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Energy Management System Based on Fuzzy fractional order PID Controller for Transient Stability Improvement in Microgrids with Energy Storage

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Abstract

The need to reduce greenhouse effect using distributed energy resources (DER) has significantly increased in recent years, particularly with the advent of deregulated market. Climate changes causes large swings in output power of renewable resources and the resulting fluctuations in frequency in the islanded Microgrid (MG). To increase performance for a wide range of power system operating conditions, an energy management systems (EMS) is proposed based on a fuzzy fractional order PID (FFOPID) controller. It is able to analyze and simulate the dynamic behavior in grid connected MGs. This controller is proposed in the MG encompassing distributed generation resources with "plug and play" ability. The performance of FFOPID controller is verified for frequency control purposes and to support internal bus voltage in both islanded and grid connected operating modes in accordance with the failure time. Energy storage (ES) is used to improve the system dynamic response, reduce the distortion and provide damping for frequency oscillations caused by renewable resources. ES overload capacity is utilized for rapid initial control of frequency in MG. To achieve this goal, EMS based on fuzzy decision mechanism combined with a PID-controller (termed as FLPID) and Fuzzy fractional order PID (termed as FFOPID) are implemented according to the characteristics and limitations of overloading and state of charge (SOC). The obtained results show good performance of FFOPID controllers by improving the transient stability following a fault that has caused the islanded operation. Simulation results have validated the effectiveness of FFOPID controllers in the system under several scenarios with superior stabilization and more robustness in comparison with the FLPID and PID controller.

Keywords: Fuzzy Logic Control, Fuzzy Fractional Order PID, power-frequency control, Microgrid, energy storage resources, energy management system

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1. Introduction

In the distribution grid and Microgrids (MG), it is required to stay stable at approximately constant frequency range and to eliminate the effect of any each type of transient load [1, 2]. This responsibility must be performed by an adequate controller [3]. Power-frequency control has been designed for supplying electric power with adequate quality. The load variations are unavoidable, so, proper control for maintaining generation-consumption equilibrium as well as ensuring frequency and transient stability is of great importance [4]. To provide acceptable power quality in MG, it is necessary to maintain frequency at predetermined certain range at fault conditions and or load variations [4–8].

In the MGs, by keeping the frequency in the allowable limit, each unit generation has also been controlled. This fact requires the control of power generation according to load variations. In some of the papers [9] classic PID controllers have been used. The main disadvantage of such controllers is constant integral term. In other word, it is not possible to change the value of this term according to the grid conditions [10]. But, by using fuzzy controllers including fuzzy fractional order controller, the integral term can be changed in a predetermined range to enhance the MG performance.

Some control design techniques have already been proposed for solving the challenge of maintaining the generation-consumption equilibrium in the MG [9, 10]. These works have used PD, PI, PID controllers [9], optimal control [11], variable structure control [12], adaptive controllers [13] and artificial intelligence based controller [14]. In [15, 16] fuzzy-neural control strategy has been proposed because of the MG random and non-linear behaviour. Since there is no need for energy storage devices and load control strategies, this strategy is economically efficient and applicable for each type of DG unit [10, 15, 16].

Optimization techniques such as PSO have been applied for setting the classic controllers coefficients accurately [17]. Controlling the variable structure for improving the MG stability and maintaining the frequency range, has been used by the genetic algorithm. Other control methods such as sliding mode control technique have also been applied for this purpose [15, 16]. During recent years, fractional order fuzzy algorithm has been used for reaching specified control design capability. This controller has been introduced as a control with very effective algorithm in the performance of the grids under noise. In this paper, a frequency control method for improving the MG transient stability by maintaining the generation and consumption equilibrium in the energy management system has been presented based on the fractional order control concept. Accordingly, the contributions of this paper are as follows:

1. The proper performance of the proposed controller to improve MG stability and fix the fault occurred to the EMS system based on a classic controller and fuzzy PID;
2. The proposed controller superior stabilization under several disturbances in the system under different applied scenarios;
3. Improving the dynamic response of the system to reduce the frequency deviation and oscillation resulting from changes in renewable resources;
4. MG frequency control to improve transient stability by maintaining the balance between production and consumption in energy management system

2. Proposed bi-level structure

The proposed bi-level structure is presented in Figure 1 for reaching the stated goals and the frequency-power control. The design of energy management system is implemented at primary level in the MG. In this level, the master and slave control strategy is modelled along with the mathematical arrangement of the system under study. PID controllers, fuzzy logic PID (FLPID) and fuzzy fractional order PID (FFOPID) are designed at secondary level. The mentionable point is that PID controller design at this level is performed by using Zigler-Nichols method [4]. Creating fuzzy adjustments, building membership function, using adequate conclusion machine and controller fuzzy making and defuzzy making stages are occurred in the FLPID controller design section. The quality of updating PID coefficients by the fuzzy controller, determining the criteria function IAE and ISE and determining the order of the proposed controller operator are explained by the PSO algorithm in the FFOPID design section. For validating the applied controller′s ability, scenarios have been applied for analysis and comparing the controllers and also the analysis of the obtained output results caused by this scenario, have been analysed and investigated. In the following paragraphs implementation of each one of the levels and also the objectives followed by them has been explained in detail.

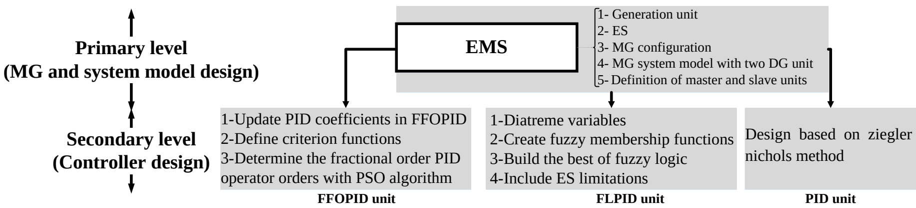


Figure 1: Proposed bi-level structure for the energy management system for the improvement of the transit stability of the MG under study

3. MG system modeling

The MG considered in this study comprises wind turbine (WT), micro-turbine (MT) and energy storage (ES) resources [18–23]. In this section, MG structure and its mathematical model are presented. MG systems include different arrays like parallel, convoluted and radial configurations.In parallel configuration, DG units including master and slave are connected together at PCC, as is shown in Figure 2. When the key S is closed, the MG is operating in grid-connected mode. In this case, the voltage and frequency of MG system is supplied by the network and all DG units control active power only. On occurrence of a fault in the MG, the master DG unit changes the controlling mechanism so as to continue appropriate performance and performing voltage regression and system frequency. For the studied system, the DG unit is considered the master and other resources as slaves. The single-line diagram of an MG with two DG units is shown in Figure 3.

The equations of the system in abc frame are as follows:

$$i_{t1,abc} + i_{t2,abc} = \frac{V_{abc}}{R} + i_{L,abc} + C \cdot \frac{dv_{abc}}{dt} \quad (1)$$

$$V_{t1,abc} = L_{t1} \cdot \frac{di_{t1,abc}}{dt} + R_{t1} \cdot i_{t1,abc} + V_{abc} \quad (2)$$

