When there is a sudden rise in the load demand, the stored energy is almost released to the power system as alternating current. The control of the converter firing angle \( \alpha \) provides the dc voltage appearing across the inductor to be continuously varying within a certain range of positive and negative values. The inductor is initially charged to its rated current \( I_0 \) by applying a small positive voltage

![Fig. 4. SMES – circuit diagram](Image)

Once the current reaches its rated value, it is maintained constant by reducing the voltage across the inductor to zero since the coil is superconducting. Neglecting the transformer and the converter losses, the dc voltage is given by

\[ E_d = 2V_{dc} \cos \alpha - 2I_0 R_C. \] (3)

Where \( E_d \) is the dc voltage applied to the inductor in kV, \( \alpha \) is the firing angle in degrees, \( I_0 \) is the current flowing through the inductor in kA, \( R_C \) is the equivalent commutating resistance in k\( \Omega \) and \( V_{dc} \) is the maximum circuit bridge voltage in kV. Charging and discharging of the SMES unit is controlled through the change of commutation angle \( \alpha \). If \( \alpha \) is less than 90°, converter acts in the converter mode (charging mode) and if \( \alpha \) is greater than 90°, the converter acts in the inverter mode (discharging mode).

**E. Control of SMES unit**

In case of fall in system frequency, when power is to be pumped back into the grid due to sudden loading in the area, the control voltage \( E_d \) is 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

$$\Delta E_d = \left[ \frac{K_{SMES}}{1 + sT_{d,c}} \right] \Delta \text{Error}_1$$  \hspace{1cm} (4)

where, $\Delta E_d$ is the incremental change in converter voltage;\n\hspace{2cm} $T_{d,c}$ is the converter time delay; $K_{SMES}$ is the gain of the control loop and $\Delta$Error is the input signal to the SMES control logic. The inductor current deviation is given by

$$\Delta I_d = \frac{\Delta E_d}{sL}$$ \hspace{1cm} (5)

Fig. 5 SMES block diagram with negative inductor current deviation feedback.

In this work, area control error (ACE) of area 1 is considered as the input signal to the SMES control logic (i.e., $\Delta$Error$_1$ = ACE$_1$). The area control error of the two areas are defined as

$$ACE_i = B_i \Delta f_i + \Delta P_{tieij}, \hspace{1cm} i,j = 1,2$$ \hspace{1cm} (6)

where $\Delta f_i$ is the change in frequency of area $i$ and $\Delta P_{ij}$ is the change in tie-line power flow out of area $i$–$j$. Thus, from eqs (4) and (6),

$$\Delta E_d = \left[ \frac{K_{SMES}}{1 + sT_{d,c}} \right] (B_1 \Delta f_1 + \Delta P_{tie12})$$ \hspace{1cm} (7)

The inductor current in the SMES unit must be restored to its nominal value quickly after a system disturbance so that it can respond to the next load perturbation immediately. Hence, the inductor current deviation can be sensed and used as a negative feedback signal in the SMES control logic so that the current restoration to its nominal value can be enhanced as shown in Fig. 5. Thus the dynamic equations for the inductor voltage deviation and current deviation of the SMES unit area is

$$\Delta E_d = \left[ \frac{K_{SMES} (B_1 \Delta f_1 + \Delta P_{tie12}) - K_{id} \Delta I_d}{1 + sT_{d,c}} \right]$$ \hspace{1cm} (8)

F. Model of PID-FLC controlled SMES system

In this system, SMES is controlled by PID-FLC controller. The schematic diagram of PID-Fuzzy with SMES is shown in Fig. 6.

IV. RESULTS AND DISCUSSION

The results obtained for three area thermal system without and with SMES for PID-Fuzzy based system are presented in this section. The comparison of results obtained for the system with and without SMES is also presented. The waveforms are shown for load variation of 0.2 p.u in area 1. Frequency deviations in all areas due to the loads change is shown in Figs. 7(a-c). It is observed that with PID-FLC-SMES, the deviations are low with lower settling time. Tie line power deviations are shown in Figs. 8(a-c). The deviations are almost zero. The deviations are shown in Fig. 8(b) with lower scale to capture the behavior of variations of tie line deviations.

Fig. 7(a) Variation in area 1 frequency w.r.t 0.2 p.u load disturbance in area 1

Fig. 7(b) Variation in area 2 frequency w.r.t 0.2 p.u load disturbance in area 1
The variations in the power generation by each Gencos in all areas for the given bilateral contracts are shown in Figs. 9(a-f). It is observed that all Gencos in all the areas share the power according to their contracts specified in the demand participation matrix. The results are compared for both the cases of PID-Fuzzy and PID-Fuzzy-SMES based three area system. The results obtained are better with SMES having lower magnitudes of variations in the frequency, tile line power flow, and share of Gencos to the corresponding DPM. The settling tile also reduces with SMES. Thus, SMES can provide better solution to LFC during the sudden demand change and the Independent System Operator can provide better ancillary service management with such devices in deregulated electricity markets where the dispatch of pool and bilateral demand has to be met in real time keeping the balance of generation and demand.
From above simulation results, we can see that three cases have been studied and compared together. From these diagrams we can easily observe the best overall response for all the cases is obtained with PID-FLC-SMES in both areas.

V. CONCLUSION

In this paper, LFC in deregulated power system with PID-Fuzzy and PID-Fuzzy-SMES has been presented. A comparative study is given between three cases, 1) Using conventional integral controller, 2) Using PID controlled Fuzzy Logic Controller, 3) Using PID-FLC controlled SMES by simulating the model in MATLAB. From the results we observe that frequency deviations, tie-line power deviations and deviation in generation of Gencos are almost zero on using PID-FLC controlled SMES in both areas. On using PID-FLC controlled SMES, the rise time, settling time decreases and the steady state error is almost zero, as compared to that of other cases. Since, LFC is an important identified ancillary service, SMES can provide better solution to LFC during the sudden demand change and the Independent System Operator can provide better ancillary service management with such devices in deregulated electricity markets.

VI. REFERENCES

[25] MATLAB 7.4.0 (R2007a), The Mathworks, Inc. USA.