# Parameters Selection of Flywheel Energy Storage System Controller on Wind-Diesel Hybrid Power System using Immune Algorithm

**Chang Hyun Kim**
**Jeong Phil Lee**
Assistant Professor
Subdivision of New & Renewable Electricity
Kyungnam College of Information & Technology
45 Jurye-ro, Sasang-gu, Busan, Korea

## Abstract

*In this paper, robust parameters selection problem of flywheel energy storage system (FESS) controller using immune algorithm (IA) is investigated to enhance dynamic characteristics of wind-diesel hybrid power system. The aim for optimal parameters selection of the controller using IA is to minimize the objective function. The objective function in IA is represented as affinity of antigen and antibody. Therefore the selected elements for calculating affinity have a decisive effect on dynamic performance of the power system. The wind generator frequency, the diesel generator frequency, the control input and the* $H_\infty$*-norm are used for calculating affinity of IA in this paper. To verify control performance of the designed FESS controller, dynamic simulations are performed under various disturbances such as sudden step change of wind power and load as well as the random change of wind power and load. The control characteristics with the designed FESS controller using IA are compared with that of the pitch controller and SMES. The simulation results show that performance of the FESS controller designed by IA is improved significantly.*

**Keywords**: flywheel energy storage system, immune algorithm, affinity, wind-diesel hybrid power system, objective function.

## 1. Introduction

Interconnection with a new and renewable energy has been increased and various loads have been complicatedly connected in power system. Irregular output of new and renewable energy and continuous load change cause frequency change of power system (Lee & Kim, 2013; Lee & Kim, 2014). Wind-diesel hybrid power system has been considered in an isolated site which is difficult to receive the electric power from the main power system. However the irregular output of the wind power source causes a fluctuation of frequency and voltage in the isolated power system (Lee & Kim 2015). In order to solve the problem, many researches about frequency control of wind-diesel hybrid power system have been carried out using various control method such as pitch control method of the wind system and diesel generation system (Tripathy, Kalantar, & Balasubramanian, 1991; Tripathy, 1997). The PI control (Nandar, 2012) and variable structure control (VSC) (Das, Aditya & Kothari, 1999), fuzzy control (Goutham Govind Raju & Mohamed Ali, 2012; Leclercq, Robyns, & Grave, 2003; Thameem Ansari, & Velusami, 2010), $H_\infty$ control (Lee & Kim, 2015; Singh, Mohant, Kishor, & Ray, 2013) and control method using the superconducting magnetic energy storage system (SMES) (Cuk Supriyadi, Hashiguchi, Goda & Tumiran, 2011; Tripathy, Kalantar, & Balasubramanian, 1991; Tripathy, 1997) were proposed.

In this paper, flywheel energy storage system (FESS) is applied to control frequency of wind-diesel hybrid power system. The FESS is an electric power storage system in which the electrical energy is stored by converting it into mechanical rotational energy. The FESS is an environment-friendly energy storage system which can be used for uninterruptible power supply (UPS), power quality improvement, storage of distributed power sources such as solar power and wind power and load leveling (Lee, et al., 2009; Lee, Han, & Park, 2011). It is possible to control the frequency quickly in spite of the sudden load change, because the active power output of an FESS is very fast (Lee & Kim, 2013; Lee & Kim, 2014; Lee & Kim, 2015).

Several design methods of the FESS controller for wind-diesel hybrid system have been proposed such as fuzzy controller (Leclercq, Robyns, & Grave, 2003), controller using genetic algorithm (GA) (Lee & Kim, 2014) and $H_\infty$ controller (Lee & Kim, 2015). Since the controller performance using GA is influenced by the objective function selection method, how to select the objective function is very important. Since the $H_\infty$ control is able to design controller including the system uncertainties in controller design stage, the designed $H_\infty$ controller provides the robust control performance.

However, an order of controller become very high order and structure of the controller is very complicated. In this paper, robust parameters selection problem of flywheel energy storage system (FESS) controller using immune algorithm (IA) is investigated to enhance dynamic characteristics of wind-diesel hybrid power system. Like the GA, the controller performance using IA is influenced by the objective function selection method, therefore the frequency, the control input and the $H_\infty$-norm are included in objective function to design robust controller. To verify control performance of the designed FESS controller, dynamic simulations are performed under various disturbances such as sudden the step change of wind power and load as well as the random change of wind power and load. The control characteristics with the designed FESS controller using IA are compared with that of the pitch controller and SMES (Tripathy, 1997).

