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Intelligent LFC Concerning High Penetration of Wind Power: Synthesis and Real-Time Application

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***Abstract*—Load-frequency control (LFC) is one of the important control problems in electric power system design and operation, and is becoming more significant today because of the increasing renewable energy sources such as wind farms. Wind power fluctuations impose additional power imbalance to the power system and may affect the frequency regulation performance, negatively. Dealing with this challenge, the present paper addresses an intelligent proportional-integral based fuzzy logic scheme for simultaneous minimization of system frequency deviation and tie-line power changes, which is required for successful operation of the LFC system concerning the high-penetration wind power in interconnected power systems. In order to obtain an optimal performance, the particle swarm optimization technique is used to online determine the membership function parameters. The physical and engineering aspects have been fully considered. The proposed control scheme is examined on the 10-machine New England test power system, and an experimental real-time implementation is also performed on the aggregated model of West Japan Power System.**

***Index Terms*—Fuzzy control, load-frequency control (LFC), particle swarm optimization (PSO) algorithm, proportional-integral (PI) control, wind power generation.**

I. INTRODUCTION

CURRENTLY, wind is the fastest growing and most widely utilized renewable energy technology in power systems. The wind turbine generators have attracted an accelerated attention in recent years. Nowadays, due to the interconnection of more distributed generators, especially the wind turbines, the electric power industry has become more complicated than ever. Since the primary energy source (wind) cannot be stored and is uncontrollable, the controllability and availability of wind power significantly differs from the conventional power generation. In most power systems, the output power of wind turbine generators varies with the wind speed fluctuation, this fluctuation results into frequency variation. Some reports have recently addressed the power system frequency control issue, in the presence of wind turbines [1]–[4].

In practice, simple proportional-integral (PI) control structure is commonly used for the load-frequency control (LFC) system, and the PI parameters are usually tuned based on trial–error method and the system operators' experience. Most of the conventional LFC synthesis methodologies provide model-based controllers that are difficult to use for large-scale power systems with nonlinearities and uncertain parameters. On the other hand, most of the applied linear modern/robust control techniques to the LFC problem suggest complex control structure with high-order dynamic controllers, which are not practical for industry practices [5].

During the last few years, several reports presenting various control methods on the frequency regulation, real power compensation, and tie-line control issues have been published. Some recent works address intelligent control techniques for the frequency regulation/LFC issue in the power systems; however, there are just few reports on the intelligent frequency control design in the presence of wind power units [1], [4], [6].

The present paper addresses an intelligent fuzzy logic tuning strategy for the PI-based LFC scheme in order to simultaneously minimize the system frequency deviation and tie-line power changes, which is required for the successful operation of interconnected power systems in the presence of high-penetration wind power. To obtain an optimal performance, the particle swarm optimization (PSO) technique is used for the online adjusting membership function parameters.

Model independency and flexibility in specifying the control objectives identify the proposed approach as an attractive solution for the LFC design in real power systems with wind power turbines and other renewable energy units. The developed PSO-fuzzy synthesis strategy also provides an optimal control methodology under uncertainties, with a high degree of flexibility.

Several studies have been already reported for the fuzzy logic-based LFC design schemes in the literature [12]–[20]; some differ significantly from each other by the number and type of inputs and outputs, or less significantly by the number and type of input and output fuzzy sets and their membership functions, or by the type of control rules, inference engine, and the defuzzification method.

The preliminary step of the present work is reported in [12]. In [12], the fuzzy system is used as the main controller (instead of the existing PI control unit). Due to the unpredictable fuzzy unit performance at the start-up iterations, the introduced fuzzy-based LFC scheme is not recommended for the real-time application. On the other hand, real-world power industry is too conservative to open the well-known PI control loop and replace by a new control technology. In response to this challenge, in the present

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work, the PI controller is remained, and the PSO-based fuzzy logic is used for online optimal tuning of its parameters. Therefore, this control configuration provides a smooth performance in start-up and transient circumstances and it could be more acceptable for the real-time LFC application.

A combined LFC design method for a two-area power system based on the PSO algorithm and optimal output feedback control is given in [13]. In [14] and [18], a self-tuning fuzzy controller with a superconducting magnetic energy storage unit is used to perform the LFC system in a two-area power system. A proportional-integral-derivative (PID)-based LFC scheme using the PSO algorithm is considered in [15] for a single area hydropower system. Sheikh *et al.* [16] present the application of an improved PSO algorithm for a PID-based LFC in a single area power system. A combination of fuzzy logic and linear generalized predictive control is also applied for the LFC synthesis in a two-area power system in [17]. Finally, Mazinan *et al.* [19] suggest a PSO-based multi-stage fuzzy controller for the LFC system under a bilateral policy scheme.