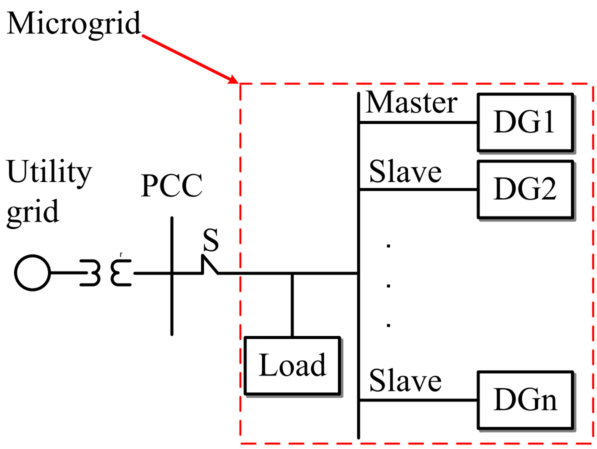


Figure 2: MG system with parallel connection of several DG units

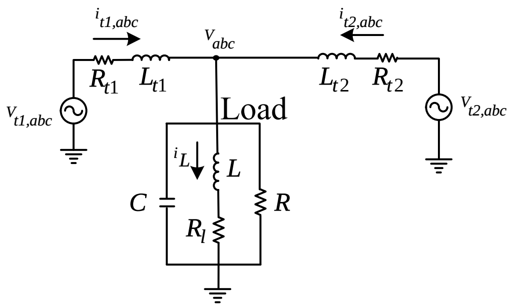


Figure 3: Circuit model of MG systems with distributed generation units

$$V_{t2,abc} = L_{t2} \cdot \frac{di_{t2,abc}}{dt} + R_{t2} \cdot i_{t2,abc} + V_{abc} \tag{3}$$

$$V_{abc} = L \cdot \frac{di_{L,abc}}{dt} + R_l i_{L,abc} \tag{4}$$

In Eqs. 1- 4, X_{abc} refers to voltage or current vector in $R^{3\times1}$ space. Their components are expressed as X quantity of each abc phase in three phase systems. In a balanced three-phase system, $X_a + X_b + X_c = 0$. This equation is for a three-phase system and applying two independent variable is sufficient to explain quantity of X_{abc}, which is equal to $[X_a \, X_b \, X_c]^T$. On the other hand, the below equation is used to transform the relation from abc coordinate to $\alpha\beta$ frame:

$$X_{\alpha\beta} = \frac{2}{3} \begin{pmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{3} \end{pmatrix} \begin{pmatrix} X_a \\ X_b \\ X_c \end{pmatrix} \tag{5}$$

According to equations 5 and 4, dynamic equations of system are achieved as:

$$\frac{dv_{\alpha\beta}}{dt} = -\frac{1}{RC} v_{\alpha\beta} + \frac{1}{c} i_{t1,\alpha\beta} - \frac{1}{c} i_{L,\alpha\beta} + \frac{1}{c} i_{t2,\alpha\beta} \tag{6}$$

$$\frac{di_{t1,\alpha\beta}}{dt} = -\frac{1}{L_{t1}}v_{\alpha\beta} - \frac{R_{t1}}{L_{t1}}i_{t1,\alpha\beta} + \frac{1}{L_{t1}}V_{t1,\alpha\beta} \tag{7}$$

$$\frac{di_{L,\alpha\beta}}{dt} = \frac{1}{L}v_{\alpha\beta} - \frac{R_l}{L}i_{L,\alpha\beta} \tag{8}$$

$$\frac{di_{t2,\alpha\beta}}{dt} = -\frac{1}{L_{t2}}v_{\alpha\beta} - \frac{R_{t2}}{L_{t2}}i_{t2,\alpha\beta} + \frac{1}{L_{t2}}v_{t2,\alpha\beta} \tag{9}$$

The system could be transformed from $\alpha\beta$ frame to dq coordinate by:

$$X_{\alpha\beta} = X_\alpha + jX_\beta = X_d q e^{j\theta} = (X_d + jXq)e^{j\theta} \tag{10}$$

$$\theta(t) = \int_0^t \omega\eta \, d\eta + \theta_0 \tag{11}$$

where ω is the network frequency. By substituting Eq. 10 in Eq. 9, the system equations in dq frame are achieved as:

$$\frac{dv_{dq}}{dt} + j\omega_0 v_{dq} = \frac{-1}{RC}v_{dq} + \frac{1}{C}i_{t1,dq} - \frac{1}{C}i_{L,dq} + \frac{1}{C}i_{t2,dq} \tag{12}$$