## 2. Wind diesel hybrid power system model

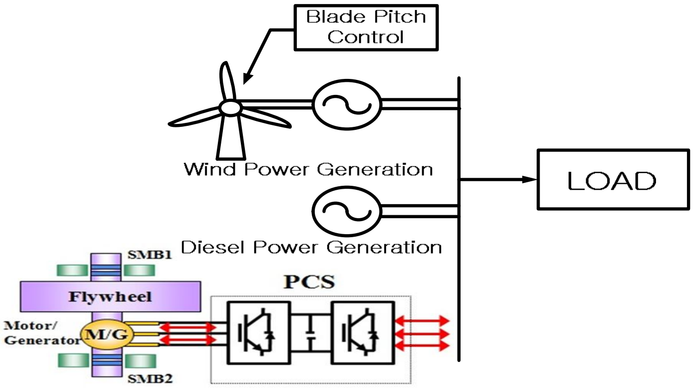


**Fig. 1 A wind diesel hybrid power generation system with FESS**

Fig. 1 shows the system configuration for the wind diesel hybrid power generation system with flywheel (Lee & Kim, 2015). Fig. 2 shows the block diagram for the wind diesel power generation system (Cuk Supriyadi, Hashiguchi, Goda, & Tumiran, 2011; Lee & Kim, 2015; Tripathy, Kalantar, & Balasubramanian, 1991) with the pitch controller and the flywheel. This block diagram model consists of a wind system model, a diesel system model, a blade pitch control and a generator model.

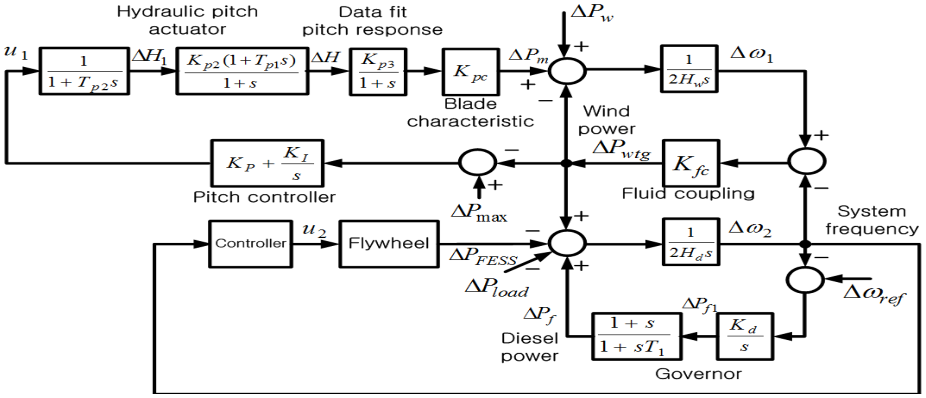


**Fig. 2: A block diagram for wind diesel power generation system with pitch controller and flywheel**

### 2.1 Wind System Model

The wind dynamics model including blade pitch control of the wind turbine (Lee & Kim, 2014; Tripathy & Mishra, 1996) is as following

$$\frac{d}{dt}\Delta H_1 = -\frac{1}{T_{p2}}\Delta H_1 + \frac{1}{T_{p2}}u_1 \qquad (1)$$

$$\frac{d}{dt}\Delta H = \left(K_{p2} - \frac{K_{p2}T_{p1}}{T_{p2}}\right)\Delta H_1 - \Delta H + \frac{K_{p2}T_{p1}}{T_{p2}}u_1 \qquad (2)$$

$$\frac{d}{dt}\Delta P_m = K_{p3}K_{pc}\Delta H - \Delta P_m \qquad (3)$$

$$\frac{d}{dt}\Delta w_1 = -\frac{1}{2H_w}\Delta P_m - \frac{K_{fc}}{2H_w}\Delta w_1 + \frac{K_{fc}}{2H_w}\Delta w_2 + \frac{1}{2H_w}\Delta P_w \qquad (4)$$

The transfer function of the hydraulic pitch actuator is split into two blocks. $\Delta H$ is the hydraulic pitch actuator variable and $\Delta H_1$ is dummy variable. $\Delta P_m$ is the wind power deviation. $\Delta P_w$ is change in the wind power input. $\Delta w_1$ is wind frequency deviation. $T_{p1}$, $T_{p2}$ is time constant of the hydraulic pitch actuator, $K_{p2}$ is the hydraulic pitch actuator gain, $K_{pc}$ is the blade characteristic gain, $K_{p3}$ is the data fit pitch response gain, $K_{fc}$ is the fluid coupling gain, $H_w$ is the inertia constant of the wind turbine system.

