Intelligent Frequency Control in an AC Microgrid: Online PSO-Based Fuzzy Tuning Approach

H. Bevrani, *Senior Member, IEEE*, F. Habibi, P. Babahajyani, M. Watanabe, *Member, IEEE*, and Y. Mitani, *Member, IEEE*

***Abstract*—Modern power systems require increased intelligence and flexibility in the control and optimization to ensure the capability of maintaining a generation-load balance, following serious disturbances. This issue is becoming more significant today due to the increasing number of microgrids (MGs). The MGs mostly use renewable energies in electrical power production that are varying naturally. These changes and usual uncertainties in power systems cause the classic controllers to be unable to provide a proper performance over a wide range of operating conditions. In response to this challenge, the present paper addresses a new online intelligent approach by using a combination of the fuzzy logic and the particle swarm optimization (PSO) techniques for optimal tuning of the most popular existing proportional-integral (PI) based frequency controllers in the ac MG systems. The control design methodology is examined on an ac MG case study. The performance of the proposed intelligent control synthesis is compared with the pure fuzzy PI and the *Ziegler-Nichols* PI control design methods.**

***Index Terms*—Fuzzy logic, intelligent control, microgrid, optimal tuning, particle swarm optimization, secondary frequency control.**

I. INTRODUCTION

THE increasing need for electrical power has made several uncommon sources enter into the power systems which increased the systems complexity and uncertainty. Renewable energy sources (RESs) are mostly used as alternative generation units in a modern power system. The increasing penetration of the RESs has many advantages, but also introduces new important challenges, as to whether these sources can operate stable beside conventional generation units or not.

Some technical challenges caused by the RESs are problem of maintaining and protecting of the RESs, contributing in the system voltage and frequency regulation, and proper control designs in both connected and disconnected modes [1]. The desired utilization of these sources requires many standards; hence, the microgrid (MG) concept was first introduced in 1998 by the Consortium for Electric Reliability Technology Solutions (CERTS) [2], [3]. The CERTS introduced an MG as an aggregation of loads and microsources operating as a single system providing both power and heat. The majority of the microsources must be power electronic-based to provide the required flexibility to ensure the operation as a single aggregated system [2], [3].

The basis of the MGs entrance into the power systems are based on the increasing reliability of the conventional power systems, as well as improvement of economical and environmental issues. The MG system using renewable energies helps to reduce global warming and to speed up entering the power industry in the deregulated environments.

The main sources of power in the MGs are small generating units of tens of kW placed at the customer site, and integrated into the power grid in the form of distributed generation (DG). In late 1990s, the main issues related to DG were widely considered by the working groups of the International Council on Large Electric Systems (CIGRE) and the International Conference and Exhibition on Electricity Distribution (CIRED) in their review reports [1]. Typical DGs are diesel engine generators (DEGs), micro turbines, photovoltaic (PV) panels, wind turbines generators (WTGs), energy storages, fuel cells (FCs), and reciprocating engines.

The MGs are placed in the low voltage (LV) and medium voltage (MV) distribution networks. With numerous microsources connected at the distribution level, there are new challenges, such as system stability, power quality, and network operation that must be resolved applying the advanced control techniques at LV/MV levels rather than high voltage levels which is common in conventional power system control. In other words, distribution networks (demand side) must pass from a passive to an active one role.

The existence of the storage devices is vital in the MG systems. Because of light inertia in most of microsources, in case of a serious event such as a load disturbance or outage of a generation unit, the main system indices are influenced, and it may lead to a critical condition. Using of energy storage devices improves the performance and stability in the MG systems. The main energy storage devices which are used as backup devices are storage batteries, flywheels, and ultra capacitors [1].

Nowadays, due to increasing importance of MGs in practice as well as academic researches, several MG projects have been studied around the world, such as the CERTS project in the United States [3], the MG project in Senegal [4], the Kythnos Island MG in Greece [5], and several projects in Japan [6]. In the presence of MGs beside common bulk generation units in the

---

Manuscript received August 11, 2011; revised November 30, 2011, March 18, 2012; accepted April 11, 2012. Date of publication June 06, 2012; date of current version December 28, 2012. This work is supported in part by the Research Office at University of Kurdistan and Mitani Laboratory at Kyushu Institute of Technology. Paper no. TSG-00326-2011.

H. Bevrani and F. Habibi are with the University of Kurdistan, Sanandaj 66177-15175, Iran (e-mail: bevrani@ieee.org).

P. Babahajyani is with the Isfahan University of Technology, Isfahan 84156-83111, Iran.

M. Watanabe and Y. Mitani are with the Kyushu Institute of Technology, Kitakyushu 804-0011, Japan.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TSG.2012.2196806

power system, the main system indices such as voltage and frequency must be controlled using appropriate control strategies. To preserve desirable performance and stability, three main control structures, i.e., central, single agent, and decentralized control are mostly used.

In the central method, the MG system proceeds to the control local loads and the system parameters by a central control unit. In this method all information about loads and DGs in the MG are collected by a central unit and are decided for loads and DGs [7]–[10]. In the single agent method, the MG system by a great controllable DG proceeds to control local loads and the system parameters. In this method, all the control actions are applied on the controllable DGs. But, the main disadvantage of this method is the high cost of the controllable DGs [11]. In the decentralized method, each DG is equipped by a local controller so needs local feedback control signal [2], [11], [12].

The control units and their associated tuning methods for modern MG systems, which should handle complex multiobjective regulation optimization problems characterized by a high degree of diversification in policies, control strategies, and wide distribution in demand and supply sources, surely must be *intelligent*. The core of such intelligent system should be based on flexible intelligent algorithms [6]. Unlike large power systems, the drooping system is poorly regulated in the MGs to support spinning reserve as an ancillary service in power markets. During last few years, several reports presenting various control methods on frequency regulation, real power compensation, and tie-line control issues, have been published. Some recent works address the scheduling of the droop coefficients for frequency regulation in the MGs [13]. As described in [14], [15], frequency stability in a power system means preserving steady frequency following a heavy disturbance with minimum loss in loads and generation units.

The present paper addresses a new online intelligent approach using a combination of the *fuzzy logic* and the *particle swarm optimization* (PSO) techniques for optimal tuning of the most popular existing proportional-integral (PI) based frequency controllers in the MG systems. In the proposed control strategy, the PI parameters are automatically tuned using fuzzy rules, according to the online measurements. In order to obtain an optimal performance, the PSO technique is used online to determine the membership functions parameters. The proposed optimal tuning scheme offers many benefits for an MG frequency control with numerous DGs and RESs, while the classical tuning methods may not be applicable to provide a desirable performance over a wide range of operating conditions. The proposed intelligent PSO-fuzzy PI control design methodology is used for secondary frequency control in an ac MG.

