Robust and Optimal FLPID Controllers Design by Bee Algorithm for AGC of Hydro-Thermal System with SMES

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บทคัดย่อ

บทความนี้ได้นำเสนอการประยุกต์ใช้วิธีฝูงผึ้ง (BA) เพื่อออกแบบตัวควบคุมฟัซซี่ลอจิกพีไอดีให้มีความเหมาะสมและมีความคงทน สำหรับการควบคุมการผลิตไฟฟ้าอัตโนมัติของระบบไฟฟ้ากำลัง (AGC) แบบโรงไฟฟ้าพลังงานน้ำเชื่อมต่อกับโรงไฟฟ้าพลังงานความร้อน ที่มีตัวเก็บสะสมพลังงานแม่เหล็กโดยใช้ตัวนำยิ่งยวด (SMES) วิธีฝูงผึ้งจะช่วยปรับค่าตัวควบคุมฟัซซี่ลอจิกพีไอดี เพื่อควบคุมความถี่ของระบบไฟฟ้ากำลังให้มีการเปลี่ยนแปลงน้อยที่สุด ภายใต้สภาวะที่โหลดมีการเปลี่ยนแปลง ผลจากการจำลองแบบชี้ให้เห็นว่าตัวควบคุมฟัซซี่ลอจิกพีไอดีที่ได้เสนอนี้ ช่วยให้ระบบไฟฟ้ากำลังที่มี SMES ทั้งโรงไฟฟ้าพลังน้ำและโรงไฟฟ้าพลังความร้อน มีประสิทธิภาพการดำเนินงานที่ดีด้านการตอบสนองพลวัต ในค่าช่วงเวลาเข้าที่ ค่าการพุ่งเกินและค่าผิดพลาดสมบูรณ์อินทิกรัล (IAE) ดังนั้น จึงส่งผลให้ระบบไฟฟ้ากำลังมีการส่งจ่ายและจำหน่ายกำลังไฟฟ้าได้อย่างมีเสถียรภาพ

คำสำคัญ การควบคุมการผลิตไฟฟ้าอัตโนมัติ, วิธีฝูงผึ้ง, การหาค่าที่เหมาะสม, ระบบไฟฟ้ากำลัง, ตัวเก็บสะสมพลังงานแม่เหล็กแบบตัวนำยิ่งยวด

Abstract

This article presents an application of bee algorithm (BA) to adjust robust and Optimal Fuzzy Logic-proportional-integral-derivative (FLPID) controllers for automatic generation control (AGC) of two areas interconnected hydro-thermal system combining superconducting magnetic energy storage (SMES) units. BA is nominated to simultaneously tune FLPID controllers to minimize frequency deviations of the power system against load disturbances. Generally, Membership Functions (MF) and Control Rules (CR) of the Fuzzy Logic Controller (FLC) were obtained by trial and error methods of creators. Simulation results indicate that the proposed FLPID controllers with SMES units in both areas perform tremendously better than other that no SMES unit and SMES unit in either thermal or hydro area in settling time, overshoot and integral absolute error (IAE). Accordingly, FLPID controllers will result to power system having stability in power transmission and distribution.

Keywords: Automatic generation control, Bee algorithm, Optimization technique, Power system, Superconducting magnetic energy storage.

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Introduction

The AGC is an outstanding topic in power system operation and control. Instead, load changes impact dynamically on the power system. These direct to frequency deviations and tie-line power deviations among interconnected areas. In order to find solution for this problem, the governor system in an AGC has been put to work. However, the governor system may no longer be able to compensate for such load changes because of its slow response [1]. In addition, a superconducting magnetic energy storage (SMES), which is competent for controlling active and reactive power significantly [2], has been anticipated as one of the most effective and significant stabilizers of power system oscillations modes [3]. Likewise, a SMES allows a power system improvement, load leveling and a AGC problem. Various design methods of AGC system combined with SMES units, have been successfully presented, for instance, a lead-lag controller a proportional control. Recently, the FLPID controller has been applied to design AGC system. The FLPID controller has a large benefit over conventional controllers. Since, it is not so sensitive to various system structures and parameters. Also, operation points can be easily implemented in a large scale nonlinear system. Besides, FLPID controller is expected as one of a sophisticated technique that is obvious to design and to implement. Nevertheless, a determination of FLPID controller is an important problem in a design. To obtain satisfied FLPID controller, designers' experiences are mandatory. The most straightforward approach is to define FLPID controller by studying an operating system or a current controller. Therefore, practical methods for tuning FLPID controller in order to reduce the output error or increase the performance index without trial and error methods are remarkably required [4].