### 2.2 Diesel System Model

The diesel dynamics model including the governor system (Lee & Kim, 2014; Tripathy & Mishra, 1996) is as following

$$\frac{d}{dt}\Delta w_2 = -\frac{1}{2H_d}\Delta w_1 - K_{fc}\Delta w_2 + \Delta P_f - \frac{1}{2H_d}\Delta P_{load} \qquad (5)$$

$$\frac{d}{dt}\Delta P_{f1} = -K_d\Delta w_2 \qquad (6)$$

$$\frac{d}{dt}\Delta P_f = -\frac{K_d}{T_1}\Delta w_2 + \frac{1}{T_1}\Delta P_{f1} - \frac{1}{T_1}\Delta P_f \qquad (7)$$

The transfer function of the diesel governor is split into two blocks. $\Delta P_f$ is the diesel governor output variable and $\Delta P_{f1}$ is dummy variable. $\Delta P_{load}$ is change in load. $H_d$ is the inertial constant of the diesel engine, $K_d$ is the gain of diesel governor, $T_1$ is time constant of the diesel governor.

### 2.3 Flywheel System model

The FESS can handle high power level and charge/discharge speed of the FESS is very fast. The FESS can be modeled by the first order transfer function. Therefore the output power of the FESS can be written as following equation (Lee & Kim, 2014).

$$\frac{d}{dt}\Delta P_{FESS} = -\frac{1}{T_{FESS}}\Delta P_{FESS} + \frac{1}{T_{FESS}}u_2 \qquad (8)$$

Where $\Delta P_{FESS}$ change of the FESS output is, $T_{FESS}$ is time constant of the FESS.

The linearized equation of the wind diesel hybrid power system in Fig. 2 including the wind system, the diesel system, the pitch control and the FESS is as following,

$$\Delta\dot{x} = A\Delta x + B\Delta u + \Gamma\Delta p \qquad (9)$$

Where, $\Delta x$ , $\Delta u$ and $\Delta p$ are the state, control and disturbance vector respectively. A, B and $\Gamma$ are constant matrices which depend on system parameters and the operating point.
The state, control and disturbance variables without controller are as following,

$$\Delta x = [\Delta H_1, \Delta H\ , \Delta P_m, \Delta w_1, \Delta w_2, \Delta f_2, \Delta P_{f1},\ \Delta P_f, \Delta P_{FESS}]$$

$\Delta u = [u_1, u_2]$, $\Delta p = [\Delta P_w, \Delta P_{Load}]$

## 3. Design of FESS controller using IA

### 3.1 Summary of $H_\infty$ control theory

The procedure for designing $H_\infty$ controller is as following (Lee & Kim, 2015).

①Select two shaping filters $W_S(S)$ and $W_T(s)$.

②Specify the control structure of Fig. 3 and derive the corresponding plant.

③Compute a $H_\infty$ controller K(s) for this plant.

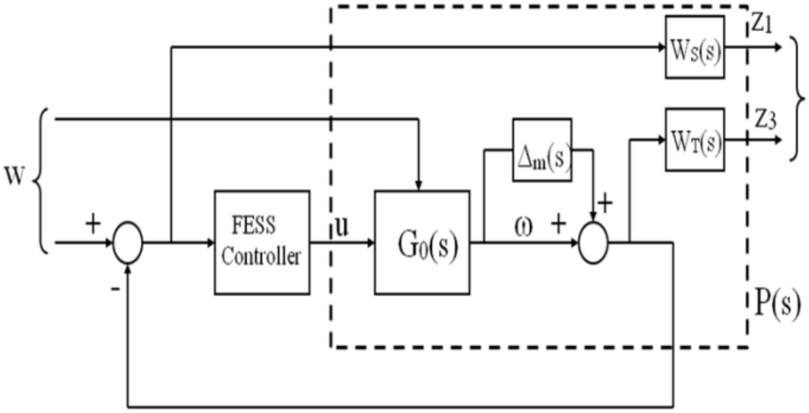


**Fig. 3: Augmented system model including weighted function**

Both disturbance attenuation and robust stability for the power system were treated simultaneously by using mixed sensitivity problem. The robust stability and the performance for uncertainties of power system in this paper were represented by the same frequency weighted transfer function of reference Lee & Kim (2015)

