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Application of Self-Tuning FPIC to AGC for Load Frequency Control in Multi-Area Power System

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***Abstract*--Since a superconducting magnetic energy storage (SMES) unit with a self-commutated converter is capable of controlling both the active and reactive power simultaneously and quickly, increasing attention has been focused recently on power system stabilization by SMES control. In this study, a self-tuning control scheme for SMES is proposed and applied to automatic generation control (AGC) in power system. The system is assumed to be consisting of two areas. The proposed self-tuning control scheme is used to implement the automatic generation control for load frequency control application adding to conventional control configuration. The effects of the self tuning configuration with fuzzy proportional integral controller (FPIC) in AGC on SMES control for the improvement of load frequency control (LFC) is compared with that of PI controlled AGC. The effectiveness of the SMES control technique is investigated when Area Control Error (ACE) is used as the control input to SMES. The computer simulation of the two-area interconnected power system shows that the self tuning FPIC control scheme of AGC is very effective in damping out of the oscillations caused by load disturbances in one or both of the areas and it is also seen that the FPIC controlled SMES performs primary frequency control more effectively compared to PI controlled SMES in AGC control.**

***Index Terms*—Proportional integral (PI) controller, fuzzy PI controller (FPIC), automatic generation control, area control error (ACE), Load frequency control and multi area power system.**

I. Introduction

Automatic generation control is a very important subject in power system operation for supplying sufficient and reliable electric power. This is achieved by AGC. In an interconnected power system, as the load demand varies randomly, the area frequency and tie-line power interchange also vary. The load frequency control by only a governor control imposes a limit on the degree to which the deviations in frequency and tie-line power exchange can be decreased. However, as the LFC is fundamentally for the problem of an instantaneous mismatch between the generation and demand of active power, the incorporation of a fast-acting energy storage device in the power system can improve the performance under such conditions. To achieve a better performance, many control strategies are proposed in literature [1-3]. Because of non-linear nature of power system, the controller designed for operation around a point based on a linear model obtained by linearization is insufficient. The operation point of a power system may change because of changing loads during the day period. In this situation, a fixed gain controller that is optimal at an operation point may not be suitable in another operating point [3]. Therefore, variable structure controller [4–5] has been proposed for AGC. For designing these control techniques, the perfect model is required which can track the state variables and satisfy system constraints. Therefore, it is difficult to apply these adaptive control techniques to AGC in practical implementations. When a small load disturbance in any area of the interconnected system occurs, tie-line power deviations and power system frequency oscillations continue for a long duration, even in the case with optimized gain of integral controllers. To damp out the oscillations in the shortest possible time, automatic generation control including SMES unit is used.

In the proposed self tuning system, the effect of FPIC in AGC on SMES control is investigated for the improvement of LFC. This is met when the control action maintains the frequency and the tie-line power interchange at the scheduled values. For this, the area control error (ACE) is used as the input to the SMES controller. The ACE is obtained from tie-line power flow deviation and the frequency deviation weighted by a bias factor β as shown in (1).

$$ACE_i = \sum_{j=1}^{n} \Delta P_{tie,\, i\, j} + \beta_i \Delta f_i \quad (1)$$

where the suffix i refer to the control area and j refer to the number of generator.

As the dynamic performance of the AGC system would obviously depends on the value of frequency bias factors, β, and integral controller gain value, K_I, the optimal values of the integral gain of the integral controllers are obtained using Integral Squared Error (ISE) technique as shown in (2), where the detail of the performance index is explained in [6]. A characteristic of the ISE criterion is that it weights large errors heavily and small errors lightly. The quadratic performance index is minimized for 1% step load disturbance in either of the areas for obtaining the optimum values of integral gain

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settings. In this study, it is seen from Fig. 1 that, in the absence of dead-band and generation rate constraints, the value of integral controller gain, $K_I = 0.34$, and frequency bias factors, $\beta=0.4$, occurs at ISE = 0.0009888.

$$ISE = \int_0^T \left(\Delta P_{tie}^2 + \Delta f_1^2 + \Delta f_2^2 \right) dt \quad (2)$$

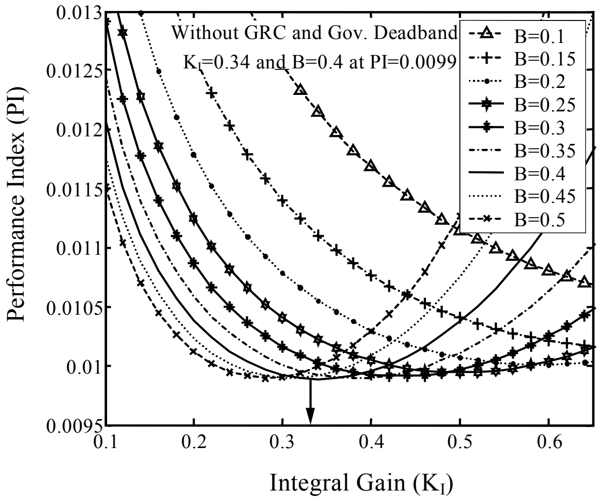

Fig.1. The optimal integral controller gain, K_I and frequency bias factor, B without DB and GRC

For PI controller, the integrator gain (K_{Ii}) of the supplementary controller is chosen as the fixed optimized value. And in FPIC technique the supplementary controller output (ΔP_{ref}) is scheduled to optimized value with fuzzy logic controller according to load disturbance. So it compromise between fast transient recovery and low overshoot in dynamic response of the system. It is seen that SMES with FPIC performs primary frequency control more effectively in AGC compared to that with fixed gain PI controller for load frequency control of multi-area power system.