All reported LFC designs in [13]–[19] have used conventional simplified linear models, without considering the integration of wind turbines or other types of renewable energy sources. The reported LFC schemes are not examined on a real-time application case study to see the control performance in a more realistic environment. Furthermore, similar to [12], most of the mentioned papers have used the fuzzy/PSO unit instead of the existing PI controller in the LFC loop. Based on the proposed control strategy in the present work, it is not necessary to open the operating LFC loop, i.e., the existing PI controller. An intelligent PSO-based fuzzy system as an online intelligent tuning unit calculates the optimal PI gains. The performed tuning mechanism has an effective role in the optimal tracking of area frequency and tie-line power changes.

To demonstrate the efficiency of the proposed control method, some nonlinear simulations on the New England 10-machine 39-bus test system concerning the integration of wind power units are carried out. A real-time laboratory experience is also performed. The results show that the proposed LFC scheme guarantees the optimal performance for a wide range of operating conditions.

The paper is organized as follows: a brief introduction on the LFC concerning wind power is given in Section II. In Section III, the fuzzy PI-based LFC scheme is presented. The proposed design is enhanced by using the PSO algorithm for adjusting the fuzzy member function parameters in Section IV. Simulation results and laboratory experiment are provided in Section V; and finally, the paper is concluded in Section VI.

II. LFC WITH WIND FARMS

The impact of wind farms (WFs) on the dynamic behavior of power system may cause a different system frequency response to a disturbance event. Since the system inertia determines the sensitivity of overall system frequency, it plays an important role in this consideration. The impact of WFs on power system inertia is a key factor in investigating the power system LFC behavior in the presence of high penetration of wind power generation [7].

The conventional LFC model is well discussed in the power system control literature. To generalize the conventional LFC model, the updated area control error (ACE) signal should represent the impacts of wind power on the scheduled flow over the tie-lines. The ACE signal is traditionally defined as a linear combination of frequency and tie-line power changes as follows [8]:

$$\mathrm{ACE} = \beta\Delta f + \Delta P_{\mathrm{tie}} \tag{1}$$

where Δf is the frequency deviation, β is the frequency bias, and ΔP_{tie} is the difference between the actual (act) and scheduled (sched) power flows for a given area with m tie-lines

$$\Delta P_{\mathrm{tie}} = \sum_{j=1}^{m}\left(P_{\mathrm{tie,act}_j} - P_{\mathrm{tie,sched}_j}\right). \tag{2}$$

For a considerable amount of wind (W) power, its impact must also be considered with the conventional (C) power flow in the overall area tie-line power. Therefore, the updated ΔP_{tie} can be expressed as follows:

$$\begin{aligned}\Delta P_{\mathrm{tie}} &= \Delta P_{\mathrm{tie}-C} + \Delta P_{\mathrm{tie}-W}\\ &= \sum_{j=1}^{m}\left(P_{\mathrm{tie}-C,\mathrm{act}_j} - P_{\mathrm{tie}-C,\mathrm{sched}_j}\right)\\ &\quad + \sum_{j=1}^{m}\left(P_{\mathrm{tie}-W,\mathrm{act}_j} - P_{\mathrm{tie}-W,\mathrm{estim}_j}\right).\end{aligned} \tag{3}$$

Using (1) and (3), an updated ACE signal can be completed as

$$\begin{aligned}\mathrm{ACE} = \beta\Delta f &+ \sum_{j=1}^{m}\left(P_{\mathrm{tie}-C,\mathrm{act}_j} - P_{\mathrm{tie}-C,\mathrm{sched}_j}\right)\\ &+ \sum_{j=1}^{m}\left(P_{\mathrm{tie}-W,\mathrm{act}_j} - P_{\mathrm{tie}-W,\mathrm{estim}_j}\right).\end{aligned} \tag{4}$$

where $P_{\mathrm{tie}-C,\mathrm{act}}$, $P_{\mathrm{tie}-C,\mathrm{sched}}$, $P_{\mathrm{tie}-W,\mathrm{act}}$, and $P_{\mathrm{tie}-W,\mathrm{estim}}$ are actual conventional tie-line power, scheduled conventional tie-line power, actual wind tie-line power, and scheduled wind tie-line power, respectively.

III. FUZZY PI-BASED LFC

As mentioned, in traditional power systems, the secondary frequency control is mostly done by the conventional PI controllers that are usually tuned based on prespecified operating points. In case of any change in the operating condition, the PI controllers cannot provide the assigned desirable performance. Although, if the PI controller can be continuously able to track the changes occurred in the power system, the optimum performance will always be achieved. Fuzzy logic can be used as a suitable intelligent method for online tuning of PI controller parameters.