### 3.2 Immune Algorithm

Immune algorithm is has been applied to various optimization problems (Chun, Kim, & Jung, 1997; Huang, 1999) as an optimization algorithm that simulates the human immune system. As compared to GA, IA performs the optimization using the memory cell in order to ensure the convergence of the optimum solution. It has affinity calculations for implementing diversity in real immune systems and performs a self-adjusting function of the immune system by an expected value calculation for the antigen. Therefore, IA may be resolved premature convergence problems by maintaining a memory mechanism and diversity of antibody.

Summary for optimization procedure of IA is as following,

① Recognition of antigen
② Initial antibody population formulation
③ Affinity calculation
④ Differentiation toward the memory cell
⑤ Boost or restriction of antibody production
⑥ Crossover and mutation
⑦ New antibody generation
⑧ ③~⑦ repetition
⑨ Optimal antibody selection according to termination criterion

### 3.3 Optimal parameters selection using IA

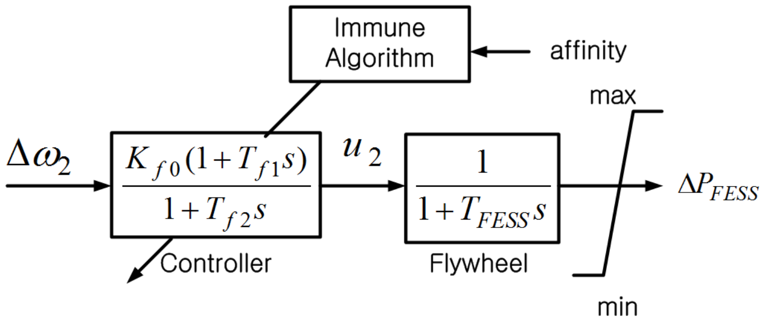


**Fig: 4 A block diagram for selecting controller parameters of the flywheel**

Fig.4 shows the block diagram for selecting parameters for the FESS controller using IA.

The input of the FESS controller is a system frequency $\Delta\omega_2$ in Fig. 4. The FESS output power limit of -0.01 ≤ $\Delta P_{FESS} \leq$ 0.01 (pukW) is considered. Parameters $K_{f0}, T_{f1}, T_{f2}$ to be optimized by IA become an antibody. In order to obtain an optimal antibody, the affinity calculation of the antigen and antibody is needed. For calculating the affinity, proposed objective function J is as following equation.

$$J = \int_{t=0}^{t=te} \left(t \cdot |\Delta\omega_1| \cdot \alpha + t \cdot |\Delta\omega_2| \cdot \beta + t \cdot |u| \cdot \gamma\right) dt + \|P\|_\infty \cdot \eta \qquad (10)$$

Where t and te is simulation time and simulation termination time, respectively. $\alpha, \beta, \gamma, \eta$ are weighting values of each parameter. In the case of the minimum value search problem of the objective function, the affinity is as following equation.

$$affinity = \frac{1}{(1+J)} \qquad (11)$$

## *4. Simulation Results*

The system parameters for the computer simulation (Lee & Kim, 2015; Tripathy, 1997) are shown in Table. 1