To demonstrate the effectiveness of the proposed control schemes, the result is compared with the *pure fuzzy PI* control method as well as classical PI control design using *Ziegler-Nichols* technique. In the developed tuning algorithm, the physical and engineering aspects of MG systems have been fully considered. Simulation studies are performed to illustrate the capability of the proposed intelligent control approach.

Two scenarios for secondary frequency control are considered. In the first scenario, it is assumed that only the DEG unit is responsible, but in the second one, the FC unit also contributes in the secondary frequency control. The FC unit acts as a backup for reducing the destructive effects of the frequency deviations [16]. Using this approach, the amount of pressure on the generator and capacity of storage energy devices, in a long term, can be reduced.

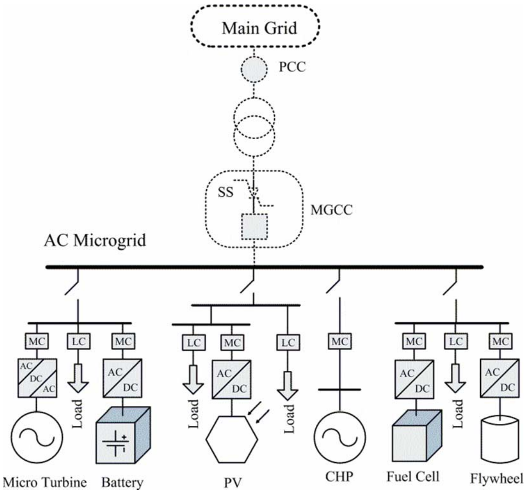


Fig. 1. Simplified ac MG structure.

This paper organized as follows: Section II provides an overview on the ac MG structures and their essential control loops. In Section III, an isolated ac MG system is introduced as case study. Conventional and pure fuzzy PI-based control designs are addressed in Section IV. In Section V, the proposed intelligent control strategy based on the fuzzy logic and PSO is explained. Several simulations for studding the performance of the applied algorithm and the results are presented in Section VI. Finally, in Section VII, the conclusions are presented.

II. AC MICROGRIDS

A. AC Microgrid Structure

An ac MG is an interconnection of domestic distributed loads and low voltage distributed energy sources, such as microturbines, wind turbines, PVs, and storage devices. A simplified ac MG architecture is shown in Fig. 1. This MG consists of a group of radial feeders as a part of a distribution system. The domestic load can be divided to sensitive/critical and nonsensitive/noncritical loads via separate feeders. The sensitive loads must be always supplied by one or more microsources, while the nonsensitive loads may be shut down in case of contingency, or a serious disturbance.

Each unit's feeder has a circuit breaker and a power flow controller commanded by the central controller or energy manager. The circuit breaker is used to disconnect the correspondent feeder (and associated unit) to avoid the impacts of sever disturbances through the MG. The ac MG can be connected to the distribution system by a point of common coupling (PCC) via a static switch (SS). The static switch is capable to island the MG for maintenance purposes or when faults or a contingency occurs.

For the feeders with sensitive loads, local power supply, such as diesel generators or energy capacitor systems (ECSs) with enough energy saving capacity are needed to avoid interruptions

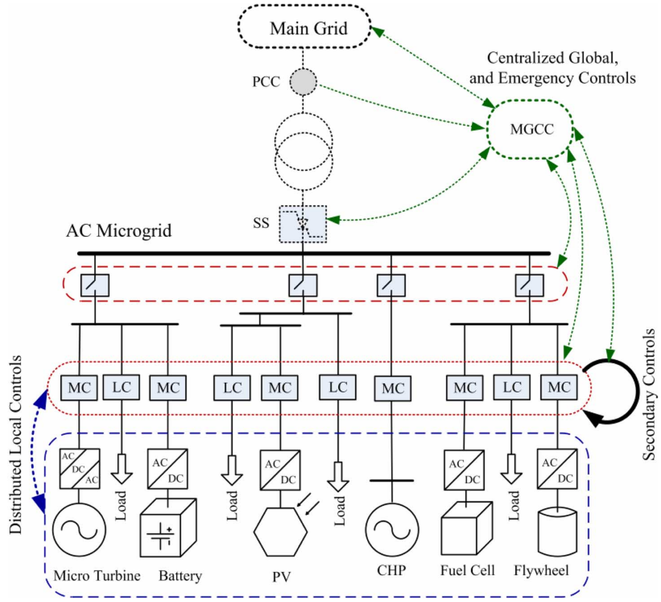


Fig. 2. A general scheme for ac microgrid controls.

of electrical supply. An MG central controller (MGCC) facilitates a high level management of the MG operation by means of technical and economical functions. The microsource controllers (MCs) control the microsources and the energy storage systems. Finally, the controllable loads are controlled by load controllers (LC).

The microsources and storage devices use power electronic circuits to connect to the ac MG. Usually, these interfaces depending to the type of unit are ac/ac, dc/ac, and ac/dc/ac power electronic converters/inverters. As the MG elements are mainly power-electronically interfaced, the MG control depends on the inverter control.

For increasing reliability in the conventional power systems, the MG systems must be able to have proper performance in both connected and disconnected modes. In connected mode, the main grid is responsible for controlling and maintaining power system in desired conditions and, the MG systems act as real/reactive power injectors. But in disconnected mode, the MG is responsible for maintaining the local loads and keeping the frequency and voltage indices at specified nominal values [1], [3], [5]

B. Control Loops in an AC Microgrid

Control is one of the key enabling technologies for the deployment of an ac MG system. An ac MG has a hierarchical control structure with different layers. It requires effective use of advanced control techniques at all levels. As already mentioned, the MGs should be able to operate autonomously but also interact with the main grid. In islanded mode, to cope to the variations, and to response to load disturbances; and performing active power/frequency regulation, and reactive power/voltage regulation, the MGs need to use proper control loops. In this mode, the ac MG operates according to the available standards, and the existing controls must properly work to supply the required active and reactive powers as well as to provide voltage and frequency stability. A general scheme for operating controls in an ac MG is shown in Fig. 2.

Each microsource is locally controlled by an MC. The LCs are installed at the controllable loads to provide load control capabilities. Each MG may need MGCC that interfaces between the MG and higher distribution networks (such as main grid).

