An On-Line PSO-based Fuzzy Logic Tuning Approach: Microgrid Frequency Control Case Study

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Published (to be published) in: International Symposium on Smart Grid Operation and Control (ISSGOC 2012).

(Expected) publication date: 2012

Citation format for published version:

Babahajyani P, Habibi F, and Bevrani H (2012) An On-Line PSO-based Fuzzy Logic Tuning Approach: Microgrid Frequency Control Case Study. in International Symposium on Smart Grid Operation and Control (ISSGOC 2012).

Isolated Microgrid Frequency Control: An Online PSO Based Fuzzy Tuning Approach

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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: **Intelligent control, Fuzzy logic, Particle swarm optimization, Microgrid, Secondary frequency control, Optimal tuning.**

I. INTRODUCTION

THE increasing need for electrical power has made several uncommon sources enter into the power systems which increase 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 properly along with the conventional generation units or not.

Some technical problems caused by the RESs are 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 a 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 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].

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. For increasing reliability in the conventional power systems, the MG systems must be able to have proper performance in the both connected and disconnected modes. In the 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 the disconnected mode, the MG is responsible for maintaining the local loads and keeping the frequency and voltage indices at specified nominal values [1, 3, 4].

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 [5] and the Kythnos Island MG in Greece [4]. In the presence of MGs beside common generation units in the 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

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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 [6-9]. 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 [10]. In the decentralized method, each DG is equipped by a local controller so needs local feedback control signal [2, 10, 11].

The control units and their associated tuning methods for modern MG systems, which should handle complex multi-objective 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. 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. As described in [12], frequency stability in a power system means preserving steady frequency following a heavy disturbance with minimum loss in loads and generation units.

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 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 on-line measurements. In order to obtain an optimal performance, the PSO technique is used on-line to determine the membership functions' parameters. The proposed optimal tuning scheme offers many benefits for a 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.

This paper organized as follows: In Section II, an isolated ac MG system is introduced as case study. Conventional PI, pure fuzzy PI and the proposed PSO fuzzy PI control designs are addressed in Section III. Several simulations for studding the performance of the applied algorithm and the results are presented in Section IV. Finally, in section V, the conclusions are presented.

II. CASE STUDY

Generally, there are many cases that the control plans for MG systems in the 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. 1. 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. 1, 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 it is sufficient for frequency studies [13].

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. For easily understanding of the MG frequency response, a simplified frequency response model is given in Fig. 2. The MG parameters are given in the Table 1.

This model can be useful to analysis/demonstrate frequency behavior of the case study. Since, the most of energy sources have intermittent nature with considerable uncertainty and fluctuation in the power system, efficient control methods must be employed to decrease the undesirable dynamic impacts.

III. CONVENTIONAL, FUZZY PI AND PSO-FUZZY PI FREQUENCY CONTROL

In traditional power systems, the secondary frequency control is mostly done by conventional PI controllers that are usually tuned based on the specified 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 able to track the changes occurred in the power system, the optimum performance will be always achieved.

TABLE I
Parameters of the MG case study.

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

Nowadays, fuzzy logic because of simplicity, robustness and reliability is used in almost all fields of science and technology, including solving a wide range of optimization and control problems in power system control and operation. Unlike the traditional control theorems, which are essentially based on the linearized mathematical models of the controlled systems, the fuzzy control methodology tries to establish the controller directly based on the measurements, long-term experiences and the knowledge of domain experts/operators.

There are several possible fuzzy logic control structures for the control design in power systems, some differing 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. In fact, it is up to the designer to decide which controller structure would be optimal for the controller synthesis problem. The applications of fuzzy logic in control systems can be classified into two main categories: *i*) using fuzzy logic system as a dynamic controller, *ii*) using fuzzy logic alone or together with another intelligent/searching algorithm as a primer for tuning the gains of the existing PI (or PID) controller. Different types of adaptive fuzzy logic controller can be found in [14-17]. Here, in order to control of Microgrid system frequency, second category has been used.

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

A comprehensive study on classical PI/PID tuning methods like Ziegler–Nichols have been presented in [18]. Using the Ziegler–Nichols method, the PI parameters are obtained as given in Table 2.

As described before, for achieving better performance, the fuzzy logic is used as an intelligent method. The fuzzy logic is able to respond to the inability of the classic control theory for covering the complex system with their uncertainties and inaccuracies.

The control framework for application of fuzzy logic system as an intelligent unit for fine tuning of traditional PI controller is shown in Fig. 3. The fuzzy PI controller has two levels which the first one is a traditional PI controller and the second one is a fuzzy system. As shown, 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 the PI control parameters, 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 set of the fuzzy rules are given in the Table 3 where membership functions corresponding to the input and output variables are arranged as Negative Large (NL), Negative Medium (NM), Negative Small (NS), Positive Small (PS), Positive Medium (PM), and Positive Large (PL). They have been arranged based on triangular membership function that is the most traditional 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 IV, the fuzzy PI controller has proper performance in comparison with the classical method, but its performance depends highly 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.