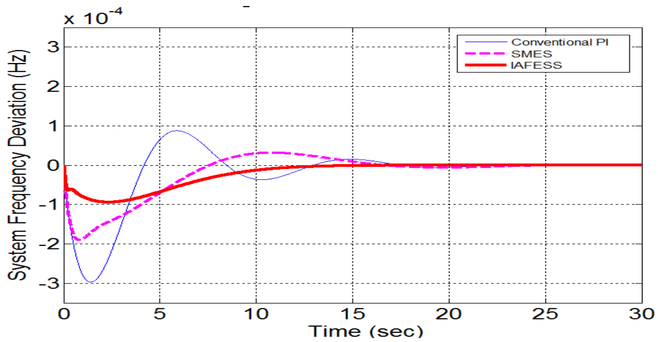
**Table 1 System Parameters**

$H_w = 3.5s$, $H_d = 8.5s$, $K_{fc} = 16.2Hz/pukW$

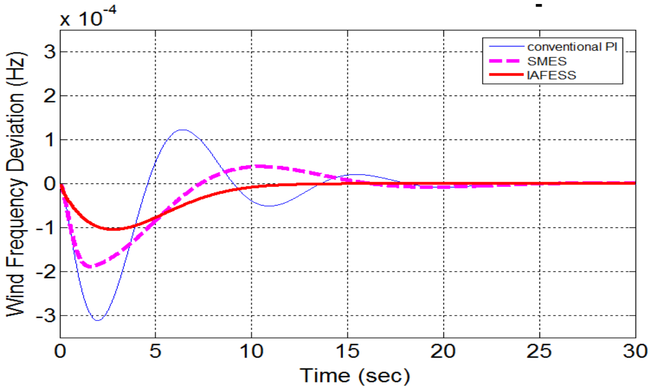
$K_{p1} = 4.0$, $K_{p2} = 1.25$, $T_{p1} = 0.60s$, $T_{p2} = 0.041s$

$K_{p3} = 1.4$, $K_{p1} = 0.08 puKw/\mathrm{deg.}$, $K_{FESS} = 0.1$

Fig. 5 shows the simulation results for the frequency deviation of the diesel and wind system with the conventional PI pitch control, SMES (Tripathy, 1997) and designed FESS controller (IAFESS) respectively for a step load change of 0.01 (p.u.kW). The frequency oscillations with IAFESS in Fig. 5(a) and (b) are significantly suppressed and settling time of the frequency response is very fast. On the other hand, maximum deviation of frequency using IAFESS is smaller than that using conventional PI and SMES.

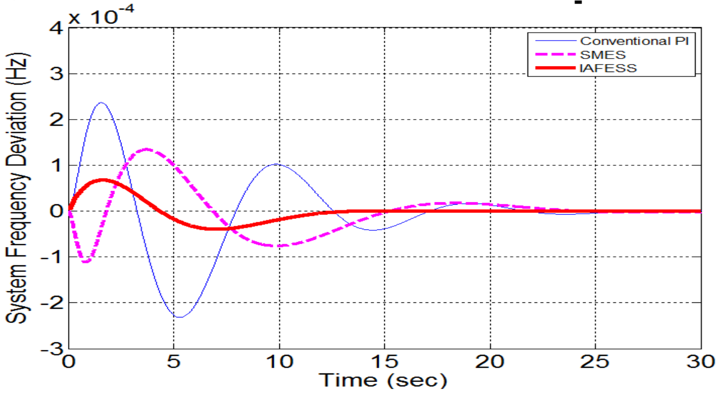


(a) Diesel system frequency deviation

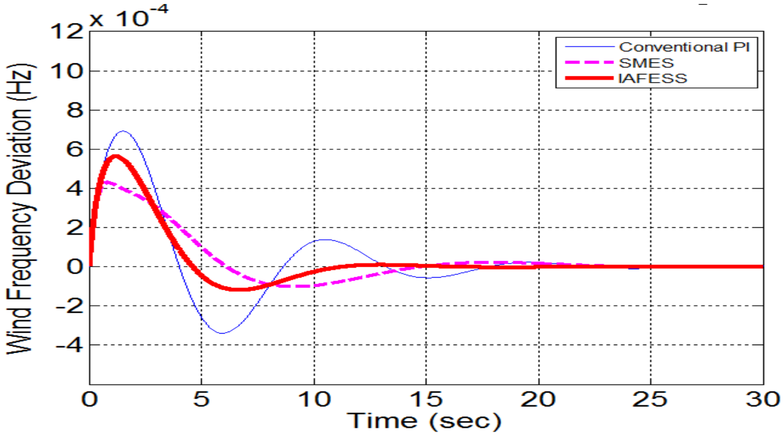


(b) Wind system frequency deviation

Fig. 5 Frequency responses for 0.01 p.u. step load variation



(a) Diesel system frequency deviation



(b) Wind system frequency deviation

Fig. 6 Frequency responses for 0.01 p.u. step wind power variation

Fig. 6 shows the simulation results for the frequency deviation of diesel and wind system with the conventional PI, SMES and IAFESS respectively for a step wind power input change of 0.01 (p.u.kW). The frequency oscillations with the IAFESS in Fig. 6(a) and (b) are significantly suppressed and settling time of the frequency response is very fast.