The fuzzy logic is able to compensate the inability of the classic control theorems for covering the complexity system with their uncertainties and inaccuracies. A fuzzy system is composed

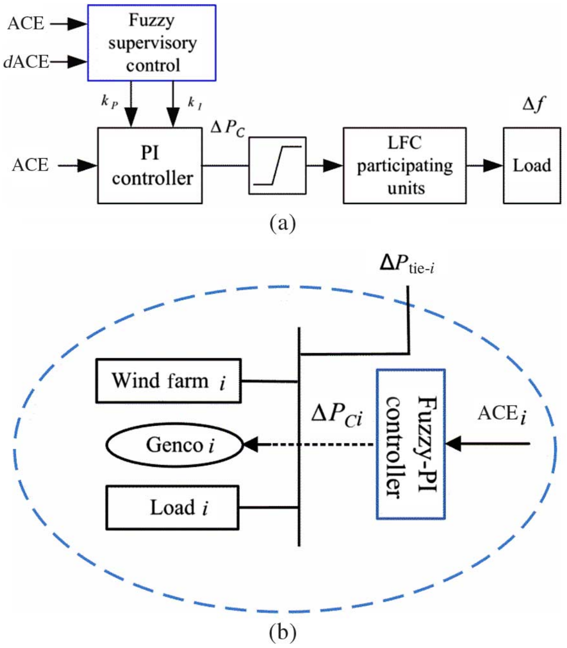

Fig. 1. Fuzzy PI-based LFC: (a) control framework and (b) typical area components.

of four main sections: fuzzification, fuzzy rule base, inference system, and defuzzification [9].

The proposed control framework for the application of fuzzy logic system as an intelligent unit for tuning of traditional PI controller is shown in Fig. 1. The fuzzy PI controller consists of two levels: a traditional PI controller and a fuzzy supervisory control unit. As shown in Fig. 1, the intelligent fuzzy system unit uses ACE (a combination of frequency deviation and tie-line power change) and its derivative to adjust the PI control parameters. Minimizing the frequency deviations due to fast changes in output power of wind turbines, and limiting the tie-line power interchanges in an acceptable range, following disturbances, are the main goals of this effort.

In each control area, ACE and its derivative are considered as input signals for the fuzzy system, and the provided control signal by the PI controller is used to change the set points of the LFC participant generating units. The inputs and outputs are brought into an acceptable range by multiplying in proper gains. The *Mamdani*-type inference system is applied and the performed fuzzy rules are considered as given in [12].

As shown in [6], the fuzzy-based LFC system provides better performance than the classical method, but its performance highly depends on the membership functions. Without precise information about the system, the membership functions cannot be carefully selected, and the designed fuzzy PI controller does not provide an optimal performance in a wide range of operating conditions. Therefore, a complementary algorithm is required for online regulation of membership functions.

IV. PSO-FUZZY PI-BASED LFC

There are several approaches toward the membership function adjustment such as trial and error and online regulating membership function method using a complementary optimization algorithm. Up to now, many search algorithms have been proposed in order to solve the optimization problems, including genetic algorithm, ant colony, and bee colony.

Considering the LFC features and the previous experience on various intelligent approaches, in the present work, the PSO is used as a flexible and powerful intelligent algorithm for online tuning of membership functions employed in the fuzzy PI controller. The PSO is an optimization algorithm, based on the probability laws, which is inspired by the natural models. This algorithm belongs to a class of direct search methods and is used to find an optimal solution for the optimization problems in a given search space. The basic difference of PSO algorithm in comparison with other intelligent methods is in the simplicity of implementation.

The PSO algorithm was presented in 1995, having an idea of social behavior of birds in finding food [10]. In this algorithm, the search process can be introduced as a group of birds that are looking for food in a particular region, randomly. There is only one area that has food and the birds are not aware of that area, but they know their distance at each step of the searching process. Hence, to get closer to the location of the food, all birds follow the nearest bird that is closer to the food place. In this algorithm, each bird is introduced as a particle and all of the particles form a group or swarm. Each particle is determined by two vectors $\boldsymbol{X}(t)$ and $\boldsymbol{V}(t)$ that represent the location and velocity of the particle at time t, respectively. Position of each particle $\boldsymbol{X}_i$ is potentially considered as an answer to the problem. Then, to find the best position (the best answer) at each time, the particles fly around the search area and change their speed and position. All particles regulate their route based on their and other's experiences at the past moment of the flight. In an n-dimensional search area, position and velocity of the ith particle at time t are shown in the following vectors

$$\begin{aligned}\boldsymbol{V}_i(t) &= [V_{i1}(t), V_{i2}(T), \ldots, V_{in}(t)]^T \\ \boldsymbol{X}_i(t) &= [X_{i1}(t), X_{i2}(t), \ldots, X_{in}(t)]^T. \end{aligned} \tag{5}$$

At each time, the particles are corresponded to an objective value, and the best positions of the particles from the beginning to this moment have been stored by the algorithm. The best position for a particle, at time t, is a position that provides the best objective value for the particle. The best position for the ith particle up to the time t, is represented by

$$p_{\text{best}}(t) = \left[p_{\text{best},i1}(t),\ p_{\text{best},i2}(t), \ldots, p_{\text{best},in}(t)\right]. \tag{6}$$

The PSO also stores the best position which is obtained by all particles up to the time t and can be shown as follows:

$$g_{\text{best}}(t) = \left[g_{\text{best},1}(t),\ g_{\text{best},2}(t), \ldots, g_{\text{best},n}(t)\right]. \tag{7}$$