A lot of the works involved with AGC of interconnected power systems relate to tie-line bias control strategy [5]. Supplementary controllers are designed to adjust area control errors to zero effectively. In spite of small load disturbances and with the optimized gain for the supplementary controllers, the power frequency and the tie-line power deviations persevere for a long duration. In these cases, the governor system may not support the frequency fluctuations according to its slow response. For compensating the power frequency and the tie-line power for the sudden load changes, an active power source with fast response such as SMES unit is supposed to be the most effective countermeasure AGC of an interconnected hydrothermal power system considering SMES [6]. The additional reported works shows that [7], SMES is found in each area of the two-area system for AGC. Using of SMES in both areas, frequency deviations in each area are effectively quashed.

In the past few years, an application of BA to solve combinatorial optimization problems has been offered [8]. Furthermore, there are a few articles for designing FLPID controller. Consequently, major objectives of this article are as followed:

1) To estimate the dynamic response examining the PID controllers in the hydro-thermal system. The PID gains are optimized using integral absolute error (IAE).

2) To apply FLPID controllers in the hydro-thermal power system including SMES units.

3) To propose BA to optimize FLPID controllers by considering settling time and overshoot.

4) To compare that no SMES unit, SMES unit in either thermal or hydro area as well as SMES units in both areas.

5) To examine the robustness of the control system under system parameter variations and load changes.

2. Problem Formulation

Many design methods of AGC system provided with SMES units have been successfully presented such as a proportional control, an adaptive control and a neural network. Regardless of the potential of control techniques with different structures, power system utilities still prefer the fixed structure controller such as PI controllers and PID controllers.

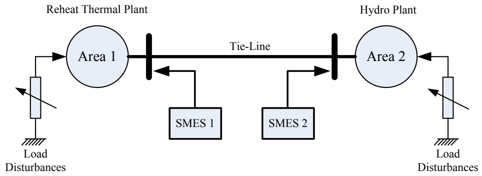


Figure 1. Schematic diagram of the two-area interconnected hydro-thermal system.

Nomenclature:

f = Nominal system frequency,
i = Subscript referred to area i (1, 2)
P_{ri} = Area rated power,
H_i = Inertia constant,
ΔP_{di} = Incremental load change,
ΔP_{Gi} = Incremental generation change,
ΔP_{Ri} = Incremental governor change
ΔP_{tie} = Tie-line power,
ΔX_{Ei} = Incremental change in governor value position
u_i = Control signal,
T_{12} = Synchronizing coefficient,