II. THE MODEL SYSTEM CONFIGURATION

The model of a two-area power system suitable for a digital simulation of AGC is developed for the analysis as shown in Fig. 2. Two areas are connected by a weak tie-line. When there is sudden rise in power demand in one area, the stored energy is almost immediately released by the SMES through its power conversion system. As the governor control mechanism starts working to set the power system to the new equilibrium condition, the SMES coil stores energy back to its nominal level. Similar is the action when there is a sudden decrease in load demand. Basically, the operation speed of governor-turbine system is slow compared with that of the excitation system. As a result, fluctuations in terminal voltage can be corrected by the excitation system very quickly, but fluctuations in generated power or frequency are corrected slowly.

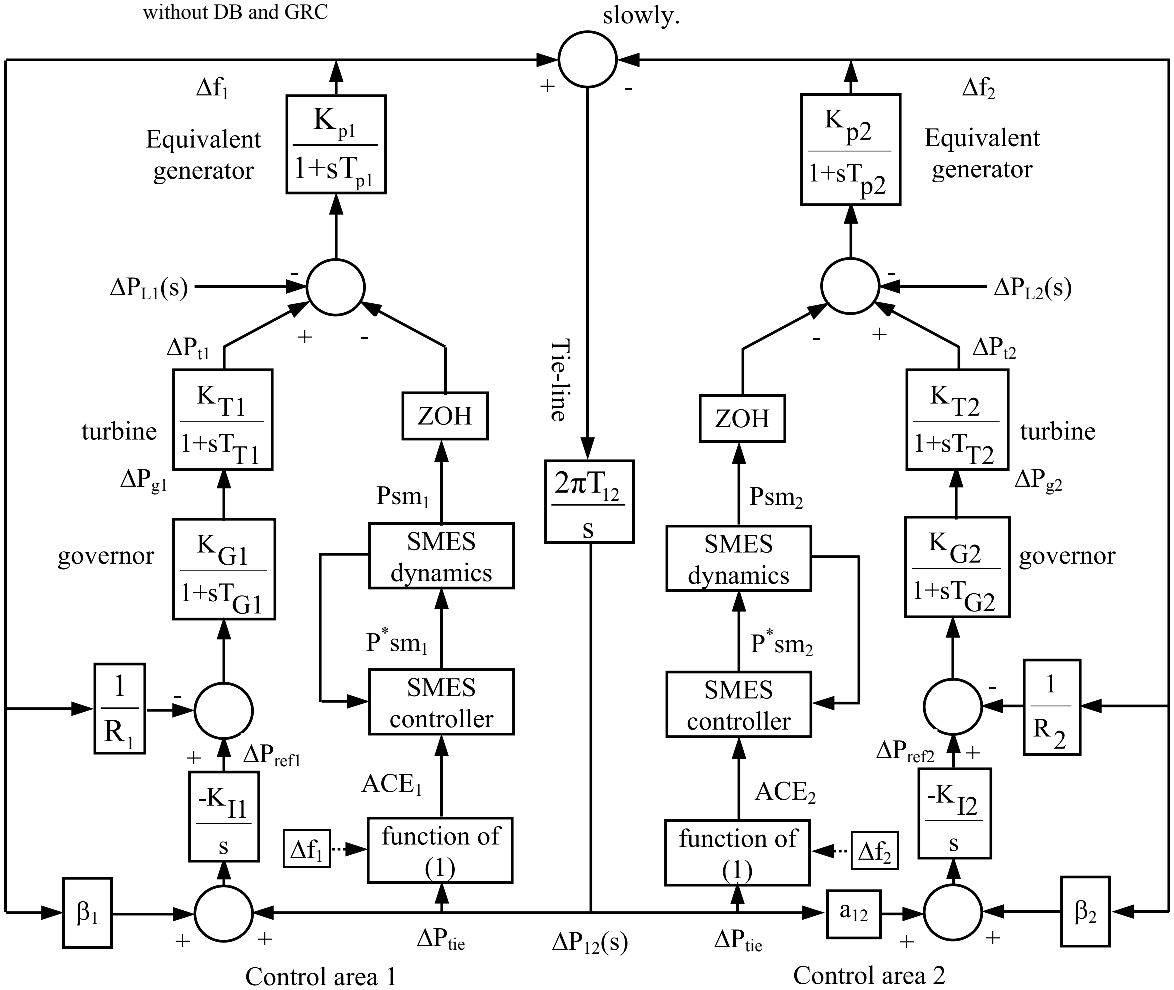

Fig. 2. Typical digital simulation model of a two-area power system

Since load frequency control is primarily concerned with the real power/frequency behavior, the excitation system model will not be required in the analysis [7]. This important simplification paves the way for the required digital simulation model of the example system of Fig. 2. The modeling and control design aspects of SMES are separately described in detail. The presence of zero-hold (ZOH) device in Fig.2 implies the discrete mode control characteristic of SMES. All parameters are same as those used in [6].

