AGC of a Multi-area Hydro-thermal System with BES and Firefly Optimized PID Controller

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Abstract—This paper presents automatic generation control of three unequal area hydro-thermal systems. Appropriate generation rate constraints are considered in each area. Proportional - Integral - Derivative (PID) controller is used as the secondary controller in the areas. A Battery Energy Storage (BES) system is incorporated in Area1 and the system dynamic responses are compared with that of without BES system. Selection of position of BES in interconnected multi area system has been done first time as an individual and observed that BES in Area-1 with 1% SLP is the best. The PID controllers gains are optimized simultaneously using a more recent evolutionary computational technique called firefly algorithm. Investigations reveal that dynamic responses of the system with BES are better than without BES. Sensitivity analysis reveals that the optimum parameters obtained at nominal conditions are quite robust and need not be reset with wide change in system loading and change in step load perturbation (SLP). The system dynamics is evaluated by considering 1% SLP in area1.

Keywords—Automatic generation control; Battery Energy Storage system; PID controller; Sensitivity Analysis.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>f</td>
<td>Nominal System Frequency (Hz);</td>
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<tr>
<td>i</td>
<td>Subscript referred to area i (1, 2, 3).</td>
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<td>*</td>
<td>Superscript denotes optimum value.</td>
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<tr>
<td>Pᵢ</td>
<td>Rated power of area i (MW);</td>
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<tr>
<td>Hᵢ</td>
<td>Inertia constant of area i (s).</td>
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<tr>
<td>ΔPᵢ</td>
<td>Incremental load change in area i (p.u).</td>
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<tr>
<td>ΔPᵢᵦ</td>
<td>Incremental generation change in area i (p.u).</td>
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<tr>
<td>T₁₂, T₂₃, T₁₃</td>
<td>Synchronizing coefficients.</td>
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<tr>
<td>Rᵢ</td>
<td>Governor speed regulation parameter of area i (Hz/pu MW);</td>
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<tr>
<td>Tᵣᵦ</td>
<td>Steam governor time constant of area i (s).</td>
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<tr>
<td>Kᵢᵦ</td>
<td>Steam turbine reheat coefficient of area i.</td>
</tr>
<tr>
<td>Tᵣᵦ</td>
<td>Steam turbine reheat time constant of area i (s).</td>
</tr>
<tr>
<td>Tᵣᵦ</td>
<td>Steam turbine time constant of area i (s).</td>
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<tr>
<td>Bᵢ</td>
<td>Frequency bias constant of area i.</td>
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<tr>
<td>Tᵣᵦ</td>
<td>2Hᵢ / fᵦ Dᵢ; Dᵢ = 1/Dᵢ (Hz/pu).</td>
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<tr>
<td>Dᵢ</td>
<td>ΔPᵢᵦ/Δfᵦ(pu/Hz), PI π.</td>
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I. INTRODUCTION

In an interconnected power system, it is required to maintain system frequency and tie-line power exchange fixed to their nominal values for efficient, economic and reliable power supply. The deviation in system frequency and tie line power is due to the mismatch between generation and demand. This mismatch is eliminated by close control of real and reactive power generated by the controllable sources in the system. The role of automatic generation control (AGC) is to maintain frequency at or very close to a specified nominal value, and to sustain the scheduled tie line power between the control areas. Literature survey shows that there are many investigations on AGC of isolated and interconnected system. The concept of modeling interconnected system was introduced by Elgerd et al. [1], [2]. Nanda et al. have studied a two area hydrothermal system [3] and shows that with electric governor in hydro area the dynamic performance is better. Saikia el al. [4] studied a three unequal area hydrothermal system using electric governor in hydro area. Nowadays, the power system includes not only the conventional equipments but also consist of flexible ac transmission system (FACTS), high voltage DC transmission system (HVDC). Accordingly system dynamic performance changes in presence of these components. Battery energy storage (BES) is also system where electric energy is stored in battery. BES plays a vital role to enhance power system stability. However, little attention has been paid in the past to investigate the effect of BES in interconnected power system. In [5]-[8], the authors investigate the effect of BES in system stability. The authors
in [5] shows the dynamic behavior of a two area thermal system with wind perturbation in presence of BES in one of the two areas. The authors in [6] - [8] have compared the dynamic responses of a two area thermal system with and without BES in both the areas and concluded the advantage of using BES. Surprisingly, till date no investigation is available in three area hydro - thermal system incorporating BES. This needs further investigations.