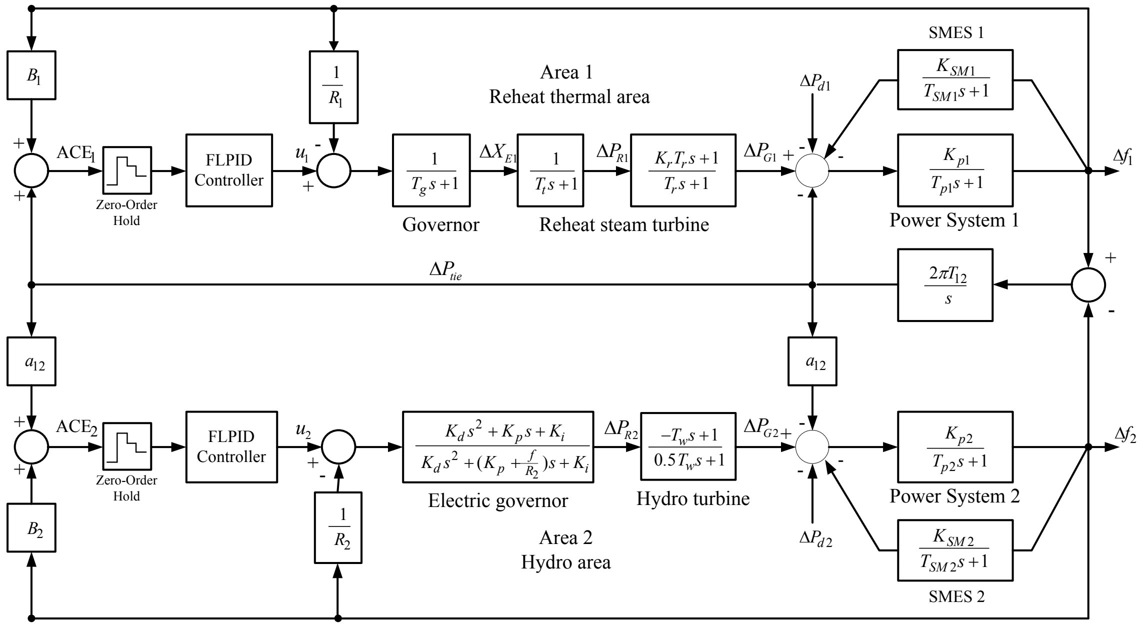


Figure 2. Block diagram of power system having digital controllers and SMES Units.

K_r = Reheat constant
T_g = Steam governor time constant,
T_t = Steam turbine time constant
T_r = Reheat time constant,
B_i = Frequency bias constant,
T_w = Water starting time,
R_i = Governor speed regulation parameter, ACE_i = Area Control Error
K_d, K_p, K_i = Electric governor derivative, proportional and integral gains, respectively, J = Cost Index

$$D_i = \Delta P_{di} / \Delta f_i \qquad T_{pi} = 2H_i / (f \times D_i)$$

$$K_{pi} = 1 / D_i \qquad a_{12} = -P_{r1} / P_{r2}$$

A controlled two-area interconnected hydro-thermal system contains a reheat steam turbine type for the reheat thermal area, an electric governor type for hydro area and SMES units as shown in figure 1 [9]. The detailed block diagram of an interconnected hydro-thermal system in a continuous-discrete mode strategy with reheat and electric governor is expressed in figure 2 and system parameters are shown in a nomenclature. Both areas have placed SMES1 and SMES2 to decrease frequency deviations. It is supposed that large loads with sudden changes, for example large steel mills, arc furnace factories etc., have been located in both areas. These generate severe frequency deviations. In this article, the optimal PID gains are designed based on the BA to decrease frequency deviations in both areas. The state space equations of this power system are shown in continuous time domain as following:

$$x^{\cdot} = Ax(t) + Bu(t) + Ld(t) \qquad (1)$$

where $\mathbf{A}$ is a system matrix, $\mathbf{B}$ is an input and $\mathbf{L}$ is disturbance distribution matrices and $x(t), u(t)$ and $d(t)$ are state, control and load changes disturbance vectors, respectively as following:

$$x(t) = [\Delta f_1 \quad \Delta P_{G1} \quad \Delta P_{R1} \quad \Delta X_{E1} \quad \Delta P_{tie} \quad \Delta f_2 \quad \Delta P_{G2} \quad \Delta P_{R2}]^T \qquad (2)$$

$$u(t) = [u_1 \quad u_2]^T \qquad (3)$$

$$d(t) = [\Delta P_{d1} \quad \Delta P_{d2}]^T \qquad (4)$$

where Δ indicates a deviation from nominal values, suffix 1 is used for the thermal area and suffix 2 is used for the hydro area.

The system output, which depends on an area control error (ACE) displayed in figure 2, is given as:

$$y(t) = \begin{bmatrix} y_{1(t)} \\ y_{2(t)} \end{bmatrix} = \begin{bmatrix} ACE_1 \\ ACE_2 \end{bmatrix} = Cx(t) \qquad (5)$$

$$ACE_i = \Delta P_{tie,j} + B_i \Delta f_i, \ i = 1,2 \qquad (6)$$

where $\mathbf{C}$ is an output matrix.