Each particle position and velocity at time $t+1$ is obtained as given below

$$\begin{aligned}V_{ij}(t+1) = W \cdot V_{ij}(t) &+ c_1 \cdot \text{rand1}_{ij} \cdot \left(p_{\text{best},ij}(t) - X_{ij}(t)\right) \\ &+ c_2 \cdot \text{rand2}_{ij} \cdot \left(g_{\text{best},j}(t) - X_{ij}(t)\right) \end{aligned} \tag{8}$$

$$X_{ij}(t+1) = X_{ij}(t) + V_{ij}(t+1). \tag{9}$$

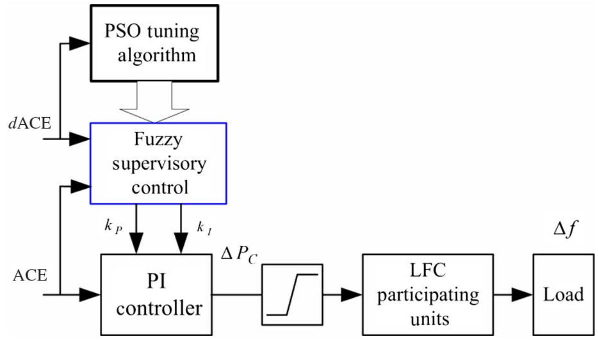

Fig. 2. Closed-loop system with PSO-fuzzy PI controller.

where V_{ij} and X_{ij} are the ith element of the velocity vector $\boldsymbol{V}$ and position vector $\boldsymbol{X}$ for the ith particle, respectively [10]. Here, $i = 1, 2, \ldots, n$ is the particle index, X_{ij} is the jth dimension of the ith particle position, V_{ij} is the jth dimension of the ith particle velocity, $p_{\text{best},ij}$ is the jth dimension of the best position of the ith particle at time t, $g_{\text{best},j}$ is the jth dimension of the best position that so far achieved by all of the particles, W is the inertia weight, rand1_{ij} and rand2_{ij} are two random numbers in the interval [0 1], $c1$ and $c2$ are training factors, and t is the time or iteration.

Several modifications have been proposed to improve the performance of the PSO algorithm. As mentioned, what this research investigates is designing an online adaptive controller, using fuzzy logic and PSO for the purpose of frequency and tie-line power regulations. The overall framework of the proposed control scheme for online adjusting of membership functions based on the PSO technique is shown in Fig. 2.

Considering the purpose of the algorithm which is to find the extremum point of the cost function, if the cost function is not properly selected, the algorithm may be stopped in the local extremum points. Initialization of the algorithm parameters is very important, because if they are not carefully selected, algorithm may never be convergent to the extremum point. The important parameters of this algorithm are the number of particles, particles dimension, particles velocity interval ($V_{\max}$, $V_{\min}$), $c1$, $c2$, and particles place interval ($X_{\max}$, $X_{\min}$). The applied PSO algorithm is extensively discussed in [21].

In all performed simulations and laboratory real-time experimental tests, described in Section V, the PSO algorithm converges in few milliseconds. Considering the time scale of real-world LFC which is in the range of few seconds to minutes [5], this convergence time is ignorable.

V. APPLICATION RESULTS

In order to illustrate the effectiveness of the proposed intelligent control strategy (PSO-fuzzy PI), first, it is examined on the well-known New England 10 generators, 39-bus system as a test case study. Then, an experimental real-time application on the aggregated model of West Japan Power System (WJPS) is explained. The results in both test systems are compared with the fuzzy PI controllers.

A. New England Test System

The New England test system is widely used as a standard system for testing of the new power system analysis and control synthesis methodologies. This system has 10 generators, 19 loads, 34 transmission lines, and 12 transformers. Here, the test system is updated by adding three WFs in buses 5, 26, and 21. A single-line diagram of the updated system is shown in Fig. 3. The system parameters are given in [1].

The total system installed capacity is 305.7 MW of conventional generation and 325.85 MW of average wind power generation. There are 100.5 MW of conventional power generation, 109.4 MW of average wind power generation, and 329.3 MW load in Area 1. In Area 2, there are 82 MW of conventional power generation, 88.25 MW of average wind power generation, and 74 MW load. In Area 3, there are 123.2 MW of conventional power generation, 128.2 MW of average wind power generation, and 219.6 MW load. All power plants in the power system are equipped with speed governor and power system stabilizer.

In the present work similar to the real-world power systems, it is assumed that conventional generation units are responsible to provide spinning reserve for the sake of load tracking and the LFC task.

Here, it is assumed that only one generator in each area is responsible for the LFC task; G1 in Area 1, G9 in Area 2, and G4 in Area 3. For the sake of simulation, random variations of wind velocity have been considered. Dynamics of wind turbines including the pitch angle control of the blades are also considered. The start-up and rated wind velocity for the WFs are specified as about 8.16 and 14 m/s, respectively. Furthermore, the pitch angle controls for the wind blades are activated only beyond the rated wind velocity. The pitch angles are fixed to 0° at the lower wind velocity below the rated one.