III. Conventional PI Control System

The general practice in the design of a LFC is to utilize a PI controller. A typical conventional PI control system is shown in Fig. 3. This gives adequate system response considering the stability requirements and the performance of its regulating units. In this case the response of the PI controller is not satisfactory enough and large oscillations may occur in the system [8-9]. For that reason, a fuzzy PI controller is designed and implemented in this study.

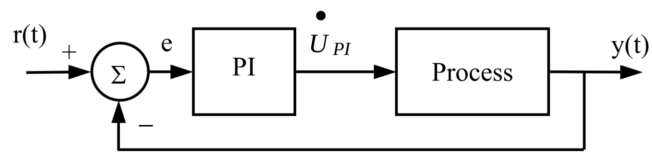

Fig. 3. A typical conventional PI controller

IV. Fuzzy PI Controller (FPIC)

A. Overview of Fuzzy PI controller

A fuzzy PI control unit arrangement shown in Fig. 4 is used, which is called the derivative-of-output and is often desirable, if the reference input contains discontinuity [10]. The discrete-time equivalent expression for PI controller can be expressed as

$$u^*(k) = K_P e^*(k) + K_I T_S \sum_{i=1}^{n} e^*(i) \tag{3}$$

where, u(k) is the control signal, e(k) is the error between the reference and the process output, T_S is the sampling period for the controller, and

$$\Delta e^*(k) = e^*(k) - e^*(k-1) \tag{4}$$

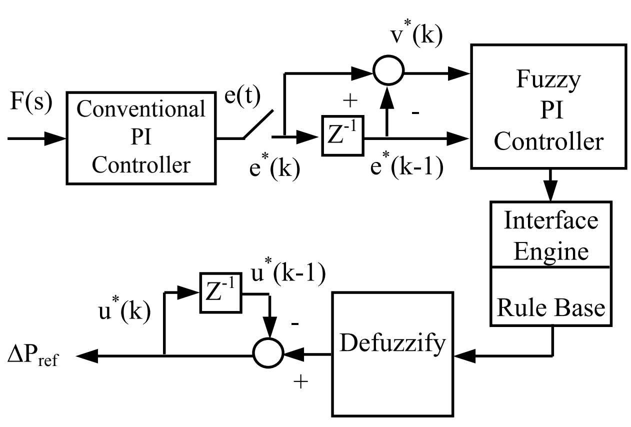

Fig. 4. Control block for fuzzy PI controller

The incremental control effort at k[th] instant is given by

$\Delta u^*(k)=K_p.v^*(k)-K_I.e^*(k-1)$ and

$$v^*(k) = \frac{\left[e^*(k) - e^*(k-1)\right]}{T_S} \tag{5}$$

where $\Delta u^*(k)$ is the incremental control effort at k[th] instant and K_P and K_I are the proportional and integral gains of digital PI controller, respectively. ΔP_{ref} is the output of the fuzzy PI controller.

B. Implementation of FPIC in Both Control Areas

For implementation of the FPIC, the same type of fuzzy PI controller is used on both control areas. In each area, the area control error is supplied to the PI controller and then output of the PI controller is fuzzified by the fuzzy logic controller (FLC). The FLC for each fuzzy PI controller has the two inputs which are defined as:

Input 1: error= $e_t = -K_I \int \left(\Delta P_{12} + \beta \Delta f\right) dt$ (6)

Input 2: rate of change of error = $c\dot{e}_t = -K_I \left(\Delta P_{12} + \beta \Delta f\right)$ (7)

The triangular membership functions for the proposed fuzzy PI controller of the three variables (e_t, $c\dot{e}_t$, P_{ref}) are shown in Fig. 5, where PI controller output (e_t) and change of PI controller output ($c\dot{e}_t$) are used as the inputs of the fuzzy logic controller. Considering these two inputs, the output of fuzzy PI controller (ΔP_{ref}) is determined. The use of two input and single output variables makes the design of the controller very straightforward. A membership value for the various linguistic variables is calculated by the rule given by

$$\mu\left(e_t, c\dot{e}_t\right) = \min\left[\mu\left(e_t\right), \mu\left(c\dot{e}_t\right)\right] \tag{8}$$

The equation of the triangular membership function used to determine the grade of membership values in this work is as follows:

$$A(x) = \frac{\left(b - 2|x - a|\right)}{b} \tag{9}$$

Where A(x) is the value of grade of membership, 'b' is the width, 'a' is the coordinate of the point at which the grade of membership is 1, and x is the value of the input variables. The control rules for the proposed strategy are very straightforward and have been developed from the viewpoint of practical system operation and by trial and error methods. The fuzzy rule base for the fuzzy PI controller is shown in Table I.