For a SMES unit, the limiter of $-0.01 \le \Delta P_{SMi,i=1,2} \le 0.01$ p.u.MW is equipped at a power output terminal. Control parameters of SMES1 and SMES2 units are set as $K_{SM1} = K_{SM2} = 0.12$ and $T_{SM1} = T_{SM2} = 0.05$ s.

3. Fuzzy Logic-Proportional Integral Derivative (FLPID) Controller

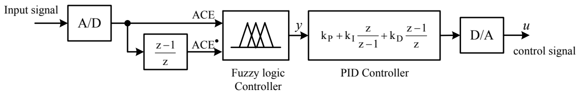


Figure 3. Structure of FLPID controller in discrete mode.

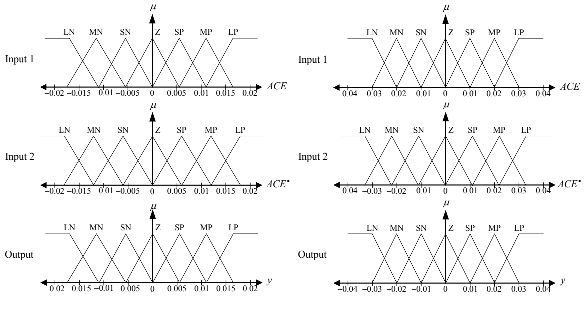
The FLPID controllers to solve this issue, as proposed in figure 3, comprise of the FLC and the conventional PID controllers, connecting in series.

The FLC has two input signals namely as ACE and $\mathrm{ACE}^{\bullet}$, then the output signal (y) of FLC is the input signal of the conventional PID controller. Lastly, the output signal from the conventional PID controller entitled the control signal (u) is applied for controlling AGC in the interconnected hydro-thermal system.

In order to obtain the system output, the control signal for the FLPID controller is given by:

$$u(z) = -\left(k_P y + k_I \frac{z}{z-1} y + k_D \frac{z-1}{z} y\right) \qquad (7)$$

The MF of FLC, shown in figure 4, includes of three MF. Each MF has seven memberships, consisting of two trapezoidal and five triangular memberships. On the point of two-inputs and one-output, CR can be shown graphically in a table where every cell shows the output MF of CR as a relationship between input 1 and 2. The CR is built from ***if-then*** statement (if input 1 and input 2, then output 1). Figure 5 shows the proper CR in this study. Let us examine the third row and the forth column in figure 5, that means, if ACE is SN and $\mathrm{ACE}^{\bullet}$ is Z then y is SN.



(a) (b)

LN: large negative; MN: medium negative;

SN: small negative; Z: zero; SP: small positive;

MP: medium positive; LP: large positive.

Figure 4. Membership function of FLPID controllers. (a) Reheat thermal area
(b) Hydro area.

		$ACE^{\bullet}$						
		LN	MN	SN	Z	SP	MP	LP
ACE	LN	*LN*	*LN*	*LN*	*MN*	*MN*	*SN*	*Z*
	MN	*LN*	*LN*	*LN*	*MN*	*SN*	*Z*	*SP*
	SN	*LN*	*LN*	*LN*	*SN*	*Z*	*SP*	*MP*
	Z	*MN*	*MN*	*SN*	*Z*	*SP*	*MP*	*MP*
	SP	*MN*	*SN*	*Z*	*SP*	*LP*	*LP*	*LP*
	MP	*SN*	*Z*	*SP*	*MP*	*LP*	*LP*	*LP*
	LP	*Z*	*SP*	*MP*	*MP*	*LP*	*LP*	*LP*

Figure 5. The CR for FLPID controllers.

For designing of the FLPID controllers, PID gains have only three parameters to tune involving a proportional gain, an integral gain and a derivative gain. The MF and CR have many parameters to tune. The MF has 2 trapezoidal and 5 triangular memberships. As a result, there are 23 parameters to tune. For the FLC with two-inputs and one-output there are 69 parameters to tune.