In AGC are generally classical controllers such as Integral, Proportional - integral, proportional - integral - derivative (PID) are used as secondary controllers and the gains of these controllers need to be optimized. Several optimization techniques such as Classical, Genetic algorithm (GA), Bacterial foraging (BF) technique, Firefly algorithm (FA) etc have been reported in the AGC literature [3], [4], [9]-[12]. The classical technique [3] based on integral squared error (ISE) is a trial and error technique and most of the cases give suboptimal result. GA is also used in some literature [9]. Recent research pointed out some deficiencies in GA performance [10]. BF technique has also been used for simultaneous optimization of some variables [10]. Recently, powerful FA [11], [12] is successfully used in an isolated CCGT plant [13]. However, the same is not utilized in optimization of several parameters in three hydrothermal systems in presence of BES. Thus, this needs further investigations.

In view of the above following are the main objectives of the present work.

a) Development of the transfer function model of a three area system incorporating BES in the system.

b) Simultaneous optimization of gains i.e. PID controllers and \((K_{p1}, K_{i1}, K_{d1}, K_{p2}, K_{i2}, K_{d2})\) others parameters such as the feedback gain of frequency fluctuation \((K_{f}),\) gains \((K_{p}, K_{i}, K_{d})\) of electric governor in the hydro area using FA.

c) Comparison of dynamic responses for dynamic responses of the system with and without BES.

d) Sensitivity analysis of the optimum parameters obtained at nominal condition.

II. THE SYSTEM INVESTIGATED

The system considered is a three unequal area hydro-thermal system. The capacities of the areas are Area1: 2000MW, Area2: 6000MW, and Area3: 12000MW. The thermal areas are provided with reheat turbine. Hydro area is provided with electric governor. The governor speed regulation parameter \(R_i = 2.4\) Hz/puMW and frequency bias \(B_i = \beta_i\) (AFRC) is considered in the system. The proportional - integral-derivative (PID) controller is used as the secondary controller in the areas. The nominal system parameters are taken from [3], [4] and are shown in Appendix. Generation rate constraint (GRC) of 3%/min in thermal areas and 270%/min for raising generation and 360%/min for lowering generation in hydro area are considered. To study the effect of BES in the system, a BES system is incorporated in Area1. The transfer model of the three unequal area hydro-thermal systems with BES is shown in Fig.1. Matlab software has been used for simulink model of the system and coding. The dynamic performance has been evaluated considering 1% step load perturbation (SLP) in area1. The variables such as the proportional gain \((K_p),\) integral gain \((K_i)\) and derivative gain \((K_d)\) of electric governor in hydro area are optimized simultaneously with gains of secondary controller (PID) using FA. The optimization is done using minimization of the cost function given by Integral squared error (ISE) as given by equation (1).

\[
J = \int_0^t \left( \Delta f_i \right)^2 + \left( \Delta P_{sw,i} \right)^2 dt
\]  

(1)
III. BATTERY ENERGY STORAGE SYSTEM (BES)

A wide application of battery energy storage (BES) system is being done in various literatures. As for example in [7] load frequency control (LFC) of an interconnected reheat thermal system considering BES system. The authors in [8] present the qualitative and quantitative comparison of conventional controllers and BES system in LFC of a typical two area interconnected power system. In this paper, we use the control system of BES system in power system frequency control. Based on previous work as in [5], the proposed control system of BES system is shown in Fig. 2. The control system includes three loops.

1) Item \( \frac{K_{PB}}{1 + sT_{bajr}} \) represents an auto balancing charging loop for the battery energy storage system. This loop could control the remaining energy of the energy storage around in the initial state, which is normally set to be 50%.

2) Symbol \( K_B \) represents the feedback gain of the frequency fluctuation in the power grid. Item \( \Delta P_{swl} - \Delta P_{swl} \) represents the compensated power, which is caused by ramp limitations of generators.

3) Item \( \frac{1}{1 + sT_{conv}} \) represents the effect of the first order delay of DC-AC power converter in the battery energy storage system.