The membership functions, knowledge base and method of defuzzification determine the performance of the fuzzy PI control scheme in a multi area power system as shown in (10).

$$\Delta P_{ref} = \frac{\sum_{j=1}^{n} \mu_j u_j}{\sum_{j=1}^{n} \mu_j} \tag{10}$$

TABLE I
FUZZY RULE BASE FOR FPIC

ce \ e	NB	NS	Z	PS	PB
NB	PB	PS	PS	PS	Z
NS	PS	PS	PS	Z	NS
Z	PS	PS	Z	NS	NS
PS	PS	Z	NS	NS	NB
PB	Z	NS	NS	NB	NB

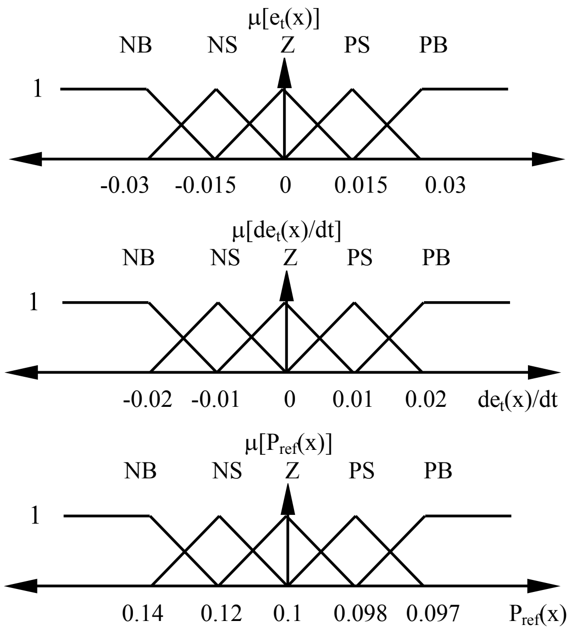

Fig. 5. Membership functions for the fuzzy variables

V. CONTROL SYSTEM

Figure 6 outlines the proposed simple control scheme for SMES, which is incorporated in each control area to reduce the instantaneous mismatch between demand and generation. Firstly, ΔP_{ref} is determined using fuzzy PI controller to obtain frequency deviation, Δf, and then tie-line power deviation, ΔP_{tie}. Finally ACE_i (i=1,2) is used as the input to the SMES controller. For quick restoration of the inductor current to its rated value, inductor current deviation is sensed and used as negative feedback signal in the SMES control loop.

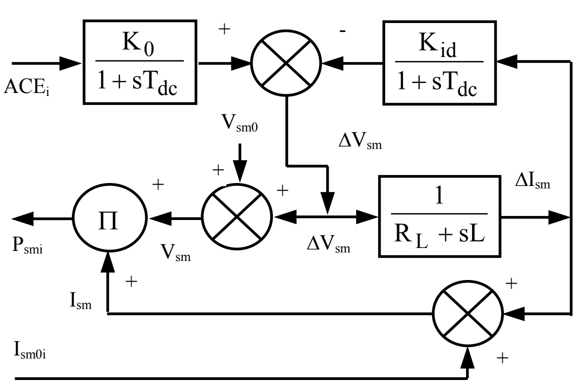

Fig. 6. SMES control system

VI. SIMULATION RESULTS

To demonstrate the beneficial damping effect of the proposed controller, computer simulations have been carried out for different load changes using the MATLAB environment. The system performances with FPIC and PI controlled AGC including SMES units are shown in Fig. 7 through Fig. 12.

Three case studies are conducted.

Case-I: a step load increase of ΔP_{L1}=0.01 pu MW is applied in area 1 only.

Case-II: same step load increase, ΔP_{L1}= ΔP_{L2}= 0.01 p.u., in both areas.

Case-III: different step load increase, ΔP_{L1}= 0.015 p.u. and ΔP_{L2}= 0.01 p.u., in both areas.

For the case–I, it is seen from Fig. 7 that with SMES, the tie power deviation significantly decreases with the addition of the proposed FPIC, but when PI controller is used in AGC, the SMES can not compensate properly. For this tie power deviation can not be reduced to zero quickly. As the load increase in both areas are same for case-II, the tie power deviation is zero as shown in Fig. 8. Again in case-III, when more load increase occur in area 1 compared to area 2, the tie power deviation also decreases considerably as viewed from Fig. 9.

It is seen from Fig. 10 to Fig. 12 that when the proposed FPIC including SMES units are used, the damping of the system frequency is improved significantly and settles to the nominal value quickly. From Figs. 10-12 it is also clear that the proposed FPIC system can reduce the real power compensation more than that in the PI control system. It is also interesting to observe that P_{sm} becomes zero and inductor current (I_{sm}) returns back to the rated value quickly after providing appropriate compensation. This enables the SMES unit to respond to a subsequent load disturbance in the power system. In these cases, it is also observed that the deviation of I_{sm} is small in both areas when the proposed control system is used. Finally frequency deviations restore to its nominal value more quickly with the proposed FPIC in AGC than that with the PI controlled AGC.