In the CR list, for two-inputs and one-output FLC, CR must be indicated in seven numbers (1-7), 1: LN, 2: MN, 3: SN, 4: Z, 5: SP, 6: MP, and 7: LP. Thence, there are 49 parameters to tune. Although, the total parameters for two-inputs and one-output the FLPID controllers are 121 (3+69+49) tuning parameters.

4. Bee Algorithm

The BA was presented by D.T. Pham [9] for optimizing numerical problems. The algorithm mimics the food foraging behavior of swarms of honey bees. The random optimization algorithm, which is gained by honey bees' method, is simple, robustness and popularity. The procedure of BA is given as below:

Step 1: Randomly generate initial solutions of *n* scout bees for parameters of k_P, k_I, and k_D. These initial solutions must be feasible candidate solutions that satisfy constraints. Set *iteration = 0*.

Step 2: Represent the values of k_P, k_I, and k_D to the PID controller in order to find time response of Δf_1, Δf_2 and ΔP_{tie} of the system.

Step 3: Evaluate the objective function to substitute Δf_1, Δf_2 and ΔP_{tie} in equation (9).

Step 4: Select *m* best solutions for neighborhood search. Separate *m* best solutions into two groups, the first group has *e* best solutions and another group has *m-e* best solutions.

Step 5: Determine the size of neighborhood search for each best solutions (*n* size).

Step 6: Determine number of employed bees (*ne*) for the best *e* solutions and number of employed bees (*ns*) for *m-e* solutions (*ne > ns*).

Step 7: Randomly generate neighborhood solutions of *ne* and *ns* employed bees for parameters of k_P, k_I, and k_D. Represent the values of k_P, k_I, and k_D to the PID controller in order to find time response of Δf_1, Δf_2 and ΔP_{tie} of the system. Evaluate the objective function to substitute Δf_1, Δf_2 and ΔP_{tie} in equation (8).

Step 8: Select the best solution of each neighborhood search.

Step 9: Check the stopping criterion. If satisfied, terminate the search,
else *iteration = iteration+1*.

Step 10: Randomly generate new initial solutions of *n-m* scout bees for parameters of k_P, k_I, and k_D. Construct the initial solutions for the next iteration by combine *m* best solutions and new *n-m* generate initial solutions. Go to Step 2.

where *n* is number of scout bees, *m* is number of the best selected sites, *e* is number of the best site, *ngh* is neighborhood size [10].

5. Implementation and Results

Simulations were performed by applying the FLPID controllers both areas, no SMES unit, SMES unit in either thermal or hydro area as well as SMES units in both areas, applied to a two-area interconnected hydro-thermal system as shown in figure 2, when using 0.01 p.u.MW step load disturbance in both areas. The identical system parameters are given in Appendix. All models were simulated in Matlab. According to investigations, the next parameters of the BA method are used:

n=10, *m* = 5, *e*=3, *ne* = 20, *ngh*=0.01, and *NC* = 20,000. In the optimization, IAE of the frequency deviation of the first area, the second area and a power deviation at tie-line are selected as the performance index. Therefore, the objective function J is prepared by:

$$\text{Minimize } J = \int_{0}^{50}\left(\left|\Delta f_1\right| + \left|\Delta f_2\right| + \left|\Delta P_{tie}\right|\right)dt \quad (8)$$

After tuning, the FLPID controllers have optimized FLPID gains are shown in table 1.

Table 1. Tuned parameters of FLPID controllers.

Area	k_P	k_I	k_D
Thermal	0.6360	0.5980	0.0039
Hydro	0.2180	0.1488	0.0015

The optimized MF of input 1, 2 and output are presented in figure 6 and the optimized CR are presented in figure 7.