Similar to the conventional power systems [15], an ac MG can operate using various control loops which can be mainly classified in four control groups: local, secondary, global, and emergency controls. The *local control* deals with initial primary control such as current and voltage control loops in the microsources. The *secondary control* ensures that the frequency and average voltage deviation of the microgrid is regulated towards zero after every change in load or supply. It is also responsible for inside ancillary services. The *global control* allows MG operation at an economic optimum and organizes the relation between an MG and distribution network as well as other connected MGs. The *emergency control* covers all possible emergency control schemes and special protection plans to maintain the system stability and availability in the face of contingencies. The emergency controls identify proper preventive and corrective measures that mitigate the effects of critical contingencies. In contrast to the local control, operating without communication, secondary, global, and emergency controls may need communication channels. While, the local controls are known as *decentralized* controllers, the global, and to some extent, secondary and emergency controllers are operating as *centralized* controllers.

Due to high diversity of generation and loads, an ac MG exhibits high nonlinearities, changing dynamics, and uncertainties that may require advanced intelligent control strategies such as the used methodology in the present work to solve. The use of more efficient control strategies would increase the performance of these systems. Since some RESs such as wind turbines and PVs are working under turbulent and unpredictable environmental conditions, the MGs have to adapt to these variations and in this way the efficiency and reliability of MGs strongly depend on the applied control strategies. The present paper is focused on the frequency regulation, as a secondary control issue.

III. CASE STUDY

Hence, in many cases, the control plans for MG systems in disconnected mode are more important than the connected mode; here, an isolated ac MG system is considered as a case study. The isolated MG system is shown in Fig. 3. The MG system contains conventional DEG, PV panel, WTG, FC system, battery energy storage system (BESS), and flywheel energy storage system (FESS). As shown in Fig. 3, the DGs are connected to the MG by power electronic interfaces which are used for synchronization in ac sources like DEG and WTG and to reverse voltage in dc sources like PV panel, FC, and energy storage devices. The FC contains three fuel blocks, an inverter for converting dc to ac voltage and an interconnection device (IC). The FC has a high order characteristic but a three-order model is sufficient for frequency studies [16].

Each microsource has a circuit breaker to disconnect from the network to avoid the impacts of sever disturbances through the MG or for maintaining purposes. Nominal values of the DG

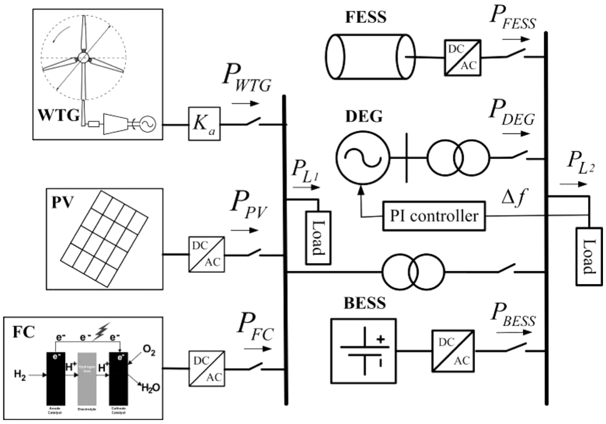


Fig. 3. Single-line diagram of the ac MG case study.

TABLE I
RATED POWER OF DG UNITS AND LOADS

Rated power (KW)		Load (KW)	
WTG	100	P_{L_1}	210
PV panel	30		
FC	70		
DEG	160	P_{L_2}	200
FESS	45		
BESS	45		

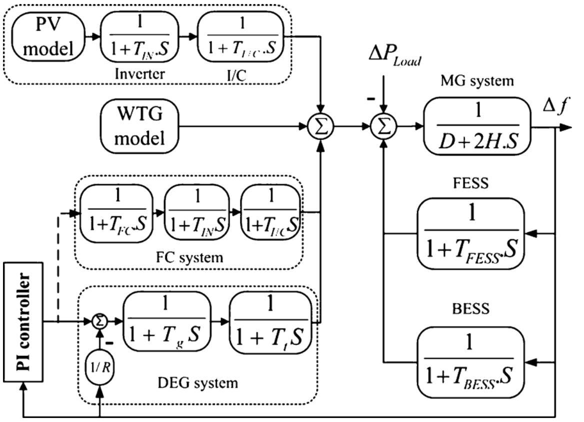


Fig. 4. Frequency response model for the ac MG system.

TABLE II
THE PARAMETERS VALUES OF THE AC MG SYSTEM

Parameter	Value	Parameter	Value
D (pu/Hz)	0.015	T_g (s)	0.08
2H (pu s)	0.1667	T_t (s)	0.4
T_{FESS} (s)	0.1	$T_{I/C}$ (s)	0.004
T_{BESS} (s)	0.1	T_{in} (s)	0.04
T_{FC} (s)	0.26	R (Hz/pu)	3

units, as well as loads are given in Table I. Mandatorily, a specific amount of power produced by the DEG is considered as spinning reserve for secondary frequency control.

For easily understanding of the MG frequency response, a simplified frequency response model for the case study is shown in Fig. 4. Parameter values of the block diagram (Fig. 4) are given in Table II.

TABLE III
PI CONTROL PARAMETERS USING THE ZIEGLER-NICHOLS METHOD

Controller parameter	Value
K_p	4.095
K_i	21.84

This model can be useful to analysis/demonstrate frequency behavior of the case study. Interested readers can find more detail on the microsources models in [17]. Since most of energy sources have intermittent nature with considerable uncertainty and fluctuation in output power, efficient control methods must be employed to decrease the undesirable dynamic impacts on the overall system performance and stability.

IV. CONVENTIONAL AND FUZZY-PI BASED FREQUENCY CONTROL

In traditional power systems, the secondary frequency control is mostly done by 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. While, if the PI controller can be continuously able to track the changes occurred in the power system, the optimum performance will be always achieved. Fuzzy logic can be used as an suitable intelligent method for online tuning of PI controller parameters.

In this section, the traditional PI controller for secondary frequency control is tuned by well-known *Ziegler-Nichols* method. Then, a pure fuzzy PI controller is also designed. The results will compared with the online PSO-fuzzy based PI design methodology in the next sections.

A comprehensive study on the classical PI/PID tuning methods like Ziegler-Nichols have been presented in [13]. Using the Ziegler-Nichols method, the PI parameters are obtained as given in Table III.