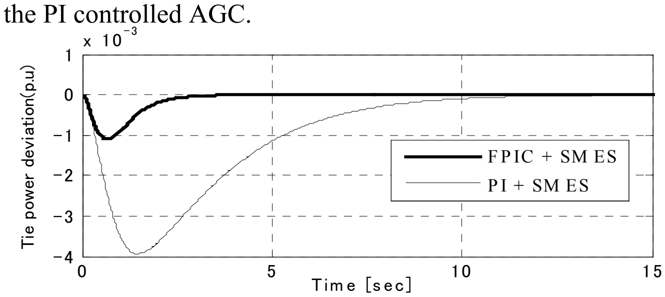

Fig. 7. Performances of tie power deviation [**Case-I**]

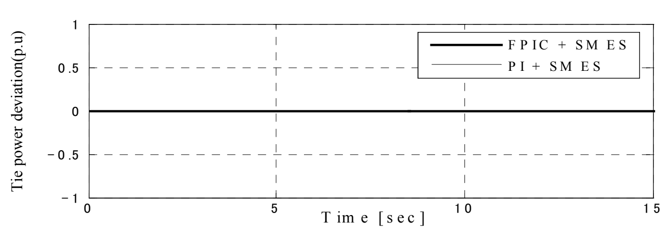

Fig. 8. Performances of tie power deviation [**Case-II**]

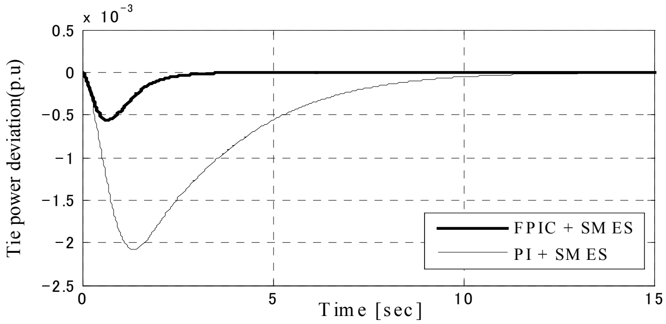

Fig. 9. Performances of tie power deviation [**Case-III**]

VII. CONCLUSIONS

The simulation studies have been carried out on a two-area power system to investigate the impact of the proposed intelligently controlled AGC including SMES units on the power system dynamic performance. The results show that the proposed FPIC scheme is very powerful in reducing the frequency deviations under a variety of load perturbations. Using fuzzy logic, the online adaptation of integral controller output (ΔP_{ref}) associated with SMES makes the proposed intelligent controllers more effective and are expected to perform optimally under variety of load disturbance when ACE is used as the input to SMES controller.

VIII. REFERENCES

[1] A. Demiroren, "Application of a Self-Tuning to Automatic Generation Control in Power System Including SMES Units", *ETEP*, Vol. 12, No. 2, pp. 101-109, March/April 2002.

[2] Nanda J, Kavi BL.:"Automatic Generation Control of Interconnected Power System", *IEE Proceedings, Generation, Transmission and Distribution*, 1988; No.125(5): pp.385–390.

[3] J. Nanda, A. Mangla and S. Suri, "Some New Findings on Automatic Generation Control of an Interconnected Hydrothermal System with Conventional Controllers", *IEEE Transactions on Energy Conversion*, Vol. 21, No. 1, pp. 187-194, March, 2006.

[4] Sivaramaksishana AY, Hariharan MV, Srisailam MC.:"Design of Variable Structure Load-Frequency Controller Using Pole Assignment Techniques", *International Journal of Control* 1984; 40(3):437–498.

[5] Tripathy SC, Juengst KP.: "Sampled Data Automatic Generation Control with Superconducting Magnetic Energy Storage", *IEEE Transactions on Energy Conversion* 1997; 12(2):187–192.

[6] M.R.I. Sheikh, S.M. Muyeen, Rion Takahashi, Toshiaki Murata and Junji Tamura, "Improvement of Load Frequency Control with Fuzzy Gain Scheduled Superconducting Magnetic Energy Storage Unit", *International Conference of Electrical Machine (ICEM, 08),* Conference CD, Paper ID-1026, 06-09 September, 2008, Portugal.

[7] Mairaj uddin Mufti, Shameem Ahmad Lone, Sheikh Javed Iqbal, Imran Mushtaq: "Improved Load Frequency Control with Superconducting Magnetic Energy Storage in Interconnected Power System", *IEEJ Transaction*, 2007, vol. 2,pp. 387-397.

[8] M.F. Hossain, T. Takahashi , M.G. Rabbani, , M.R.I. Sheikh and M.S. Anower, "Fuzzy-Proportional Integral Controller for an AGC in a Single Area Power System" *4th international conference on Electrical & computer Engineering (ICECE)*, pp. 120-123, 19-21 December 2006.