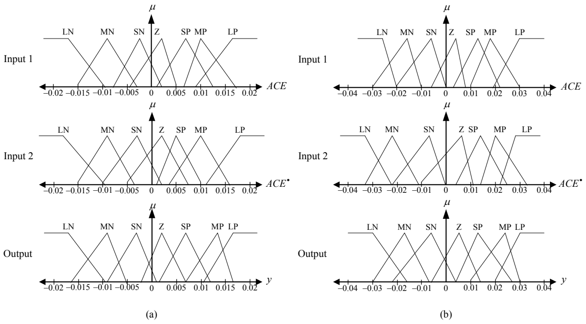
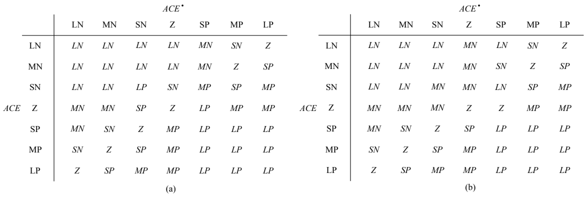


Figure 6. Optimized MF for optimal FLPID controllers. (a) Reheat thermal area
(b) Hydro area.



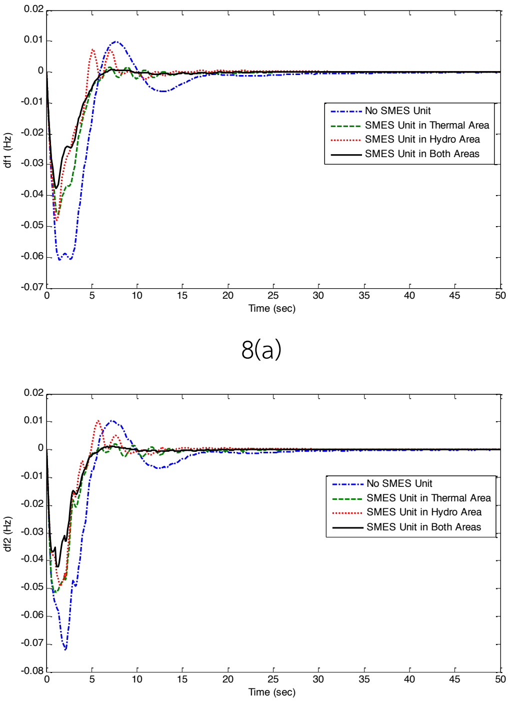
(a)

		$ACE^{\bullet}$						
		LN	MN	SN	Z	SP	MP	LP
	LN	*LN*	*LN*	*LN*	*LN*	*MN*	*SN*	*Z*
	MN	*LN*	*LN*	*LN*	*LN*	*MN*	*Z*	*SP*
	SN	*LN*	*LN*	*LP*	*SN*	*MP*	*SP*	*MP*
ACE	Z	*MN*	*MN*	*SP*	*Z*	*LP*	*MP*	*MP*
	SP	*MN*	*SN*	*Z*	*MP*	*LP*	*LP*	*LP*
	MP	*SN*	*Z*	*SP*	*MP*	*LP*	*LP*	*LP*
	LP	*Z*	*SP*	*MP*	*MP*	*LP*	*LP*	*LP*

(b)

		$ACE^{\bullet}$						
		LN	MN	SN	Z	SP	MP	LP
	LN	*LN*	*LN*	*LN*	*MN*	*LN*	*SN*	*Z*
	MN	*LN*	*LN*	*LN*	*MN*	*SN*	*Z*	*SP*
	SN	*LN*	*LN*	*MN*	*MN*	*LN*	*SP*	*MP*
ACE	Z	*MN*	*MN*	*MN*	*Z*	*Z*	*MP*	*MP*
	SP	*MN*	*SN*	*Z*	*SP*	*LP*	*LP*	*LP*
	MP	*SN*	*Z*	*SP*	*MP*	*LP*	*LP*	*LP*
	LP	*Z*	*SP*	*MP*	*MP*	*LP*	*LP*	*LP*

Figure 7. The optimized CR for optimal FLPID controllers. (a) Reheat thermal area
(b) Hydro area.



8(a)

8(b)

Figure 8. The frequency deviation of both areas for different SMES units.
(a) Reheat thermal area (b) Hydro area.