In the performed application, the important inherent requirement and basic constraints such as governor dead band and generation rate constraint imposed by physical system dynamics are considered. For the sake of simulation, three step load disturbances are simultaneously applied to the three areas at 15 s: in Area 1, 4.56% of total area load, 8% of total area load in Area 2, and 8% of total area load in Area 3. The simulation results are shown in Figs. 4–6. All unitized values are given based on the values of the largest generator nominal power, i.e., 150 MW. Wind speed pattern and total wind power generation are shown in Fig. 4.

In Fig. 5, the frequency deviation (Δf) of the closed-loop system following the applied load disturbances is shown for all areas. These figures show the superior performance of the proposed PSO-fuzzy PI-based LFC scheme to the fuzzy PI-based LFC design in deriving the frequency deviation close to 0. The tie-line power interchanges of all areas are shown in Fig. 6. It can be seen that the tie-line power flows in the case of using the fuzzy PI-based LFC design show more oscillations and poor performance in keeping the tie-line power interchanges in an acceptable tolerance close to the scheduled values. Also, in this object, the proposed PSO-fuzzy PI controller performs a better response.

B. Real-Time Laboratory Experiment

Since the LFC as a supplementary control is known as a long-term control problem (few seconds to several minutes [5], [8]), it

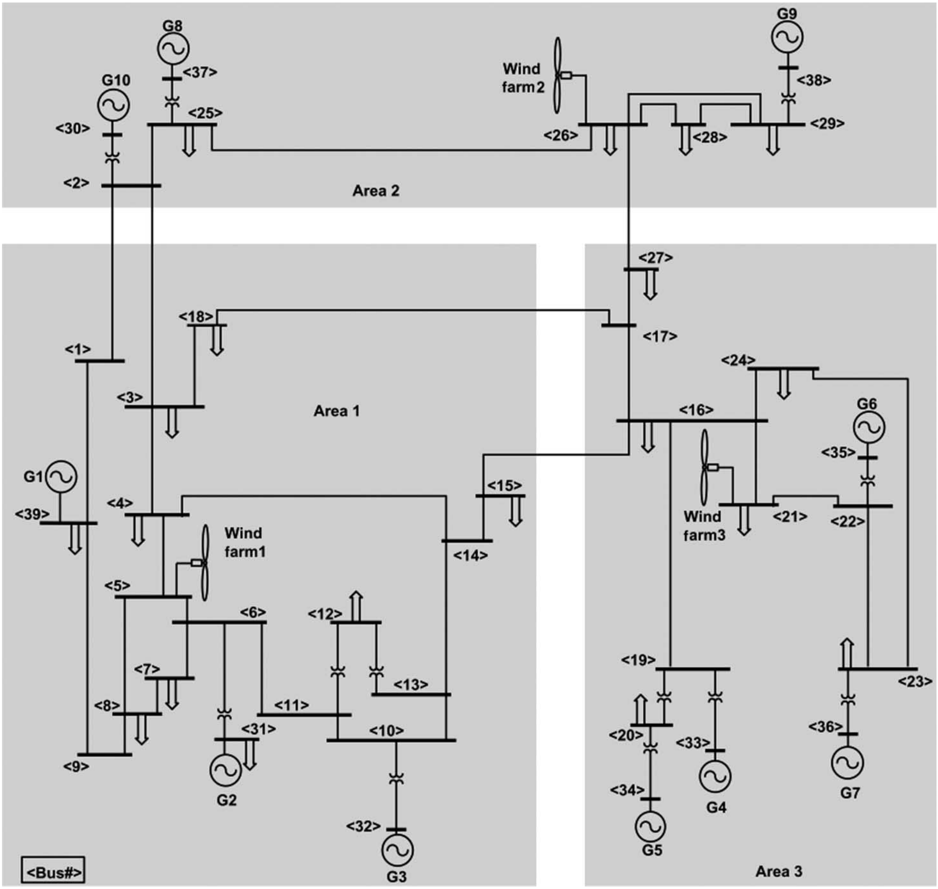

Fig. 3. Single-line diagram of 39-bus test system with three WFs.

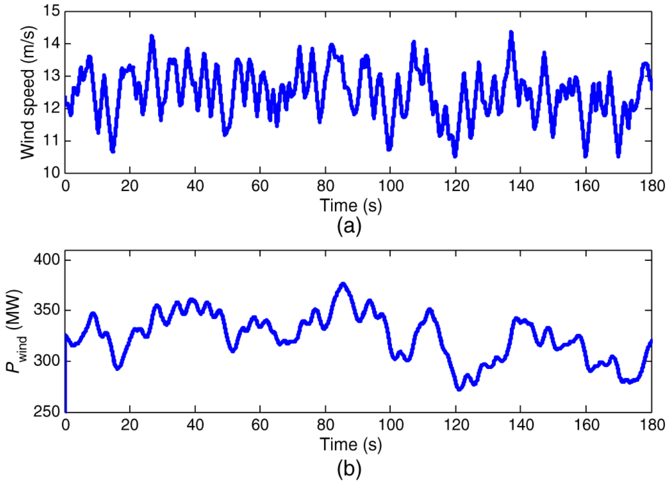

Fig. 4. Wind velocity and power: (a) wind velocity pattern and (b) total wind power generation.

is expected that the proposed LFC methodology to be successfully applicable to the real-world power systems.