$$\frac{dI_{t1,dq}}{dt} + j\omega_0 I_{t1,dq} = -\frac{1}{L_{t1}}v_{dq} + \frac{R_{t1}}{L_{t1}}i_{t1,dq} + \frac{1}{L_{t1}}V_{t1,dq} \tag{13}$$

$$\frac{dI_{L,dq}}{dt} + j\omega_0 I_{L,dq} = \frac{1}{L}v_{dq} - \frac{R_l}{L}i_{L,dq}\frac{1}{L}v_{t2,dq} \tag{14}$$

$$\frac{dI_{t2,dq}}{dt} + j\omega_0 I_{t2,dq} = -\frac{1}{L_{t2}}v_{dq} - \frac{R_{t2}}{L_{t2}}i_{t2,dq} + \frac{1}{L_{t2}}v_{t2,dq} \tag{15}$$

Separating the real and imaginary parts in Eq. 14, the dynamic equations of a system are achieved in dq frame:

$$\frac{dv_q}{dt} = -\omega_0 v_d - \frac{1}{RC}v_q + \frac{1}{c}i_{t1,q} - \frac{1}{c}i_{L,q} + \frac{1}{c}i_{t2,q} \tag{16}$$

$$\frac{di_{t1,d}}{dt} = -\frac{1}{L}v_d - \frac{R}{L}i_{t1,d} + \omega_0 i_{t1,q} + \frac{1}{l}i_{t1,d} \tag{17}$$

$$\frac{di_{L,d}}{dt} = \frac{1}{L}v_d + \omega_0 I_{l,q} - \frac{R}{L}i_{L,d} \tag{18}$$

$$\frac{di_{t1,q}}{dt} = -\frac{1}{L}v_q - \omega_0 I_{t1,d} - \frac{R}{L}i_{t1,d} + \frac{1}{L}v_{t1,d} \tag{19}$$

$$\frac{di_{L,q}}{dt} = \frac{1}{L}v_q - \frac{R}{L}i_{L,q} + \omega_0 i_{L,d} \tag{20}$$

$$\frac{dI_{t2,d}}{dt} = -\frac{1}{L}v_d + \omega_0 I_{t2,q} - \frac{R}{L}i_{t2,d} + \frac{1}{L}i_{t2,d} \tag{21}$$

$$\frac{dI_{t2,q}}{dt} = -\frac{1}{L}v_q - \omega_0 i_{t2,q} - \frac{R}{L}i_{t2,q} + \frac{1}{L}v_{t2,q} \tag{22}$$

The generalized state-space form defined in rotating frame is presented as follows:

$$\dot{x} = Ax + Bu \tag{23}$$

$$y = Cx \tag{24}$$

Where the inputs, outputs and state variables of the system are respectively given by

$$X = [V_d\ V_q\ I_{t1,d}\ I_{t1,q}\ I_{L,d}\ I_{L,q}\ I_{t2,d}\ I_{t2,q}]^T \tag{25}$$

$$u = [V_{t1,d}\ V_{t1,q}\ V_{t2,d}\ V_{t2,q}]^T \tag{26}$$

$$y = [V_d\ V_q\ I_{t2,d}\ I_{t2,q}]^T \tag{27}$$

The MG system has four inputs, four outputs and eight state variables. Represented model could be generalized to a MG with n number of DG.

4. Fuzzy logic PID (FL-PID) controller

A fuzzy logic controller to control the load-frequency of the MG system is proposed in this paper. The main purpose of controlling time-frequency, the balance between production and consumption frequency. Vector control for the PID controller can be calculated from the following equation:

$$U_{PID} = K_p \Delta_f + \int K_i \cdot \Delta_p dt + K_d \frac{df}{dt} \tag{28}$$

Simulation studies used in power system show that the conventional PID controller has large over shoot and long settling time [24]. Also, the time of control parameter optimization in classical PID controller is long and the control parameters cannot be precisely determined.