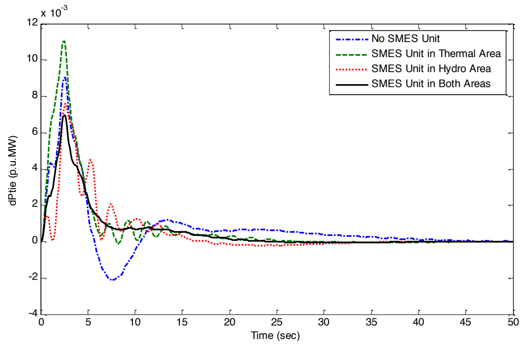
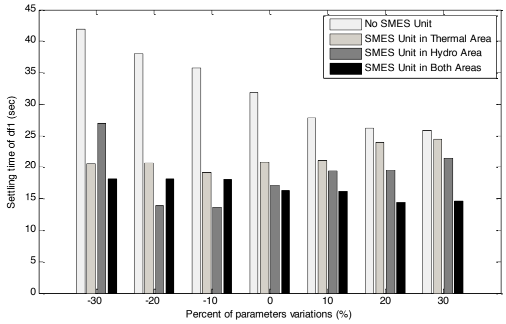


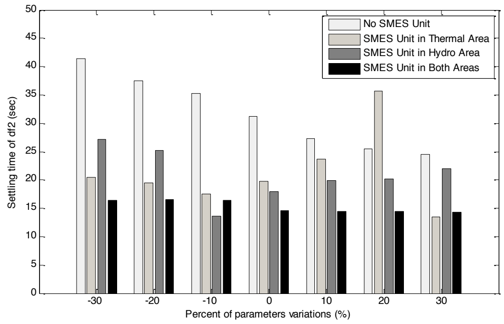
Figure 9. The power deviation of both areas for different SMES units.

The frequency deviations of both areas after a load change are demonstrated in figure 8-9. The SMES unit in either thermal or hydro area highly improve the system performance comparison to no SMES unit. Moreover, SMES units in both areas are significantly superior to the no SMES unit. They give a better performance than no SMES unit and SMES unit in either thermal or hydro area. The settling time and overshoot are reduced considerably.

Moreover, the robustness of each controller against system parameters variations are evaluated by the IAE. These values are computed under an occurrence of load disturbances whilst all system parameters are varied from -30% to 30% of formal values. The comparison results shown in figure 10-11 clarify values of settling time and overshoot of both areas, respectively. This illustrates that the robustness of SMES units in both areas against parameters variations is superior to no SMES unit and SMES unit in either thermal or hydro area.

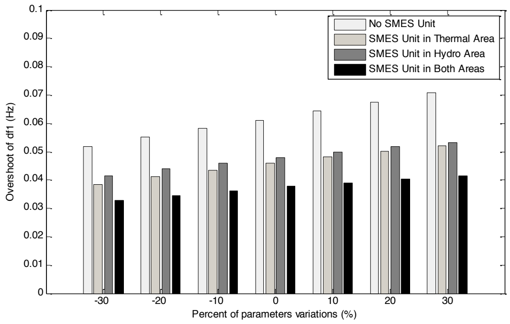


10(a)

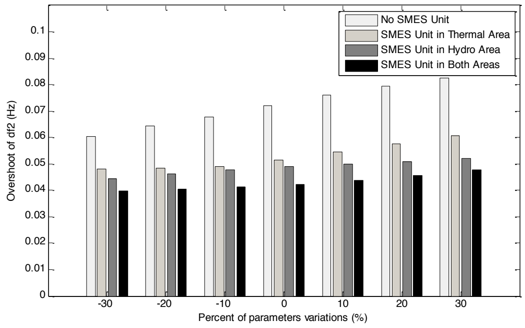


10(b)

Figure 10. Comparison results of settling time of both areas under parameters variations.
(a) Reheat thermal area (b) Hydro area.



11(a)



11(b)

Figure 11. Comparison results of overshoot of both areas under parameters variations. (a) Reheat thermal area (b) Hydro area.