As described before, to achieve a better performance, the fuzzy logic is used as an intelligent method. The fuzzy logic (introduced in 1965 [18]) is able to compensate the inability of the classic control theory for covering the complex system with their uncertainties and inaccuracies. A fuzzy system is composed of four main sections: fuzzification, fuzzy rule base, inference system, and defuzzification [19].

The proposed control framework for application of fuzzy logic system as an intelligent unit in order to fine tuning of traditional PI controller is shown in Fig. 5. The fuzzy PI controller consists two levels: a traditional PI controller and a fuzzy system unit. As shown in Fig. 5, the intelligent fuzzy system unit uses frequency deviation and load perturbation inputs to adjust the PI control parameters. In order to apply the fuzzy logic to the isolated MG system for tuning of PI controller, a set of fuzzy rules consisting of 18 rules is used to map input variables, Δf (frequency deviation) and ΔP_L (load perturbation), to output variables, K_p (proportional gain) and K_i (integral gain).

The performed fuzzy rules are given in Table IV. The membership functions corresponding to the input and output variables are arranged as Negative Large (NL), Negative

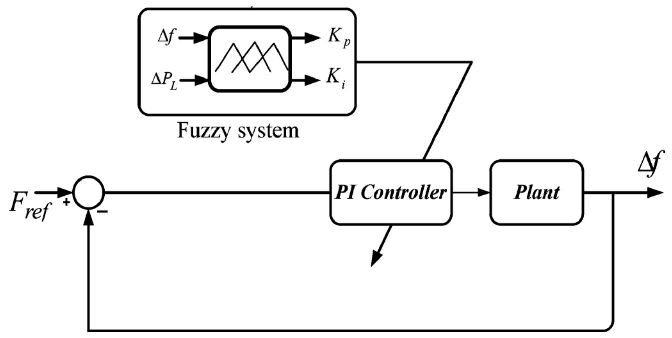


Fig. 5. Fuzzy PI based secondary frequency control.

TABLE IV
THE FUZZY RULES SET

Δf ΔP_L	NL	NM	NS	PS	PM	PL
S	NL	NM	NS	PS	PS	PM
M	NL	NL	NM	PS	PM	PM
L	NL	NL	NL	PM	PM	PM

Medium (NM), Negative Small (NS), Positive Small (PS), Positive Medium (PM), and Positive Large (PL). They have been arranged based on triangular membership function which is the most popular one. The antecedent parts of each rule are composed by using AND function (with interpretation of minimum). Here, Mamdani fuzzy inference system is also used.

As will be shown in Section VI, the fuzzy PI controller has proper performance in comparison to 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 optimal performance in a wide range of operating conditions. Therefore, a complementary algorithm is used to online regulating of membership functions.

V. PSO-FUZZY PI FREQUENCY CONTROL

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 (GA), Ant Colony, and Bee Colony.

In this paper based on the MG system features and previous experience on various intelligent approaches [6], [20], [21], for online tuning of membership functions employed in the fuzzy PI controller, the PSO as a flexible and powerful intelligent algorithms is used.

The PSO is an optimization algorithm, based on the probability laws, which is inspired by the natural models. This algorithm belongs to class of direct search methods and is used to find an optimal solution for the optimization problems in a given search space. Basic difference of the PSO algorithm in comparison with other intelligent methods is in the simplicity of implementation. Other outstanding features of the PSO algorithm can be pointed as follows [22]–[24]:

- It uses the cost function information to navigate search action in the problem space.
- Only numerical values for the cost functions can be used. This feature facilitates the PSO to use on the nonderivative cost functions.
- In comparison of other methods, due to use of probability rules, more flexible and robust control frameworks can be achieved by the PSO algorithm.
- The PSO provides a high accuracy result, without using complex operations.
- It is able to overcome premature convergence which increases the search action ability.
- Achieving to the optimal response from any given initial search point is guaranteed.
- The PSO time optimization in comparison of other optimization methods such as GA is much less.
- It is easy to use the PSO in online optimization mode.
- To achieve the optimal response is not used complex operations which are simplified to use it.

The PSO algorithm was presented in 1995, having the idea of social behavior of birds in finding food [25], [26]. In this algorithm, the search process can be introduced as a group of birds that looking for food in a particular region, randomly. There is only one area that has the food and the birds are not aware of that area, but they know their distance at each step of the searching process. So, to get closer to the location of the food, all of the 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 $X(t)$ and $V(t)$ that respectively represent the location and velocity of the particle at the time (t). Position of each particle Xi is potentially considered as an answer of 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 of the particles regulate their route based on their and other's experiences at the past moment of the flight [27]. In an n-dimensional search area, position and velocity of *i-th* particle at time t are respectively shown with the following vectors:

$$V_i(t) = [V_{i1}(t), V_{i2}(t), \dots, V_{in}(t)]^T$$
$$X_i(t) = [X_{i1}(t), X_{i2}(t), \dots, X_{in}(t)]^T . \quad (1)$$

At each time, 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 *i-th* particle up to the time t, is represented by

$$p_{\text{best}}(t) = [p_{\text{best},i1}(t),\ p_{\text{best},i2}(t),\ \dots,\ p_{\text{best},in}(t)] . \quad (2)$$

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

$$g_{\text{best}}(t) = [g_{\text{best},1}(t),\ g_{\text{best},2}(t),\ \dots,\ g_{\text{best},n}(t)] . \quad (3)$$

Each particle position and velocity at time $(t+1)$ is obtained as given in (4)–(5), where V_{ij} and X_{ij} are *i-th* element of the

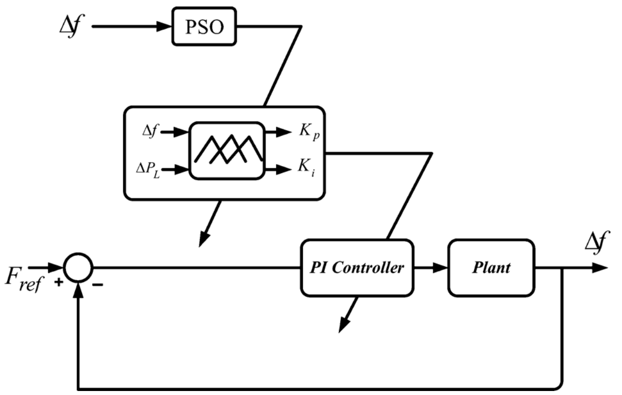


Fig. 6. Closed-loop system with PSO-fuzzy PI controller.

velocity vector V and position vector X for the *i-th* particle, respectively [26].