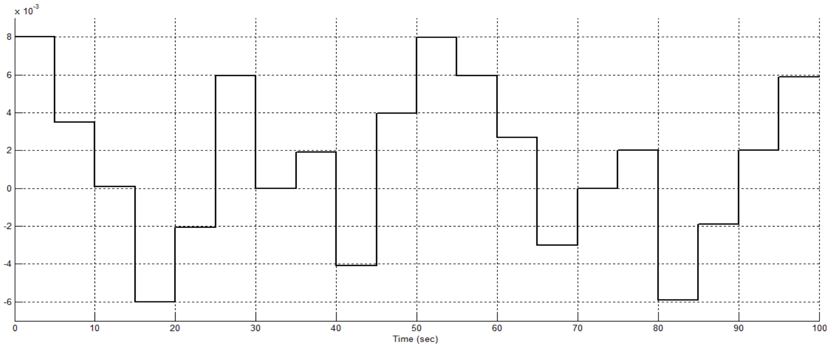
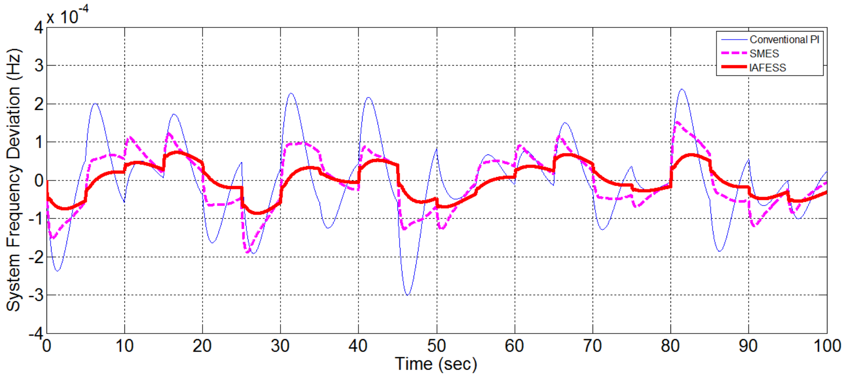
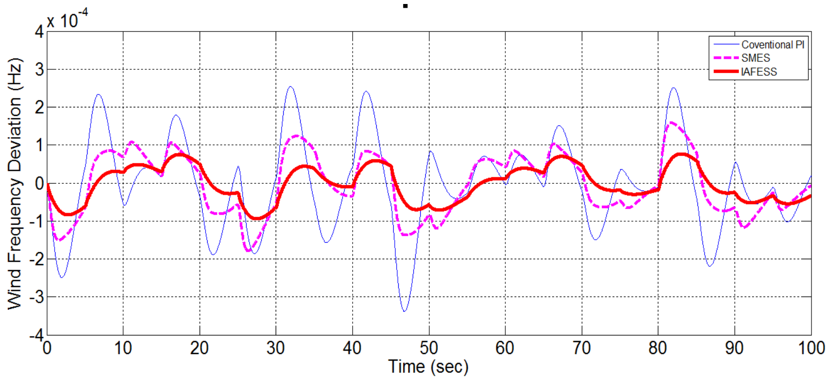


**Fig. 7 Random load variation**



**(a) Diesel system frequency deviation**

.



**(b) Wind system frequency deviation**

**Fig. 8: Frequency responses for random load variation**

Fig. 7 shows random load changes. Fig. 8 shows a comparison of the dynamic simulation results for frequency variation when a random load changes like Fig. 7 are applied. The frequency oscillations with the IAFESS in Fig. 8 are significantly suppressed and settling time of the frequency response is very fast. The results showed that the IAFESS was more robust than that using the conventional PI and SMES.