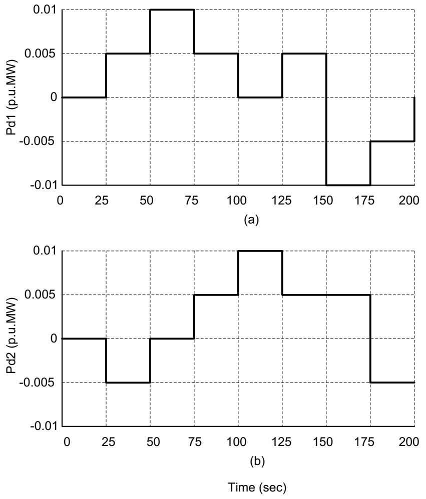
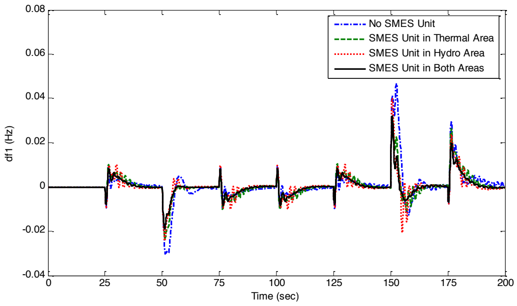
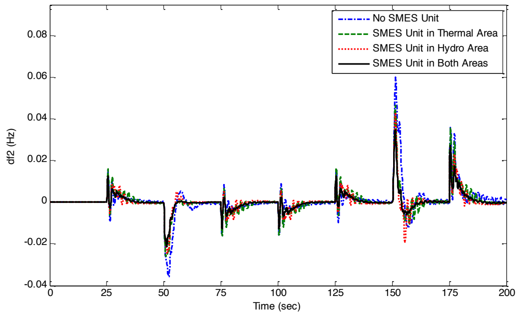


Figure 12. Random step load change in thermal and hydro areas. (a) Reheat thermal area (b) Hydro area.

Eventually, frequency control effects of the FLPID controllers with SMES units are analyzed under different random step load variations which are applied to both areas as demonstrated in figure 12. The outcomes of frequency deviations of both areas are unveiled in figure 13. Furthermore, figure 14 shows results of changes in tie-line power. The frequency deviations and changes in tie-line power are improved considerably by the no SMES unit in comparison with the case of SMES unit in either thermal or hydro area and SMES units in both areas.



13(a)



13(b)

Figure 13. Time response of Δf_1 and Δf_2 under random load change.
(a) Reheat thermal area (b) Hydro area.

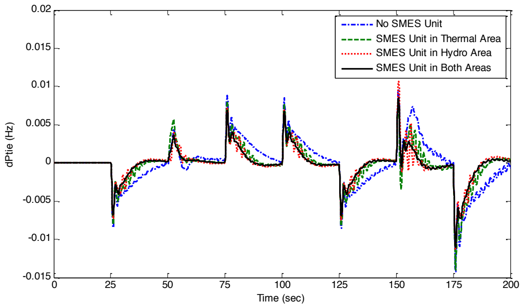


Figure 14. Time response of ΔP_{tie} under random load change.

6. Conclusions

In conclusions, an application of BA has been used for optimal FLPID controllers for AGC of a two-area interconnected hydro-thermal system with SMES. Designers gain benefits by saving time from the proposed technique for designing the FLPID controller, comparing with conventional design procedures. A number of studies have been performed with the optimal FLPID controllers to test the effectiveness and robustness. Last but not least, simulation results show that the optimal FLPID controllers with SMES units in both areas perform significantly better than other that no SMES unit and SMES unit in either thermal or hydro area in settling time, overshoot and IAE. Hence, the optimal FLPID controllers are efficient and robust over various operating conditions.

7. Appendix

In the following, most parameters of the two-area interconnected hydro-thermal system in figure 2 as in [9] and some of parameters have been modified:

$f = 60$ Hz, $T_r = 10.0$ s, $T_t = 0.3$ s,
$T_w = 1.0$ s, $T_g = 0.08$ s, $K_r = 0.5$, $K_P = 1.0$,
$K_d = 4.0$,
$K_i = 5.0$, $H_1 = H_2 = 5$, $R_1 = R_2 = 2.4$
Hz/p.u.MW, $P_{tie,\max} = 200$ MW,
$P_{r1} = P_{r2} = 2000$MW, $D_1 = D_2 = 8.33 \times 10^{-3}$
p.u.MW/Hz

8. References

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