$$V_{ij}(t+1) = W \cdot V_{ij}(t) + c_1 \cdot \mathrm{rand1}_{ij} \cdot (p_{\mathrm{best},ij}(t) - X_{ij}(t)) + c_2 \cdot \mathrm{rand2}_{ij} \cdot (g_{\mathrm{best},j}(t) - X_{ij}(t)) \quad (4)$$

$$X_{ij}(t+1) = X_{ij}(t) + V_{ij}(t+1). \quad (5)$$

Here, $i = 1, 2, \ldots n$ is particle index, X_{ij} is the *j-th* dimension of the *i-th* particle position, V_{ij} is the *j-th* dimension of the *i-th* particle velocity, $p_{\mathrm{best},ij}$ is the *j-th* dimension of the best position of the *i-th* particle at time t, $g_{\mathrm{best},j}$ is the *j-th* dimension of the best position that so far achieved by all of the particles, W is the inertia weight, $\mathrm{rand1}_{ij}$ and $\mathrm{rand2}_{ij}$ are two random number in the interval [0 1], c_1 and c_2 are training factors, and t is the time or iteration.

Several modifications have been proposed to improve the performance of the PSO algorithm [27], [28]. As mentioned, what this research investigates is designing an online adaptive controller, using fuzzy logic and PSO, for the purpose of frequency regulation in an ac MG system. The overall control framework for online adjusting of membership functions for the fuzzy rules, based on the PSO technique is shown in Fig. 6.

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 ($V_{\max}$, $V_{\min}$), c_1, c_2, and particles place interval ($X_{\max}$, $X_{\min}$). In general, the PSO algorithm can be summarized in the following ten steps:

Step 1. Selecting the algorithm parameters, including $V_{\min}$, $V_{\max}$, N (number of the particles), c_1, c_2, $X_{\min}$, $X_{\max}$, and W (inertia weight) that is fixed at 0.9 in this study.
Step 2. Initializing particles $(Xi(t), Vi(t))$, randomly.
Step 3. Initializing the P_{best} vectors for all of the particles, using random initial values obtained in Step 2 for the position vectors.
Step 4. Updating the fuzzy system parameters, using particle position vector $Xi(t)$ and calculating the fitness value for each particle, using the cost function.
Step 5. Determining the g_{best} using the objective values of the particles.
Step 6. Updating the particle velocity vectors Vi and positioning vectors Xi according to (4) and (5).
Step 7. Updating the parameters of the fuzzy system membership functions by the position vector of each particle and calculating the objective value for each particle.
Step 8. Updating the P_{best} for each particle.
Step 9. Updating the g_{best}. If the objective value of the $g_{\mathrm{best}}(t+1)$ is better than the objective value of the $g_{\mathrm{best}}(t)$, then

$$\mathrm{gbest} = \mathrm{gbest}\ (t+1). \quad (6)$$

Step 10. If the stop condition is met, algorithm will stop and the optimal parameter values are achieved; otherwise, return to Step 6.

The computational flow chart for the proposed online PSO based optimal design approach is shown in Fig. 7.

VI. SIMULATION RESULTS AND DISCUSSION

For comparing the classic fuzzy PI and PSO-fuzzy PI controllers, several simulation tests are carried out and the performances of the proposed control methods are evaluated. To illustrate the dynamic response of the MG system, the closed-loop system is examined in the face of a multiple step load disturbance which is plotted in Fig. 8(a). The MG frequency response using the conventional fuzzy PI and PSO-fuzzy PI (optimal PI) controllers in the face of multiple step load disturbance is shown in Fig. 8(b). The Δf, and ΔP_L are frequency deviation, and load disturbance pattern, respectively; which their values are given in $p.u.$ As shown, the proposed optimal PSO-fuzzy PI controller regulates the system frequency following disturbance quite better than the pure fuzzy PI and classical PI controllers. The optimal fuzzy-PI controller has suitable performance in terms of settling-time, as well as control effort and minimizing of frequency deviations.

A better performance of the proposed intelligent control methodology is clearly visible from system frequency response following first step increase in the load disturbance, [Fig. 8(b)]; and the proposed optimal controller could eliminate the system frequency deviations before starting second step increase in the load disturbance more effective than the other controllers. For the sake of comparison in a sever condition, performance of the PSO-fuzzy PI fuzzy-PI, and conventional PI controllers are examined following a large step load disturbance of 0.1 *p.u.* as shown in Fig. 9. In this case also, the proposed optimal control method provides a much better performance, specifically in settling time characteristic point of view.

A. Robustness Against Parameters Variation

Power system parameters are constantly changing and, this may degrade the closed-loop system performance, seriously. As indicated in the previous sections, one of the main advantages of the intelligent control methods is robustness against environmental and dynamical changes. For showing the adaptive property of the PSO-fuzzy PI controller, the main system parameters,

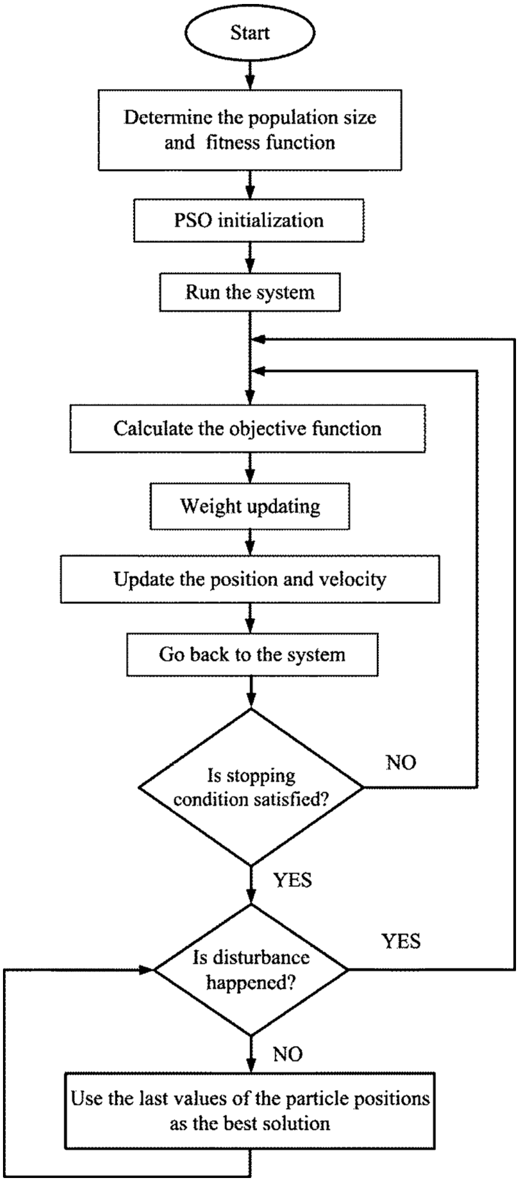


Fig. 7. The online PSO algorithm flowchart.