To illustrate the capability of the proposed control strategy in real-time LFC applications, an experimental study has been performed on a large-scale analog power system simulator (APSS) at the Research Laboratory of the Kyushu Electric Power Company. For the purpose of this study, a longitudinal four-machine infinite bus system representing the WJPS network is considered as the test system. A single-line diagram of the study system with the proposed control loop is shown in Fig. 7(a).

All generator units are thermal type, with separately conventional excitation control systems. The set of four generators represents a control area (Area 1), and the infinite bus is considered as other connected systems (Area 2). The detailed information of the system and the parameters of each generator unit and its associated turbine system (including the high-pressure, intermediate-pressure, and low-pressure parts) are given in [11]. Some parameters for the laboratory test bench including rated power and line impedances are also listed in Tables I and II (Appendix). Although, in the given model, the number of generators is reduced to four, it closely represents the dynamic behavior of the WJPS. The whole power system [shown in Fig. 7(a)] has been implemented using the APSS. Fig. 7(b) shows an overview of the applied laboratory experiment devices including the generator panels, monitoring displays, and control desk. The proposed control scheme including PSO-fuzzy supervisory control and PI controller have been built in a personal computer, and were connected to the power system using a digital signal processing board equipped with analog-to-digital (A/D) and digital-to-analog (D/A) converters. The converters act as the physical interfaces between the personal computer and the analog power system hardware.

The performance of the closed-loop system is tested in the presence of load disturbances. The nominal area load demands are also fixed at the same values given in [11]. Almost 10% of total demand power is supplied by the installed WF.

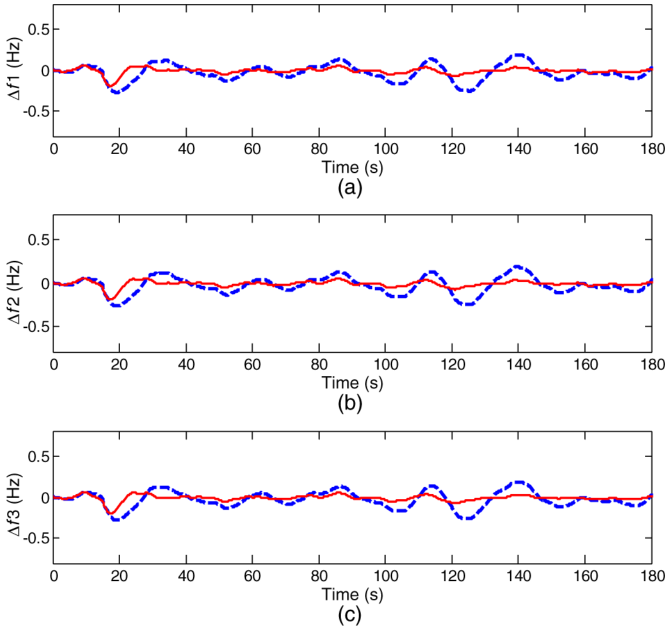

Fig. 5. Frequency deviations: (a) Area 1, (b) Area 2, and (c) Area 3; proposed PSO-fuzzy PI (solid) and fuzzy PI (dashed).

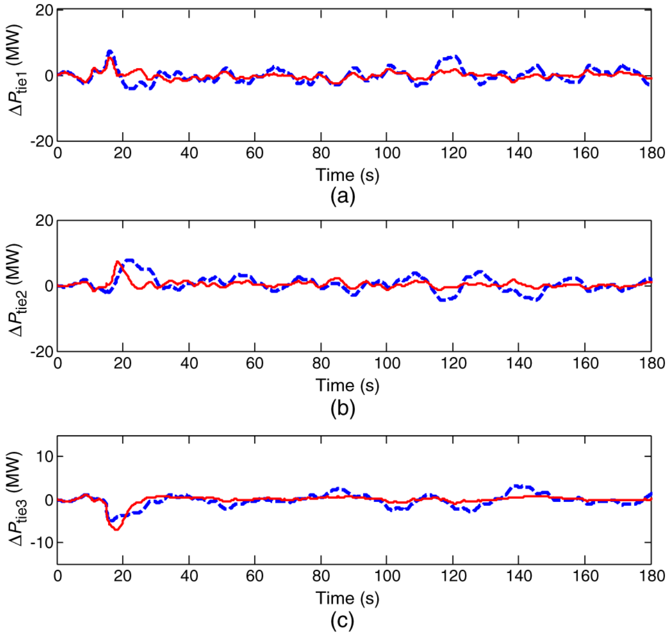

Fig. 6. Tie-line power interchanges: (a) Area 1, (b) Area 2, and (c) Area 3; proposed PSO-fuzzy PI (solid), fuzzy PI (dashed).