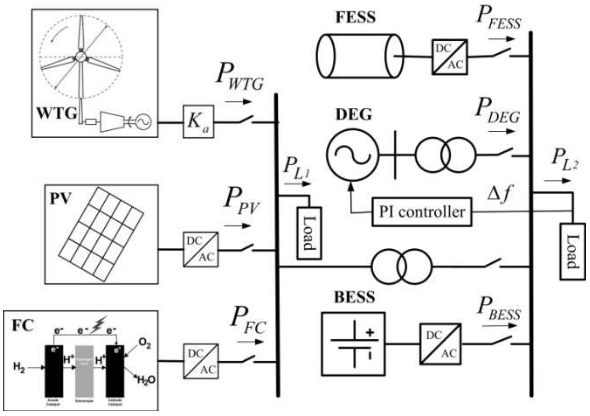


Fig. 1. Single-line diagram of the ac MG case study

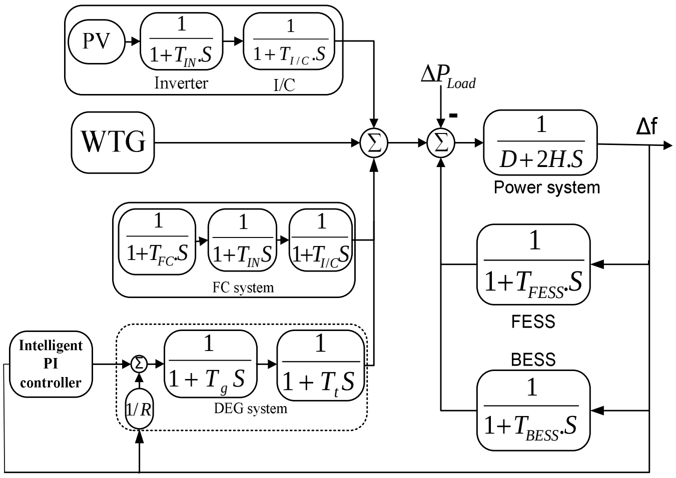


Fig . 2. Simplified ac MG frequency response model

TABLE II

PI control parameters using the Ziegler–Nichols method.

Controller parameter	Value
K_P	4.095
K_I	21.84

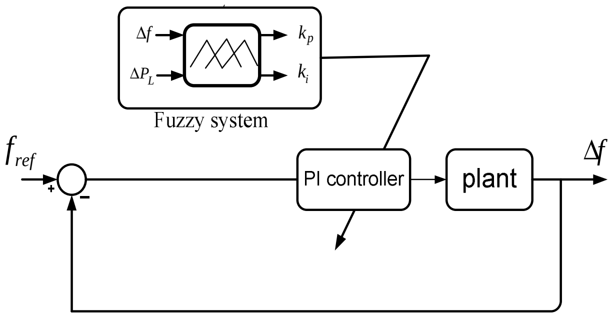


Fig . 3. Fuzzy PI based secondary frequency control.

TABLE III
The fuzzy rules set

Δf	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

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.

The optimal performance of a fuzzy system is highly related to the parameters of membership functions. There are several approaches toward the membership function adjustment such as trial and error which is a slow method and, online regulating membership function method that uses complementary intelligent optimizations. In this paper, for online tuning of membership functions employed in the fuzzy PI controller, the particle swarm optimization (PSO) is used.

The PSO algorithm is an optimization technique based on the probability laws, which inspired from the natural models. This algorithm is classified as direct search methods and is used to find the best response of the optimization problems in a given search space [19 -21].

According to the above discussion, what this research investigates is designing an on-line 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. 4.

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 will be stopped in the local extremum points.

IV. SIMULATION RESULTS

For comparing the classical, fuzzy PI and the 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. 5a. 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. 5b.

Δf , and ΔP_L are MG frequency deviation, and load disturbance, respectively; which their values are given in $p.u.$ As shown, the proposed optimal PSO fuzzy PI controller regulates the system frequency following the incoming disturbance quite better than the pure fuzzy PI and classical PI controllers.