[9] M.S. Anower, M.G. Rabbani, M.F. Hossain, M.R.I. Sheikh and M. Rakibul Islam, "Fuzzy Frequency Controller for an AGC for the Improvement of Power System Dynamics", *4th international conference on Electrical & computer Engineering (ICECE)*, pp. 5-8, 19-21 December 2006.

[10] Ambalal V. Patel, "Simplest Fuzzy PI controllers under various Defuzzification Methods," International Journal of Computational Cognition Vol. 3, No. 1, March, 2005, (http://www.Yangsky.com/Yangijcc.comhtm).

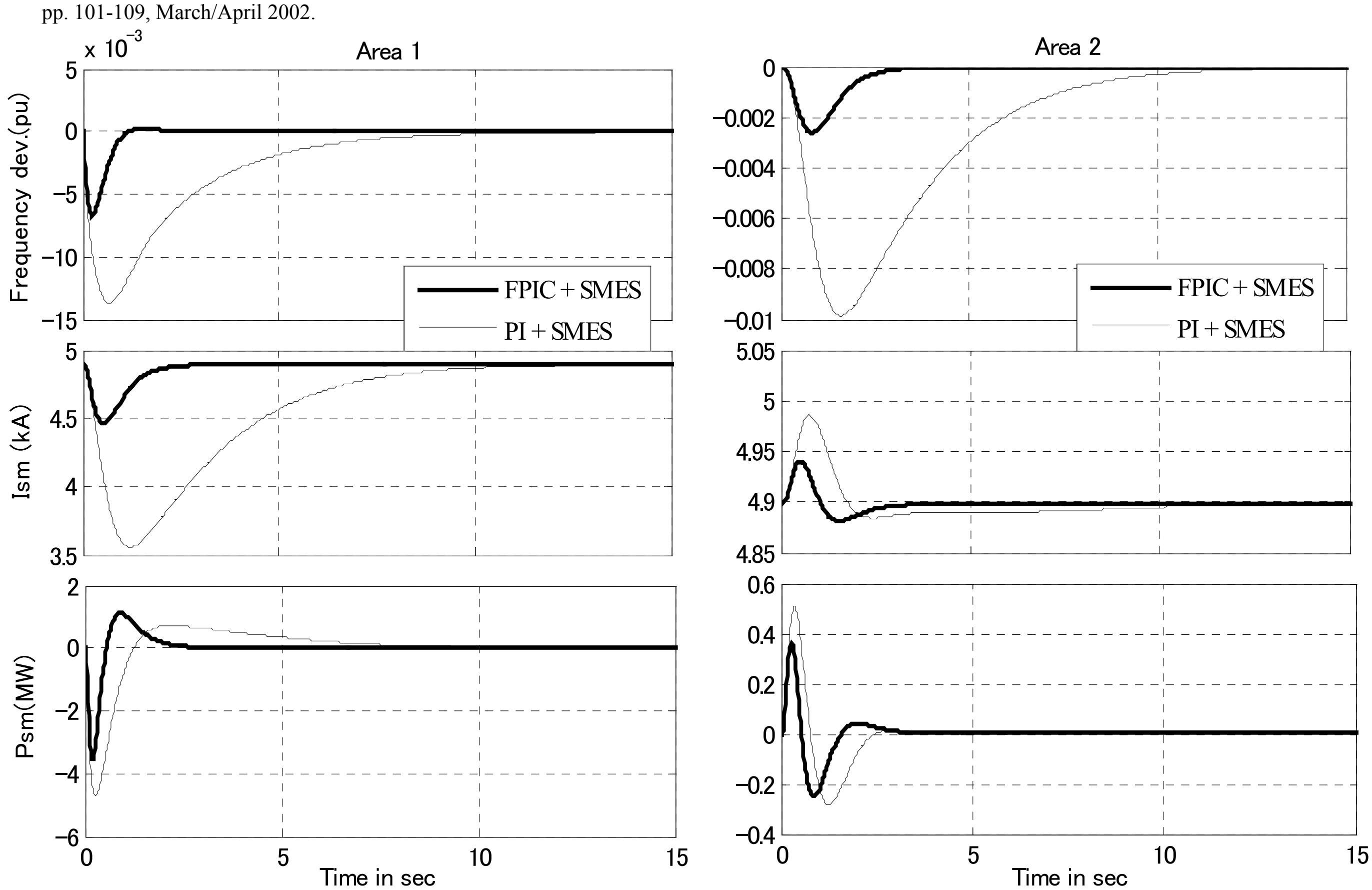

Fig. 10. System performances for a step load increase ΔP_{L1}= 0.01 p.u. in area-1 [**Case-I**]