As a severe test scenario, the power system is examined in the presence of a sequence of step load changes. The load change pattern and the system response are shown in Fig. 8. The participation factors for Gen 1, Gen 2, Gen 3, and Gen 4 are fixed at 0.4, 0.25, 0.20, and 0.15, respectively. The applied step disturbance, and the closed-loop system response including frequency deviation (Δf), tie-line power change (ΔP_{tie}), and ACE are also shown in Fig. 8.

Fig. 8 shows that the frequency deviation, tie-line power change, and in result the ACE signals are properly maintained within a narrow band. The corresponding control action signals for all generating units are shown in Fig. 9.

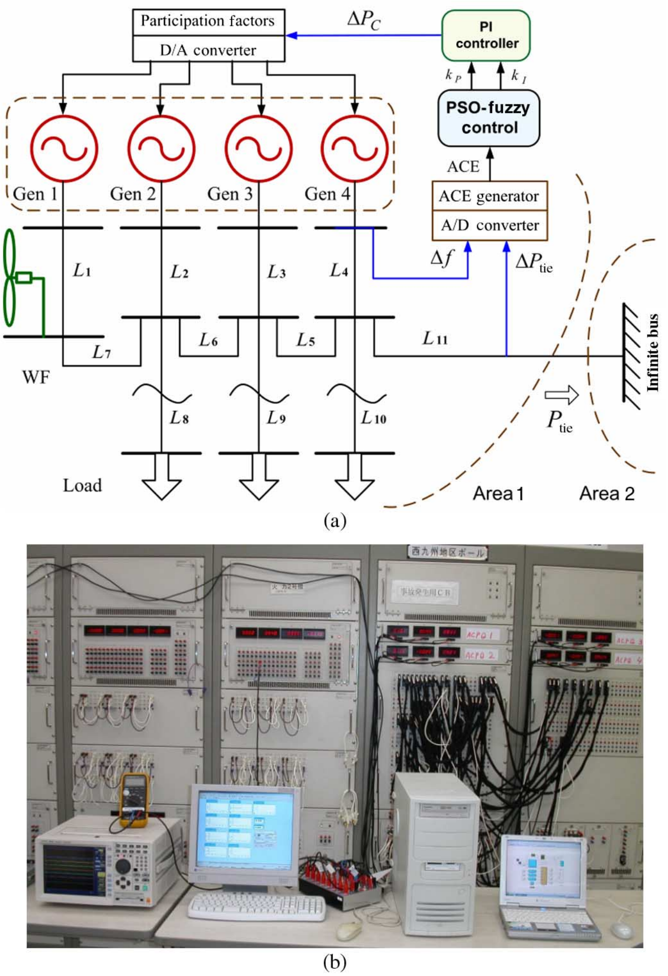

Fig. 7. Performed laboratory experiment: (a) block diagram representation and (b) physical configuration.

The obtained results show that the designed controllers can ensure a good performance despite load disturbances. It is shown that the proposed intelligent LFC system acts to maintain area frequency and total exchange power closed to the scheduled values by sending corrective smooth signal to the generators in proportion to their participation in the LFC task. Better transient and regulation performance for the PSO-fuzzy PI method in experimental study is due to having an adaptive property against the uncertainty and environmental changes.

Since the infinite bus cannot behave similar to an actual control area, the present test system can be considered as a suitable example to evaluate LFC control schemes. The experimental results illustrate that the system performance using the proposed PSO-fuzzy PI-based LFC system is quite better than the conventional PI-based LFC scheme.

VI. CONCLUSION

In practice, simple PI controllers are commonly used in the LFC systems that provide a poor performance in the presence of high penetration of wind power and serious disturbances.