The controller designed based on fuzzy logic (as shown in Figure 4) for system under study is involved the following four main steps.

Step 1 Define the states and input/output control variables and their variation ranges (understanding of the system dynamic behavior);

Step 2 Create the degree of fuzzy membership function and complete fuzzification (identify appropriate fuzzy sets and membership functions);

Step 3 Decide how the action will be executed by assigning strengths to the rules (define a suitable inference engine);

Step 4 Combine the rules and defuzzify the output (determine defuzzification method).

The input signals to the fuzzy variables Δf and ΔP triangular membership functions is converted. Terms of settings includes: m (high), ml (intermediate), l (small). These settings are applied uniformly to achieve better accuracy in terms of transient and steady performance. Phase optimization of fuzzy variables and fuzzy (fuzzification) is generated by a set of rules of inference. The machine control rules are listed in Table 1. To achieve optimal evaluation of the output signal, a fuzzy control method works as follows:

1. Using membership functions to represent the fuzzy inputs stabilizer;

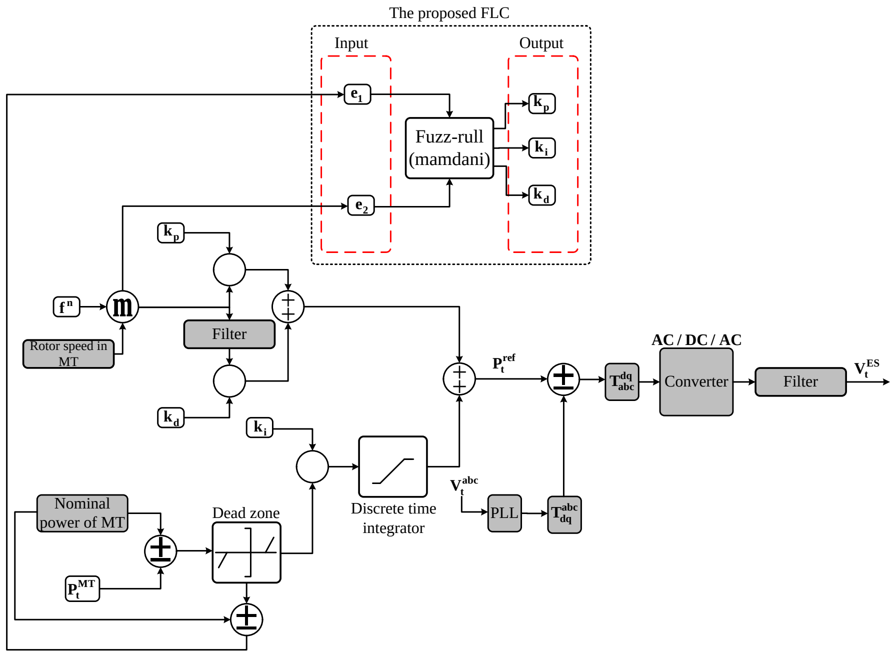


Figure 4: The proposed FLPID controller

2. Setting the output membership function.

As shown in Figure 4, the fuzzy controller has five blocks (two inputs and three outputs). Input information is converted to controlling region by the fuzzification block. While the independent input variables determine comparison needs to have better performance, the inference mechanism determines fuzzy logic performance and the output of each regulation using IF-THEN rules. In this study, the Mamdani fuzzy inference machine was used to control the proposed fuzzy logic and range of controller is selected separately in order to improve system power.