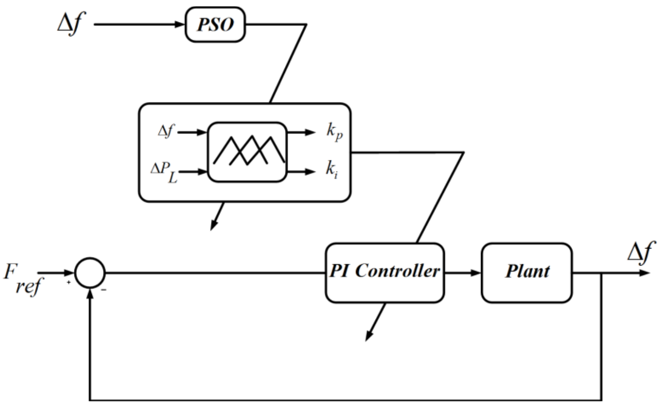
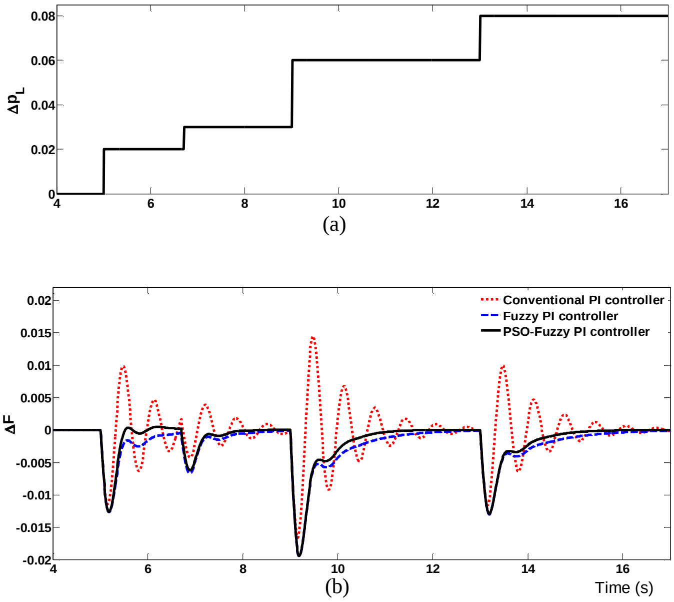


Fig. 4. Closed-loop system with PSO-fuzzy PI controller

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 power system parameters, in the frequency response model (Fig. 2) are significantly changed according to Tables 4 and 5.

The closed-loop frequency response after applying these changes to the MG system parameters, are shown in Fig. 6 and Fig. 7, respectively. Fig. 6 showa that the conventional controller cannot handle the applied parameters perturbation. From Fig. 7, it can be seen that difference between the proposed optimal PSO-fuzzy PI controller with other two controllers is more significant for a higher range of parameter variation.



(a)

(b)

Fig. 5. a) Multiple step load disturbances, b) MG frequency response.

TABLE V
Uncertain parameters and variation range

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

TABLE IV
Uncertain parameters and variation range

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

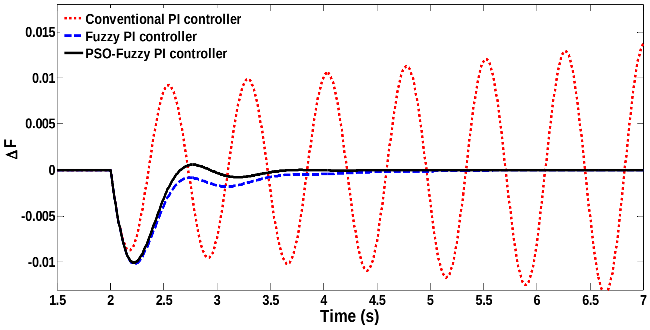


Fig. 6. Frequency response according to the parameters changes shown in Table 4.

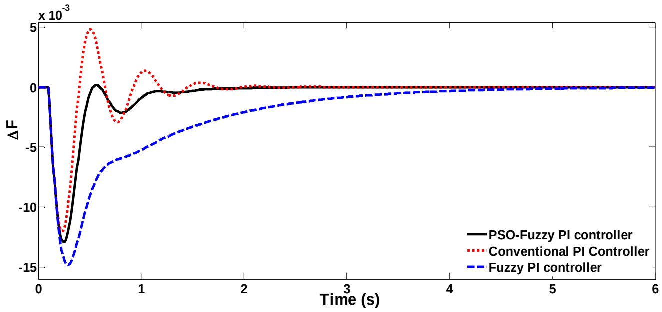


Fig. 7. Frequency response according to the parameters changes shown in Table 5.

V. 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 problem 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 during the simulation time. Because of severe dependence of the fuzzy systems on their membership functions, particle swarm optimization algorithm is used to improve the membership function parameters.

The performed simulation tests demonstrate the effectiveness of the proposed PSO-fuzzy PI control technique in comparison with two other design methods.

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Symposium on Smart Grid Operation and Control

ISSGOC 2012

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Pooya Babahajyani

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**“Isolated Microgrid Frequency Control:
An Online PSO Based
Fuzzy Tuning Approach”**

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