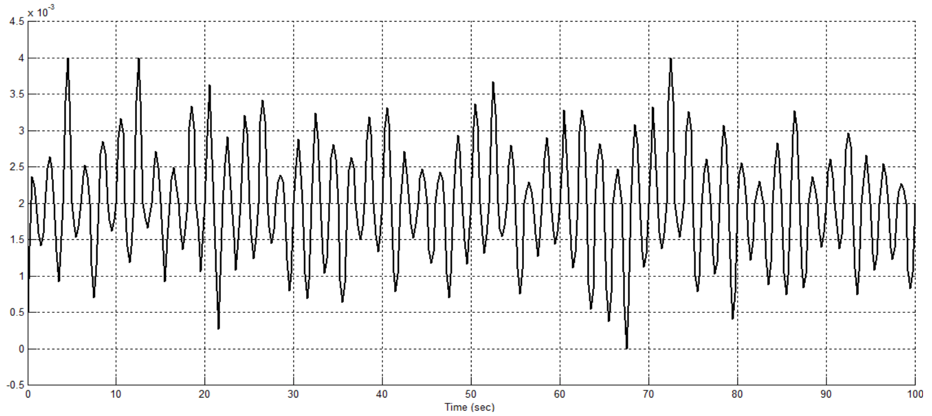
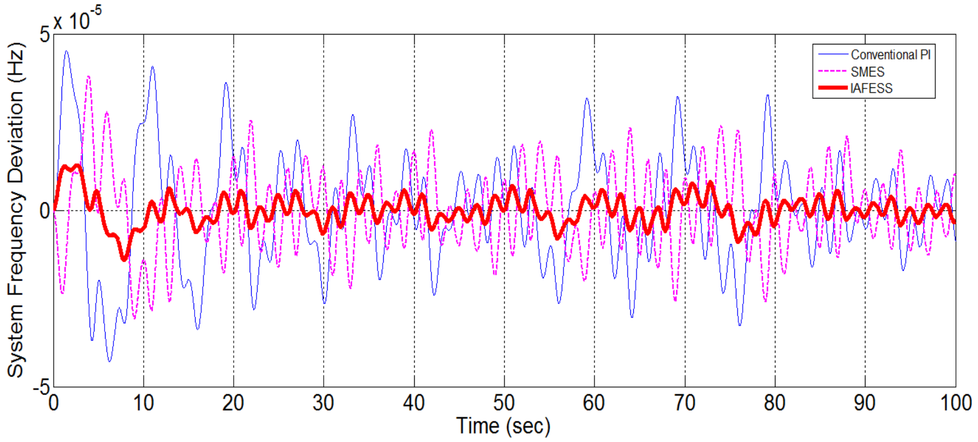
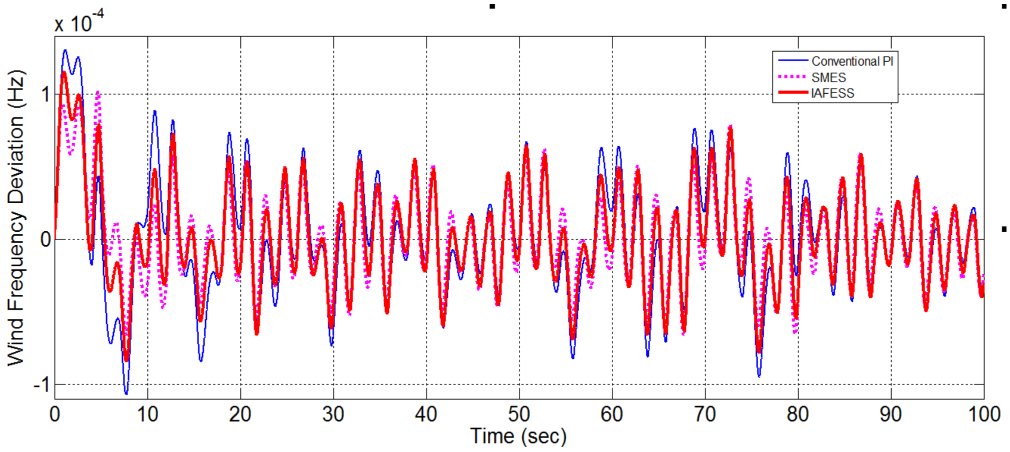


**Fig. 9 Random wind power input change**



**(a) Diesel system frequency deviation**



**(a) Wind system frequency deviation**

**Fig. 10: Frequency responses for random wind power input change**

Fig. 9 shows random wind power input changes. Fig. 10 shows a comparison of the dynamic simulation results for frequency variation when a random wind power changes like Fig. 9 are applied. The frequency oscillations with the IAFESS in Fig. 10 are significantly suppressed and settling time of the frequency response is very fast. The results showed that the IAFESS was more robust than that using the conventional PI and SMES.

## *5. Conclusion*

In this paper, the robust controller problem of FESS using IA is investigated to enhance dynamic characteristics of wind-diesel hybrid power system. The frequency, the control input and the $H_\infty$-norm are included in objective function to design robust controller.

To verify control performance of the designed FESS controller, dynamic simulations are performed under various disturbances such as sudden the step change of wind power and load as well as the random change of wind power and load. The simulation results showed that the FESS controller using IA provided better dynamic responses in comparison with the conventional PI and SMES.