Frequency error is estimated by difference of nominal frequency with MT rotor speed. In order to control system power, power error is estimated by difference of nominal power with real amount of mechanical power. The inputs and output are brought into an acceptable range by multiplying in proper gains. Power and frequency deviation from the nominal value used as inputs to the proposed controller. P_{ref} is also obtained according to the process depicted in Figure 4. By use of phase locked loop (PLL) and abc to odq transformation, three-phase grid voltage is converted to P_{ref}. Finally, by converting dqo to abc, reference voltage (V_{ref}) is generated and fed into pulse width modulation (PWM) block with a carrier frequency of 5000 Hz, and is used to generate the firing pulses for power switches of the inverter. A filter is used to remove inverter switching harmonics and finally, filter output enter to ES. Regulations which are related to membership functions are estimated in same methods for each fuzzy logic controller. For example, if error (e) is bigger than setting amount, it is expected that output of controller become big. So, output will be very close to a predefined expected amount. Other fuzzy rules are considered in Tables 1 and 2. As seen in Table 1, The rule base works on vectors composed of frequency gradient (ΔF) and $\frac{\Delta F}{\Delta P}$. Fuzzy logic controller

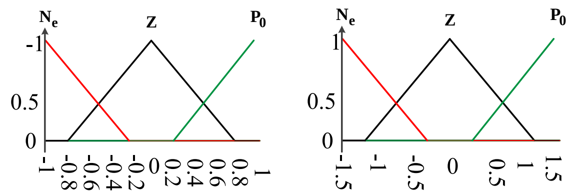
Table 1: Fuzzy logic-based rules for the proposed controller

$\frac{\Delta F}{\Delta P}$		N_e			ΔF Z			P_0		
		k_p	K_i	K_d	K_p	K_i	K_d	K_p	K_i	K_d
	N_e	m	m	1	m	ml	1	ml	ml	ml
ΔP	Z	1	1	ml	1	1	1	ml	ml	1
	Po	ml	ml	ml	m	ml	m	ml	m	m

Table 2: Fuzzy logic-based rules for K_p, K_i and K_d

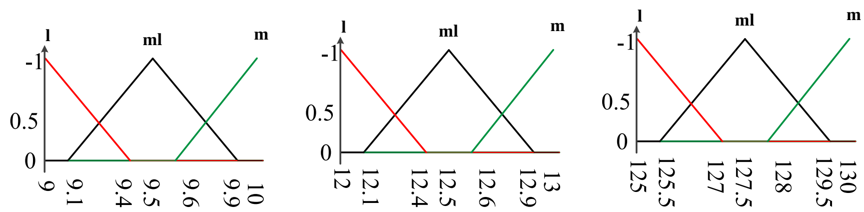
$\frac{\Delta F}{\Delta P}$	K_i			K_p			K_d		
	N_e	Z	P_0	N_e	Z	P_0	N_e	Z	P_0
N_e	m	ml	ml	m	m	ml	1	1	ml
Z	1	1	ml	1	1	ml	ml	1	1
Po	ml	ml	m	ml	m	ml	ml	m	m

as shown in Figures 5 and 6 includes two input membership function and three output memberships.



(a) Frequency error (b) Power error

Figure 5: Symmetric fuzzy membership functions for inputs



(a) k_i (b) k_d (c) k_p

Figure 6: Fuzzy memberships function for outputs

The power error and frequency error in the proposed controller is estimated by

$$e_p = P_{MT} - P_0 \tag{29}$$

$$e_f = f_{Nominal} - F_0 \tag{30}$$

System stability in terms of MT deviation (termed as error e) and MT power is measured in order to design the controller. Proposed fuzzy controller used of same principles and controlling signals. A combined system controller FL-PID is proposed in order to provide frequency control and support internal bus voltage during internal disturbances. Whenever a fault or power interruption occurs in the system, the controller supplies the load through ES injected power. In this study, the efficiency indicator, P_{index}, based on frequency deviation is determined to explain the effectiveness of controller by

$$P_{index} = \int_0^T \mid \Delta F \mid \, dt \tag{31}$$

where ΔF is the absolute deviation of the system frequency and T is the simulation time.