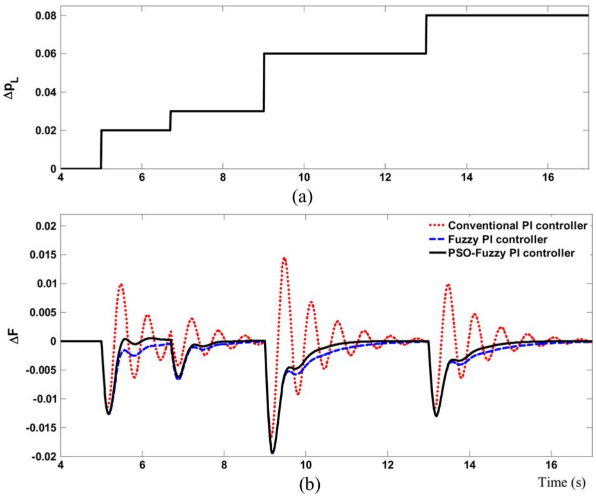


Fig. 8. (a) Multiple step load disturbances. (b) MG frequency response.

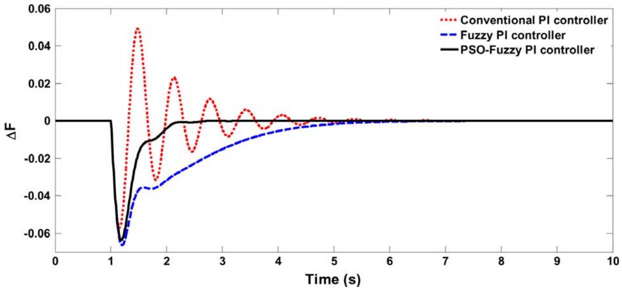


Fig. 9. Frequency control following a step load disturbance of 0.1 pu.

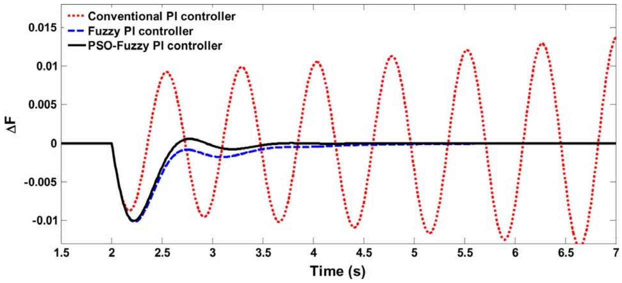


Fig. 10. Frequency response according to the parameters changes shown in Table V.

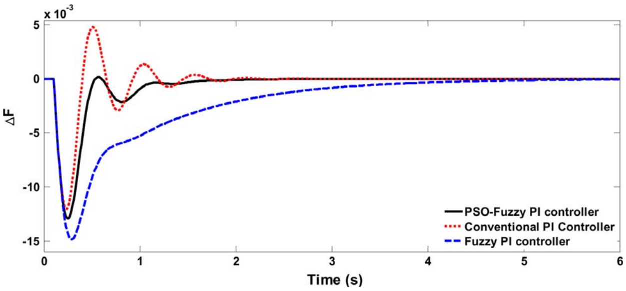


Fig. 11. Frequency response according to the parameters changes shown in Table VI.

TABLE V
UNCERTAIN PARAMETERS AND VARIATION RANGE

Parameter	Variation range	Parameter	Variation range
R	+30%	T_g	+50%
D	-40%	T_{FESS}	-45%
H	+50%	T_{BESS}	+55%
T_t	-50%		

in the frequency response model (Fig. 4), i.e., D (damping coefficient), H (inertia constant), R (droop constant), T_t(turbine time constant), T_g(generator time constant), T_{FESS} (FESS time constant), and T_{BESS} (BESS time constant) are significantly changed according to Tables V and VI. The closed-loop frequency response after applying these changes to the MG system parameters, are shown in Figs. 10 and 11, respectively. It can be seen from Fig. 10 that the conventional controller cannot handle the applied parameters perturbation (given in Table V). Fig. 11 shows that difference between the proposed optimal PSO-fuzzy PI controller with other two controllers is more clear for the second set of parameter variation (Table VI).

TABLE VI
UNCERTAIN PARAMETERS AND VARIATION RANGE

Parameter	Variation range	Parameter	Variation range
R	-60%	T_g	-62%
D	-55%	T_{FESS}	-35%
H	+48%	T_{BESS}	-50%
T_t	-53%		

TABLE VII
CALCULATED VALUES FOR THE PERFORMANCE INDEX (7)

Controller / Scenario	Conventional	Pure fuzzy-PI	PSO-fuzzy PI
S-1	0.00024	0.00020	0.00015
S-2	0.00426	0.00272	0.00110
S-3	unstable	3.2e-5	2.1e-5

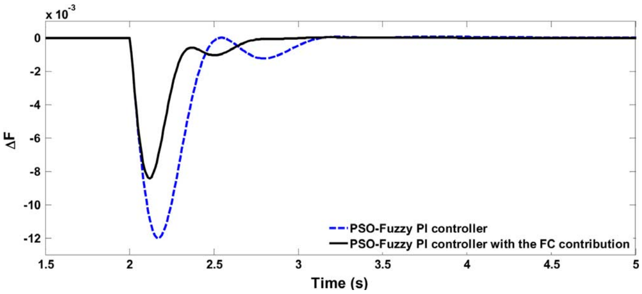


Fig. 12. Frequency deviation in case of contribution of both FC and DEG in frequency control.

Here, to illustrate the effectiveness of the PSO fuzzy-PI controller quantitatively, the following frequency deviation-based performance index (P_{Index}) is defined:

$$P_{\mathrm{Index}} = \int_0^T |\Delta f|^2 dt \tag{7}$$

where $|\Delta f|$, and T are absolute value of the frequency deviations, and simulation time period, respectively. The performance index is calculated for three simulation scenarios, and results are given in Table VII. Scenarios 1 and 2 (S-1 and S-2) investigate impacts of the multiple step load disturbance and a severe step load disturbance of 0.1 pu on the MG system frequency, respectively. Impact of perturbation in the system parameters according to Table V is investigated as Scenario 3 (S-3). As shown in Table VII, calculated values for the performance index in all test simulation scenarios are quite better when the PSO fuzzy-PI controller is used.