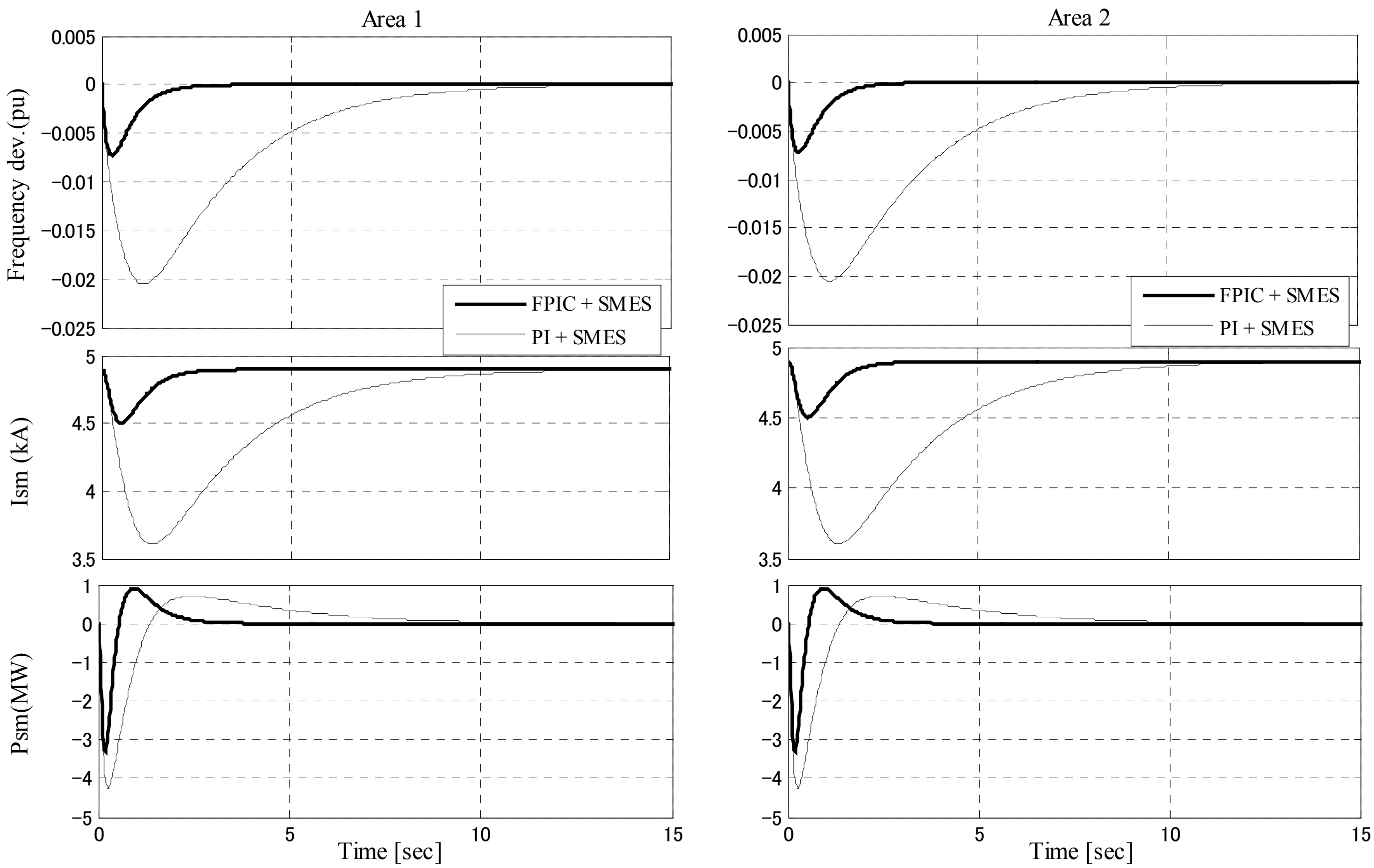

Fig. 11. System performances for a step load increase $\Delta P_{L1} = \Delta P_{L2} = 0.01$ p.u. in both areas [**Case-II]**