5. Fuzzy fractional order PID (FFOPID)controller

In the controllers fuzzy fractional order PID (FFOPID), the operators I and D are of fractional degree. So, by controlling the integrating fractional degree and differentiating fractional degree two more degrees of freedom will be added to the variables K_p, K_i and K_d which of these two variables, one is for the integrating fractional order λ and the other is for the μ differentiator. The controlling transfer function FOPID can be written as follows: [25]

$$C(S) = K_p + \frac{K_i}{s^{\lambda}} + K_d S^{\mu} \tag{32}$$

FFOPID control signal is as follows in the time domain:

$$u(t) = (K_p + K_i D^{-\lambda} + K_d D^{\mu})e(t) \tag{33}$$

Figure 7 demonstrates the FFOPID controller and describes how the integrating and differentiator orders can be variable along the vertical and horizontal axes. If $\lambda = 1$ and $\mu = 1$ states normal PID controllers. When $\lambda = 1$ and $\mu = 0$ controller PI can be obtained. If $\lambda = 0$ and $\mu = 1$ PD controller is obtained. When the values of λ and μ are the integer values of zero or one, they form the PI, PD and PID normal controllers which are considered special cases of fractional order FFOPID.

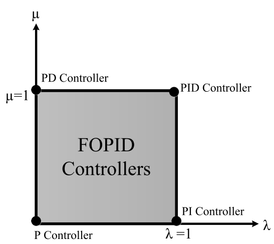


Figure 7: PID figure of fractional and classic order

6. Fuzzy fractional order PID (FFOPID) controller unit implementation

In FFOPID, parameters such as K_p, K_i, K_d, and λ must be adjusted. In this unit, the PID coefficients are updated adaptively by the fuzzy controller and the operators fractional order has been adjusted with the PSO optimization algorithm. Frequency error and power error have been considered as fuzzy controller input and its output are the FFOPID coefficients which enter the FFOPID controller. On

Table 3: Fuzzy rules for K_p

k_p / $\frac{\Delta f}{\Delta p}$	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	ZO
NS	PM	PM	[illegible]	[illegible]	ZO	ZO	NS
ZO	PM	PM	[illegible]	[illegible]	NS	NS	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	[illegible]	NM	NM	NB
PB	ZO	ZO	NM	[illegible]	NM	NB	NB

NB: Negative Big, NM: Negative Medium, NS: Negative Small, ZO: Zero, PS: Positive Small, PM: Positive Medium, PB: Positive Big.

the other hand, for [illegible] order [illegible] operator, a crit[illegible]ction has been defined regard[illegible]ng e[illegible] to the PSO algorithm. Then by minimizing this cost function, it will find the best orders of operator which will have desired performance. At the end, by setting these coefficients, the created control signal is sent to the resources and it will continue until the error is less than threshold (here zero). Figure 8 shows an outline of the implemented FFOPID controllers.

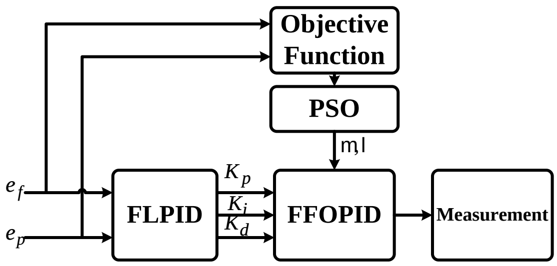


Figure 8: Structure of a FFOPID controller

In this system min-max field fuzzy min-max deduction has been used. Also for defuzzying it gravity centre method has been used. The inputs of fuzzy controller are frequency error and power error which each one of them are respectively located in the limits [-1,1] and [-1.5,1.5]. Three outputs have been considered for this controller. Also for all the inputs and outputs, 7 membership function has been selected with triangular shape which their range have been respectively considered as $K_p = [125, 130], K_i = [9, 10], K_d = [12, 13]$. Because of selecting 7 numbers membership functions, the number of regulations which have been written for this system, are 49 regulations which each one of them follow the IF-THEN condition. Settings of the regulations have monotonously been used for achieving better accuracy at transient and steady conditions. In the tables (1,2,3,4,5) the regulations related to the coefficients FLPID and FFOPID have been shown.