B. Cooperation in Frequency Control

Finally, two scenarios are examined for the secondary frequency control issue. First, the DEG is considered as only responsible unit for frequency control which the results are shown in the previous figures. The impacts of the FC contribution in the secondary frequency control are considered as second scenario. The output of the PSO-fuzzy PI controller is divided between the DEG and the FC units according to their participation factors. The result of this cooperation framework using the proposed intelligent technique is shown in the Fig. 12.

As expected, due to the FC system participation in the secondary frequency control, the initial drop, as well as other frequency deviations is reduced.

C. Discussion

The variability and uncertainty are two major attributes of variable RESs that notably impact on optimum power flow, power quality, voltage and frequency control, system economics, and load dispatch in the MG as well as the main grid. Integration of RESs into MG systems may increase uncertainties during abnormal operation and introduces several technical implications and opens important questions, as to whether the traditional control approaches to operation in the MGs are still adequate. The main question arises is what happens to the frequency regulation requirements in an ac MG if numerous DGs are added.

The present work can be considered as an effort to response above questions. Although, often all types of DGs/RESs are not available in a typical MG, but here to provide a comprehensive case study (Fig. 3) and to analyze the frequency response of various microsources, almost all kind of DGs are considered. It is shown that an effective frequency control (such as PSO-fuzzy PI control) performs a major role in managing short-term fluctuation of variable renewable power. Without intelligent control and regulation systems, it may be very difficult to integrate large number of DGs into the MGs. For this purpose in practice, the intelligent meters, devices, and communication standards should be firstly prepared to enable flexible matching of generation and load.

This work is mainly focused on the frequency regulation problem in the isolated ac MGs from a technical point of view. The key aspect in the present paper is how to handle changes in topology caused by switching in the network and how to make the frequency control system robust and able to take advantage of the potential flexibility of distributed MGs and energy resources. The contribution of DGs in the frequency control task in an ac MG refers to the ability of these units to regulate their power output, either by disconnecting a part of generation or by an appropriate control action.

Further works are needed to address economic, environmental, and other important technical issues for the MGs in both connection and disconnection operating modes. In the following, some of these issues are briefly pointed out:

- As the electric industry seeks to reliably integrate numerous MGs into the bulk power system in new environment, considerable effort will be needed to accommodate and effectively manage these unique operating and planning characteristics. Since the coming power from some DGs/RESs, such as wind turbine is stochastic; still it is difficult to use their kinetic energy storage in frequency control, effectively [6]. Further studies are needed to coordinate the timing and the size of the kinetic energy discharge with the characteristics of other DG units.

- Most significant components in the intelligent frequency control system of the future will thus be systems for metering, controlling, regulating, and monitoring indices, allowing the resources of the MG to be used effectively in terms of both economics and operability. To achieve this vision, the future frequency control systems must include advanced monitoring, processing, communications, and information technology.
- Further study is needed to define new grid codes and standards for contribution of MGs (connected to the main grid) to the overall frequency control as well as other ancillary services, and for investigation of their behavior in case of abnormal operating conditions in electric network. In this respect, reliability-focused equipment standards must be also further developed to facilitate the reliable integration of additional MGs into the bulk power system. From a bulk power system reliability perspective, a set of interconnection procedures and standards are required which applies equally to all MGs interconnecting to the power grid. Finally, frequency performance standards compliance verification remains a major open issue for the MGs in different operation modes.

VII. CONCLUSION

In this paper, following a brief review on Microgrids and their control loops, the reasons for control of these networks are highlighted and some previous achievements are mentioned. An important issue raised in the ac microgrids is frequency regulation in the presence of disturbances, uncertainties, and load changes.

In practice, simple PI controllers are commonly used that provide a poor performance in the presence of serious disturbances. In response to this challenge in the present paper, an adaptive control method is used to control the frequency of an ac microgrid system. This controller has two levels including a classical PI controller and a fuzzy system, which improve 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.

Two scenarios for the secondary frequency control are considered. In the first one, only DEG unit contributed in the frequency control and in the next scenario, both DEG and FC units participated in the secondary frequency control task. The performed simulation tests demonstrate the effectiveness of the proposed PSO-fuzzy PI control technique in comparison of other two design methods.

REFERENCES

[1] C. Chowdhury, S. P. Chowdhury, and P. Crossley, "The institution of engineering and technology," in *Microgrids and Active Distribution Networks*. London, U.K.: Inst. Eng. Technol., 2009.

[2] R. H. Lasseter, A. Akhil, C. Marnay, J. Stephens, J. Dagle, R. Guttromson, A. Meliopoulous, and R. J. Yinger, "The CERTS microgrid concept," White Paper, Transmission Reliability Program, Office of Power Technologies, U.S. Dept. Energy,, Apr. 2002.

[3] R. H. Lasseter, J. H. Eto, B. Schenkman, J. Stevens, H. Vollkommer, D. Klapp, E. Linton, H. Hurtado, and J. Roy, "CERTS microgrid laboratory test bed," *IEEE Trans. Power Del.*, vol. 26, pp. 325–332, Jan. 2011.

[4] H. Camblong, J. Sarr, A. T. Niang, O. Curea, J. A. Alzola, E. H. Sylla, and M. Santos, "Micro-grids project, part 1: Analysis of rural electrification with high content of renewable energy sources in Senegal," *Renewable Energy*, vol. 34, pp. 2141–2150, Oct. 2009.

[5] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay, "Microgrids," *IEEE Power Energy Mag.*, vol. 5, pp. 78–94, Jul.–Aug. 2007.

[6] H. Bevrani and T. Hiyama, *Intelligent Automatic Generation Control*. New York: CRC, Apr. 2011.

[7] N. J. Gil and J. A. P. Lopes, "Hierarchical frequency control scheme for islanded multi-microgrids operation," in *Proc. IEEE Int. Conf. Power Tech, Lausanne*, Jul. 1–5, 2007, pp. 473–478.

[8] C. L. Moreira and J. A. Peças Lopes, "MicroGrids dynamic security assessment," in *Proc. IEEE Int. Conf. Clean Electr. Power*, Capri, May 21–23, 2007, pp. 26–32.