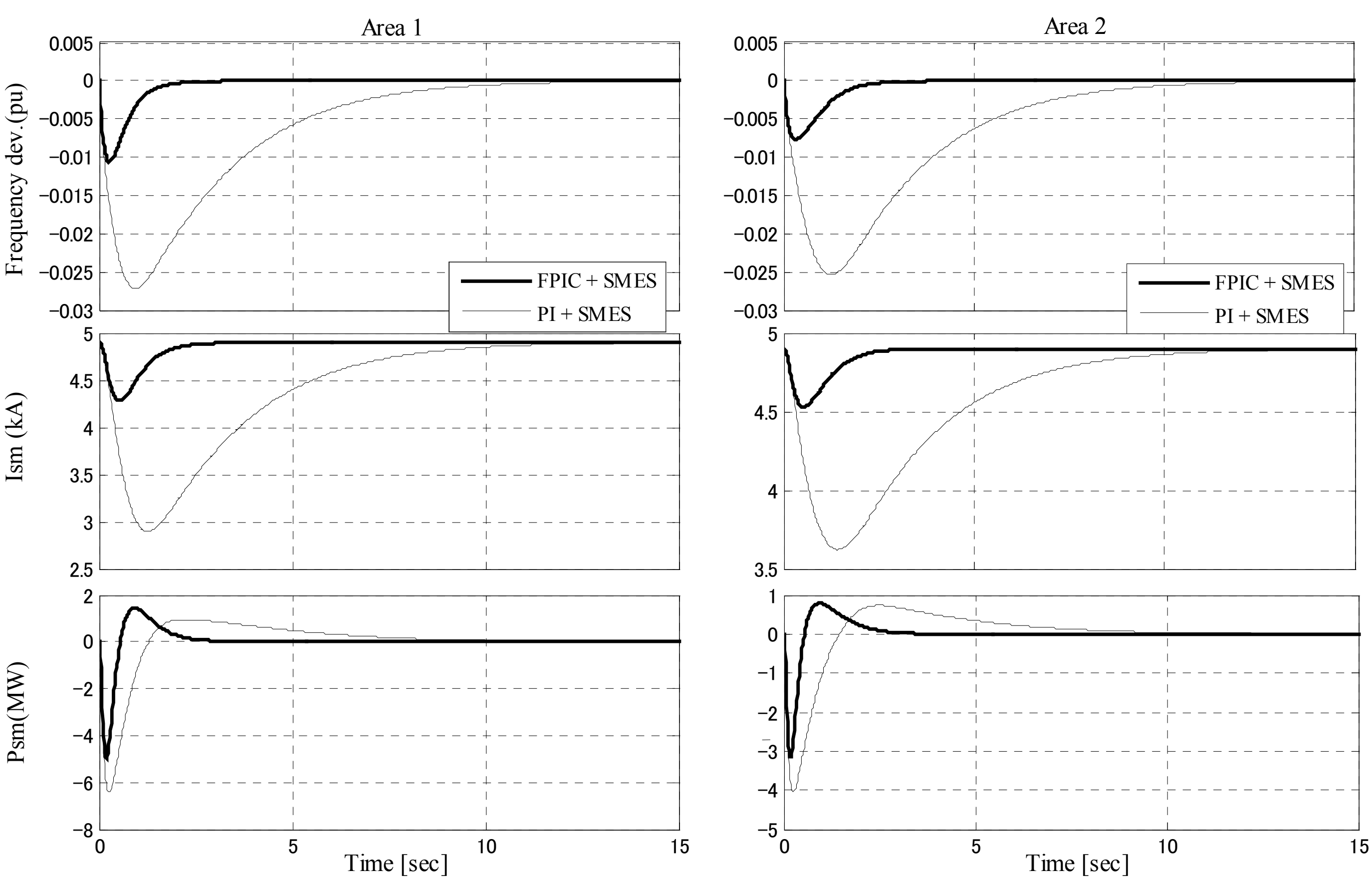

Fig. 12. System performances for a step load increase $\Delta P_{L1} = 0.015$ p.u. & $\Delta P_{L2} = 0.01$ p.u. in both areas[**Case-III**]

IX. Biographies

M.R.I. Sheikh was born in Sirajgonj, Bangladesh on October 31,1967. He received his B.Sc. Eng. and M.Sc. Eng. Degree from Rajshahi University of Engineering & Technology (RUET), Bangladesh, in 1992 and 2003 respectively, all in Electrical and Electronic Engineering. He is currently an Associate Professor in the Electrical and Electronic Engineering Department, RUET. Presently he is working towards his Ph.D Degree at the Kitami Institute of Technology, Hokkaido, Kitami, Japan. His research interests are, Power system stability enhancement including wind generator by using SMES, FACTs devices and Load Frequency Control of multi-area power system.
Mr. Sheikh is the member of the IEB and the BCS of Bangladesh.

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Rion Takahashi received the B.Sc. Eng. and Dr. Eng. Degrees from Kitami Institute of Technology, Japan, in 1998 and 2006 respectively, all in Electrical and Electronic Engineering. Now he is working as research assistant in Department of Electrical and Electronic Engineering, Kitami Institute of Technology. His major research interests include analysis of power system transient, FACTS and wind energy conversion system. He is the member of IEEE.

Toshiaki Murata completed his Electrical Engineering Curriculum of the Teacher Training School from Hokkaido University, Japan. Since 1969, he had been a Research Assistant at the Kitami Institute of Technology, Japan. He received Dr. Eng. degree from Hokkaido University in 1991. Presently he is an associate professor at the Kitami Institute of Technology. Dr. Murata is a member of IEE of Japan and Society of Instrument and Control Engineers, Japan.

Junji Tamura received his B. Sc. Eng. Degree from Muroran Institute of Technology, Japan, in 1979 and M.Sc. Eng. and Dr. Eng. degrees from Hokkaido University, Japan, in 1981 and 1984 respectively, all in electrical engineering. In 1984, he became a lecturer and in 1986, an associate professor at the Kitami Institute of Technology, Japan. Currently he is a professor at the Kitami Institute of Technology. Dr. Tamura is a member of IEE of Japan and a senior Member of the IEEE Power Engineering Society.