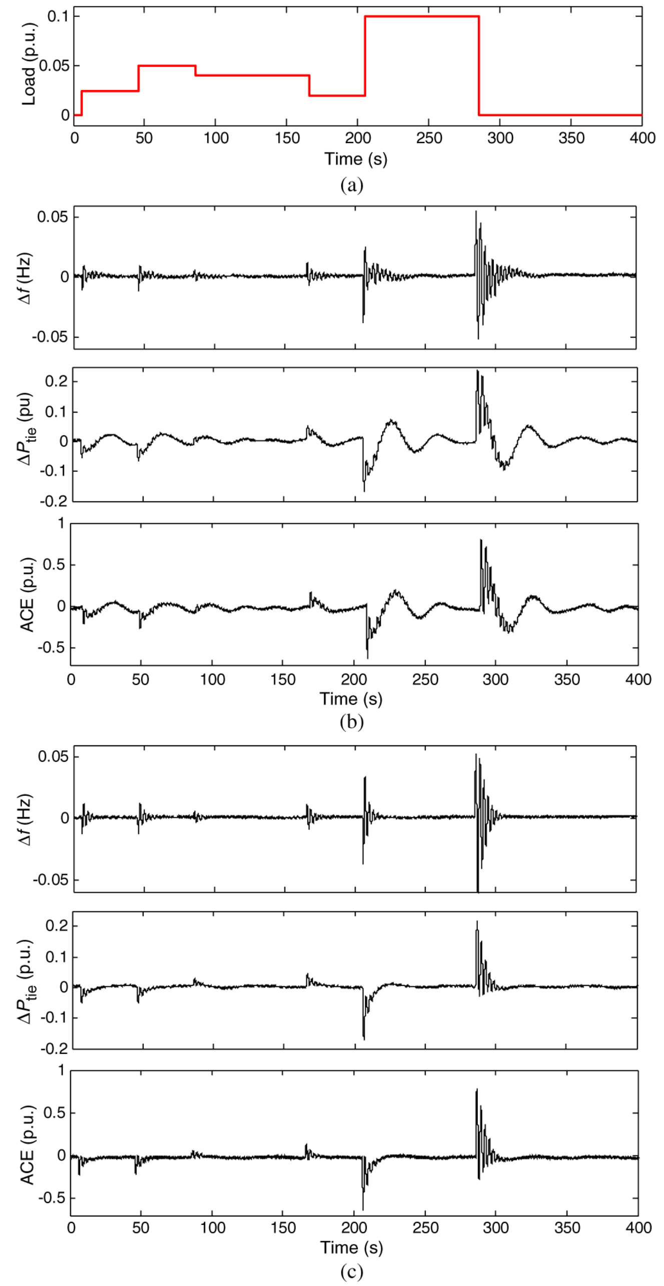

Fig. 8. System response following a sequence of step load changes: (a) load change pattern, (b) fuzzy PI, and (c) proposed PSO-fuzzy PI.

In response to this challenge in the present paper, an adaptive control method is employed for LFC design in an interconnected power system. The designed LFC system has two levels including a PI controller and a fuzzy system, which adjusts the coefficients of the PI controller. Because of severe dependence of the fuzzy systems to their membership functions, the PSO algorithm is used to improve the membership function parameters.

The proposed method was applied to the New England power test system. An experimental examination is also performed in APSS laboratory of Kyushu Electric Power Company. The results show that in comparison with conventional fuzzy PI design, the new intelligent LFC scheme presents a desirable performance which is achieved by effective adjusting of generation to minimize frequency deviation and regulate tie-line power flows.

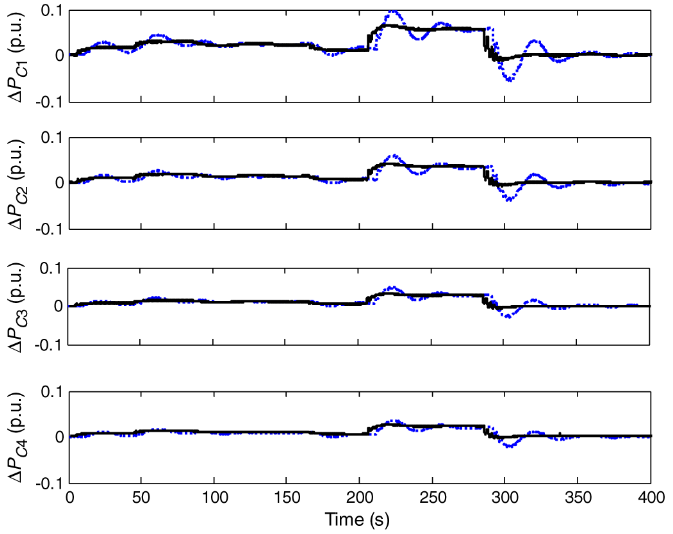

Fig. 9. System response following a sequence of step load changes: proposed PSO-fuzzy PI (solid) and fuzzy PI (dashed).

APPENDIX

TABLE I
GENERATOR PARAMETERS FOR THE REAL-TIME EXPERIMENT

Parameter	Gen 1	Gen 2	Gen 3	Gen 4
Rated power (MVA)	1000	600	1000	900
Droop characteristic R (Hz/p.u.)	3.00	3.00	3.30	3.30
Bias factor β (p.u./Hz)	0.3483	0.3473	0.3180	0.3827
Damping coefficient D (p.u./Hz)	0.0150	0.0150	0.0150	0.0150
Inertia constant $2H$ (s)	8.05	7.00	8.05	6.00
Participation factor α	0.4	0.25	0.20	0.15

TABLE II
LINE PARAMETERS FOR THE REAL-TIME EXPERIMENT

Line	Impedance (Ω)	Line	Impedance (Ω)
L_1	$0.0270 + j0.1304$	L_7	$0.01101 + j0.0829$
L_2	$0.0700 + j0.1701$	L_8	$0.0277 + j0.2238$
L_3	$0.0440 + j0.1718$	L_9	$0.0400 + j0.1718$
L_4	$0.0270 + j0.1288$	L_{10}	$0.0613 + j0.2535$
L_5	$0.01408 + j0.1105$	L_{11}	$0.1248 + j0.9085$
L_6	$0.01101 + j0.0829$		

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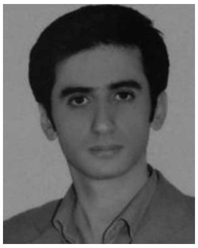

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