[9] J. Peças Lopes, A. Moreira, and A. G. Madureira, "Defining control strategies for MicroGrids islanded operation," *IEEE Trans. Power Syst.*, vol. 21, pp. 919–920, May 2006.

[10] C. Yuen, A. Oudalov, and A. Timbus, "The provision of frequency control reserves from multiple microgrids," *IEEE Trans. Ind. Electron.*, vol. 58, pp. 173–183, Jan. 2011.

[11] M. Datta, T. Senjyu, A. Yona, T. Funabashi, and C.-H. Kim, "A coordinated control method for leveling PV output power fluctuations of PV-diesel hybrid systems connected to isolated power utility," *IEEE Trans. Energy Convers.*, vol. 24, pp. 153–162, Mar. 2009.

[12] E. Barklund, N. Pogaku, M. Prodanovic, C. Hernandez-Aramburo, and T. C. Green, "Energy management in autonomous microgrid using stability-constrained droop control of inverters," *IEEE Trans. Power Electron.*, vol. 23, pp. 2346–2352, Sep. 2008.

[13] H. Bevrani, A. Ghosh, and G. Ledwich, "Renewable energy sources and frequency regulation: Survey and new perspectives," *IET Renew. Power Gener.*, vol. 4, pp. 438–457, 2010.

[14] P. Kundur, J. Paserba, V. Ajjarapu, Hill, J. Dagle, A. Stankovic, C. Taylor, T. Van Cutsem, and V. Vittal, "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions," *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp. 1387–1401, Aug. 2004.

[15] H. Bevrani, *Robust Power System Frequency Control*. New York: Springer, 2009.

[16] S. Obara, "Analysis of a fuel cell micro-grid with a small-scale wind turbine generator," *Int. J. Hydrogen Energy*, vol. 32, pp. 323–336, Mar. 2007.

[17] D. J. Lee and L. Wang, "Small-signal stability analysis of an autonomous hybrid renewable energy power generation/energy storage system part I: Time-domain simulations," *IEEE Trans. Energy Convers.*, vol. 23, no. 1, pp. 311–320, 2008.

[18] A. Zadeh, "Fyzzy sets," *Inf. Control*, vol. 8, pp. 338–353, 1965.

[19] J. M. Mendel and G. C. Mouzouris, "Designing fuzzy logic systems," *IEEE Trans. Circuits Syst. II, Analog Digit. Signal Process.*, vol. 44, pp. 885–895, Nov. 1997.

[20] H. Bevrani and P. R. Daneshmand, "Fuzzy logic-based load-frequency control concerning high penetration of wind turbines," *IEEE Syst. J.*, vol. 6, pp. 173–180, 2012.

[21] F. Daneshfar and H. Bevrani, "Load-frequency control: A GA-based multi-agent reinforcement learning," *IET Gener., Transm., Distrib.*, vol. 4, pp. 13–26, 2010.

[22] M. Dorigo and T. Stützle, *Ant Colony Optimization*. Cambridge, MA: MIT Press, 2004.

[23] R. C. Eberhart, Y. Shi, and R. Kennedy, *Swarm Intelligence*. San Mateo, CA: Morgan Kaufmann, 2001.

[24] A. Engelbrecht, *Fundamentals of Computational Swarm Intelligence*. Hoboken, NJ: Wiley, 2005.

[25] R. Eberhart and J. Kennedy, "A new optimizer using particle swarm theory," in *Proc. 6th Int Symp. Micro Mach. Hum. Sci. (MHS)*, Oct. 4–6, 1995, pp. 39–43.

[26] J. Kennedy and R. Eberhart, "Particle swarm optimization," in *Proc. IEEE Int. Conf. Neural Netw.*, 1995, pp. 1942–1948.

[27] C. Dong, G. Wang, and Z. Chen, "The inertia weight self-adapting in PSO," in *Proc. 7th World Congr. Intell. Control Autom. (WCICA)*, Jun. 25–27, 2008, pp. 5313–5316.

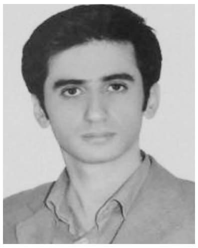
[28] Z. Meijie, L. Hanxing, S. Weiwe, and Z. TongLin, "Improvement of particle swarm optimization based on neighborhood cognizance and swarm decision," presented at the Int. Conf. Wirel. Commun., Netw., Mobile Comput. (WiCom2007), .

Hassan Bevrani (S'90–M'04–SM'08) received the Ph.D. degree in electrical engineering from Osaka University, Osaka, Japan, in 2004.

Since 2000, he has been an Academic Member with the University of Kurdistan, Sanandaj, Iran. From 2004 to 2011, he worked as a Postdoctoral Fellow, Senior Research Fellow, and Visiting Professor with Kumamoto University (Japan), Queensland University of Technology (Australia), and Kyushu Institute of Technology (Japan), respectively. His current research interests include smart grids, intelligent and robust control applications in power systems and power electronic industry.

Farshid Habibi was born in Sanandaj, Iran, in 1985. He received the B.S. and M.S. degrees in electrical engineering from University of Kurdistan, Kurdistan, Iran, in 2009 and 2012, respectively.

Currently, he is working as a Lecturer with the Linear Control Lab at the University of Kurdistan. His research area includes micro/smart grids, power electronic, intelligent/robust control methods, and power system dynamics and operation.



Poya Babahajyani (S'09) was born in Sanandaj, Iran, in 1987. He received the B.Eng. degree in electrical engineering from the University of Kurdistan, Sanandaj, in 2009 and the M.Sc. degree in control from the Isfahan University of Technology, Isfahan, Iran, in 2012.

His research interests include robust and intelligent control and their applications in power electronics and the power system industry.

Masayuki Watanabe (S'03–M'05) received the B.Sc., M.Sc., and Dr.Eng. degrees in electrical engineering from Osaka University, Japan, in 2001, 2002, and 2004, respectively.

Currently, he is an Associate Professor in the Department of Electrical Engineering and Electronics of Kyushu Institute of Technology, Japan. His research interest is in the area of the analysis of power systems.

Yasunori Mitani (M'87) received the B.S., M.S., and Dr.Eng. degrees in electrical engineering from Osaka University, Osaka, Japan, in 1981, 1983, and 1986, respectively.

Currently, he is a Professor in the Department of Electrical, Electronic, and Computer Engineering, Kyushu Institute of Technology, Fukuoka, Japan. He was a Visiting Research Associate at the University of California, Berkeley, from 1994 to 1995. His research interests are in the areas of analysis and control of power systems.