## *References*

Chun, J. S., Kim, M. K. and Jung, H. K., (1997). Shape Optimization of Electromagnetic Devices using Immune Algorithm, IEEE Trans. On Magnetics, 33(2), pp. 1876-1879.

Cuk Supriyadi A.N, Takuhei Hashiguchi, Tadahiro Goda and Tumiran, (2011). Control Scheme of Hybrid Wind-Diesel Power Generation System, From Turbine to Wind Farms - Technical Requirements and Spin-Off Products, Dr. Gesche Krause (Ed.), ISBN: 978-953-307-237-1, InTech

Das, D., Aditya, S. K. and Kothari, D. P., (1999). Dynamics of Diesel and Wind Turbine Generator on an Isolated Power System, Electrical Power and Energy System, 21, pp. 183-189

Goutham Govind Raju, R and Mohamed Ali, S., (2012). Fuzzy Based Gain Scheduled PI Controller for an Isolated Wind-Diesel Hybrid Power System, Bulletin of Electrical Engineering and Infomatics, 1(3), pp.213-224

Huang, S. J., (1999). Enhancement of thermal unit commitment using Immune Algorithms Based Optimization Approaches, Electrical Power and Energy System 21, pp. 245-252

Lee, J.P., Jeong, N. H., Ham. Y. H., Han. S. C., Jung, S. Y., Park, B. C. and Sung, T. H., (2009). Assessment of the Energy loss for SFES with Rotational Core Type PMSM/G, IEEE Trans. On App. Superconductivity, 19(3)

Lee, J.P., Han, S. C. and Park, B. C. (2011). Experimental Estimation on Magnetic Friction Superconductor Flywheel Energy Storage System. Journal of Magnetics, 16(2), pp. 124-128, doi: 10.4283/JMAG.2011.16.12.124

Lee, J. P. and Kim, H. G., (2013) Load Frequency Control of Power System using Energy Storage System, International Smart Grid Conference &Exhibition, Jeju, Korea, pp.640-646

Lee, J. P. and Kim, H. G., (2014). Application of Flywheel Energy Storage System in Hybrid Distributed Generation System, The 20th International Conference on Electrical Engineering, Jun 15-19, jeju, Korea, pp.390-394

Lee, J. P. and Kim, H. G., (2015). Design of Robust Controller of Flywheel Energy Storage System for Hybrid Distributed Generation System, International Smart Grid Conference, October 12-14, Gwangju, Korea. Pp. 430-434

Leclercq, L., Robyns, B. and Grave. J. M., (2003). Control Based on Fuzzy Logic of a Flywheel Energy Storage System Assocciated with Wind and Diesel Generator, Mathematics and Computer in Simulation 63, pp. 271-280

Mori, K. Tsukiyama, M and Fukuda, T., (1993). Immune Algorithm with Searching Diversity and Its Application to Resource Allocation Problem, T. IEE Japan, 113-C(10), pp. 872-978

Nandar, C. S. A., (2012). Robust PI Control of Smart Controllable Load for Frequency Stabilization of Microgrid Power System, Elsevier, Renewable Energy, pp. 1-8, http://dx.doi.org/10.1016/t.renene.2012.10.032

Singh. V. P., Mohanty. S. R., Kishor, N. and Ray, P. K., (2013). Robust H-infinity Load Frequency Control in Hybrid Distributed Generation System, Electrical Power and Energy Systems 46, pp. 294-305

Thameem Ansari, M. Md and Velusami, S., (2010). Dual Mode Lingustic Hedge Fuzzy Logic Controller for ans Isolated Wind-Diesel Hybrid Power System with Superconducting Magnetic Energy Storage Unit, Energy Conversion and Management 51, pp. 169-181

Tripathy, S. C. Kalantar, M. and Balasubramanian, R., (1991). Dynamics and stability of wind and diesel turbine generators with superconducting magnetic energy storage unit on an isolated power system, IEEE Trans. On Energy Conversion, 6(4), pp. 579-585, Dec.

Tripathy, S. C. and Mishra, I. P., (1996). Dynamic performance of wind-diesel power system with capacitive energy storage, Energy Convers. Mgmt, 37(12), pp. 1787-1798

Tripathy, S. C., (1997). Dynamic simulation of hybrid wind-diesel power generation system with superconductor magnetic energy storage, Energy Convers. Mgmt, 38( 9), pp. 919-930