IV. FIREFLY ALGORITHM

The firefly algorithm (FA) is a novel meta-heuristic algorithm inspired by the social behavior of fireflies induced by Yang [9]. The algorithm was based on the idealized behaviour of the flashing characteristics of fireflies. The idealized flashing characteristic of the firefly is based on the following assumptions. (a) All fireflies are unisex so that one firefly is attracted to other fireflies regardless of their sex, (b) Attractiveness is proportional to their brightness. Thus for any two flashing fireflies, the less bright one will move towards the brighter one. The attractiveness and brightness decrease as their distance increases. If no one is brighter than a particular firefly, it moves randomly, and (c) The brightness or light intensity of a firefly is affected or determined by the form of the objective function to be optimised. For a maximization problem, the brightness is proportional to the objective function. Other forms of brightness can be defined in a similar way to the fitness function in GA or the BF Technique. Based on these three rules, the execution process of firefly algorithm is shown in Fig.3 and the details regarding FA is available in [11]. The convergence curves for Genetic algorithm (GA) and Firefly algorithm (FA) are shown in Fig.4, from which, it is clearly seen that FA convergence very fast than GA for the tested system. In this optimization, the parameters of FA are tuned for optimal performance and their tuned values are number of firefly = 10, Maximum generation = 80, \( \beta = 0.3 \), \( \alpha = 0.4 \), and \( \gamma = 0.5 \). The minimum and maximum limits of the controller gains (\( K_p, K_i, K_d \)) are 0 and 1.

V. RESULT AND ANALYSIS

A. Three Area System with and without BES at nominal Conditions

In this case the PID controller gains and parameters are optimized using Firefly algorithm. When the system is provided with PID controllers with BES, the optimum values are \( K_{P1}^* = 0.0017, K_{P2}^* = 0.0067, K_{P3}^* = 0.0002, K_{I1}^* = 0.5805, K_{I2}^* = 0.5449, K_{I3}^* = 0.4600, K_{D1}^* = 0.1653, K_{D2}^* = 0.1074, K_{D3}^* = 0.0001, K_B^* = 1.4, K_p^* = 1.026, K_i^* = 5.035, K_d^* = 3.993 \). When the system is provided with PID controllers without BES, the values of \( K_p, K_i, K_d \) are fixed at \( K_p = 1.026, K_i = 5.035, K_d = 3.993 \), the optimum values are \( K_{P1}^* = 0.0486, \)
KP2* = 0.0247, KP3* = 0.0274, KI1* = 0.1459, KI2* = 0.0734, KI3* = 0.0501, KD1* = 0.2422, KD2* = 0.0001. The dynamic responses corresponding these optimum gains of the system with and without BES are compared and shown in Fig. 5a-5f.

From the critical examination of the dynamic responses of Fig.5, the overshoot and settling time are noted and shown in TABLE.I. From TABLE.I and the responses, it is clearly seen that the responses corresponding to PID controllers in presence of BES system are better than that of without BES from the point of view of settling time, magnitude of oscillations and peak deviations.

B. Selection of Position of BES

BES is incorporated in Area-1, Area-2, and Area-3 independently with 1% SLP in Area-1. Already the optimization of controller gains and parameter KB are optimized in section V. A. When BES is incorporated in Area-2 and Area-3, the gains of PID controllers (KP3, KI1, KI2) are optimized in each case separately by keeping parameters KB* = 1.4 (as obtained in section V.A) of BES using FA. When the BES is in Area-2, the optimum values are KP1* = 1.921, KP2* = 0.93755, KP3* = 0.2752, KI1* = 1.059, KI2* = 0.75564, KI3* = 0.6830, KD1* = 0.6019, KD2* = 0.82605, KD3* = 0.1583. When the BES is in Area-3, the optimum values are KP1* = 0.0017, KP2* = 0.0067, KP3* = 0.0002, KI1* = 0.5805, KI2* = 0.5449, KI3* = 0.6400, KD1* = 0.1653, KD2* = 0.1074, KD3* = 0.0011. The dynamic responses are obtained corresponding to BES in Area-1, 2, 3 and compared (Fig.6).
Fig. 6. Comparison of dynamic responses of PID controller in three unequal area hydro-thermal system in presence of BES at different positions of BES with $K_{p*}, K_{i*}, K_{d*}, K_{b*}$ corresponding to 1% SLP in Area-1 (a) $\Delta f_1 = f(t)$, (b) $\Delta P_{tie1-2} = f(t)$.

Critical observation of the dynamic responses of Fig. 6, it is clearly seen that the responses of the system with BES in Area-1 are better in comparison to that of Area-2 and Area-3 from the point of view of magnitude of oscillations, settling time and peak deviations, individually. Hence, Area-1 is the better position of BES than the others.

C. Sensitivity Analysis

Sensitivity analysis has been carried out to see the robustness of the optimum gains PID controllers and parameters $K_{p*}$ of BES obtained at nominal condition ($K_{p1*} = 0.0017, K_{p2*} = 0.0067, K_{p3*} = 0.0002, K_{i1*} = 0.5805, K_{i2*} = 0.5449, K_{i3*} = 0.6400, K_{d1*} = 0.1653, K_{d2*} = 0.1074, K_{d3*} = 0.0001, K_{b*} = 1.4$) obtained at nominal loading conditions to wide changes in system loading and the magnitude of SLP. In order to do this, keeping $K_{p}, K_{i}, K_{d}$ are fixed ($K_{p} = 1.026, K_{i} = 5.035, K_{d} = 3.993$) simultaneous optimization of $K_{p1}, K_{i1}, K_{d1}, K_{b1}$ is done for $\pm 20\%$ changed system loading from nominal, and at changed magnitude of SLP (1%, 2%) using FA. The optimum values are shown in TABLE.II. The dynamic responses at changed condition with $K_{p1*}, K_{i1*}, K_{d1*}, K_{b1*}$ corresponding to 30% and 50% loading are compared and shown in Fig. 7, Fig. 8, and Fig. 9.
Critical observation of the dynamic responses, it is clearly seen that responses are more or less same. Thus, it is not required to reset the gains and other parameters obtained at nominal when loading and size of disturbances changes. Only five dynamic responses are shown for justification of this statement.

VI. CONCLUSION

Comparison of dynamic characteristics of the proportional - integral - derivative (PID) controller in a three unequal area hydro-thermal system with and without BES system in presence of GRC is done for the first time in automatic generation control. The firefly algorithm (FA) is used for simultaneous optimization of different parameters such as PID controller gains, gains of electric governor and feedback gain of frequency fluctuation controllers in presence of BES system. The FA is simple and fast optimization technique and successfully optimized variables. Selection of position of BES in interconnected multi area system has been done as an individual analysis first time. Sensitivity analysis reveals that the optimum PID gains and parameters in presence of BES system in Area-1 obtained at nominal condition are robust and need not be reset for wide changes in the system loading or size of SLP.

APPENDIX

Nominal parameters of the system are: \( f = 60 \text{Hz} \); \( R_e = 2.4 \text{ Hz/} \text{per unit MW} \); \( T_g = 0.08s \); \( P_{\text{max}} = 200 \text{MW} \); \( T_r = 10.0 \text{s} \); \( H_1 = 5 \text{s} \); \( P_{r1} = 2000 \text{MW} \); \( P_{r2} = 6000 \text{MW} \); \( P_{r3} = 12000 \text{MW} \); \( T_1 = 0.3s \); \( K_{p1} = 1.0263 \); \( K_{d1} = 3.9934 \); \( K_{i1} = 5.0346 \); \( T_1 = 1.0 \text{s} \); \( D_1 = D_2 = D_3 = 8.33 \times 10^{-3} \text{p.u.} \); \( u_1 = 0.086 \text{ p.u.} \); \( T_r = 5 \text{s} \); \( K_{p2} = 0.2 \); \( K_{d2} = 0.01 \); \( K_{i2} = 0.01 \); \( P_{t} = 120 \text{Hz/p.u.} \); \( P_{t} = 20 \text{sec} \); For BES system the nominal parameters are: \( T_{\text{charge}} = 100s \); \( K_{pB} = 0.2 \); \( K_{dB} = 1.4 \). [6]-[8]. BES capacity ( 20MW/40MW h)

REFERENCES