The membership function FFOPID has been shown in Figures 9 and 10 for the inputs and outputs of the controllers.

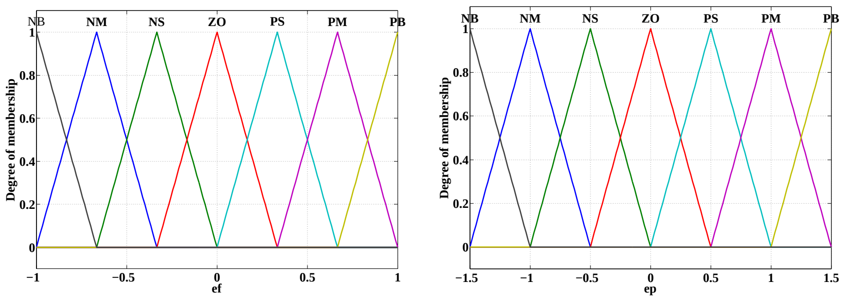
The selected criterion function includes integral of absolute error-IAE and integral of square error- ISE which have been presented in the Eqs 34 and 35. The criterion function F has been minimized by the PSO optimization algorithm. The main motivation of applying these functions, is minimizing the effects of the error and the power variations.

Table 4: Fuzzy rules for K_i

k_i		Δ_f						
	$\frac{\Delta f}{\Delta p}$	**NB**	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
	NB	NB	NB	NM	NM	NS	ZO	ZO
	NM	NB	NB	NM	NS	NS	ZO	ZO
	NS	NB	NM	NS	NS	ZO	PS	PS
Δp	ZO	NM	NM	NS	ZO	PS	PM	PM
	PS	NM	NS	ZO	PS	PS	PM	PB
	PM	ZO	ZO	PS	PS	PM	PB	PB
	PB	ZO	ZO	PS	PM	PM	PB	PB

Table 5: Fuzzy rules for K_d

k_d		Δ_f						
	$\frac{\Delta f}{\Delta p}$	**NB**	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
	NB	PS	NS	NB	NB	NB	NM	PS
	NM	PS	NS	NB	NB	NB	NM	PS
	NS	ZO	NS	NM	NM	NS	NS	ZO
Δp	ZO	ZO	NS	NS	NS	NS	NS	ZO
	PS	ZO	ZO	ZO	ZO	ZO	ZO	ZO
	PM	PB	NS	PS	PS	PS	PS	PB
	PB	PB	PM	PM	PM	PS	PS	PB



(a) Frequency error

(b) Power error

Figure 9: Fuzzy membership functions for the inputs

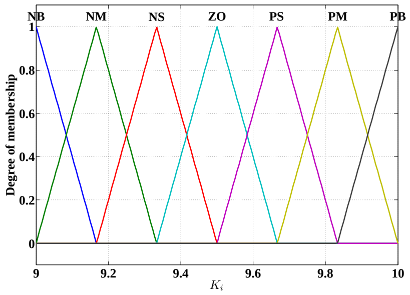
$$f_1 = IAE = \int | e_f | \, dt + \int | e_p | \, dt \tag{34}$$

$$f_2 = ISE = \int | e_f^2 | \, dt + \int | e_p^2 | \, dt \tag{35}$$

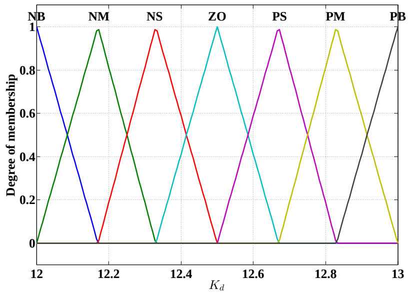
$$F = w_1 f_1 + w_2 f_2 \tag{36}$$

where e_f is frequency error, e_p is power error and also w_1 and w_2 are respectively, weights allocated to f_1 and f_2 which their values for each one of them have been selected equal to 0.5. The controller coefficients in the controllers PID, FLPID and FFOPID have been presented in Table 6.

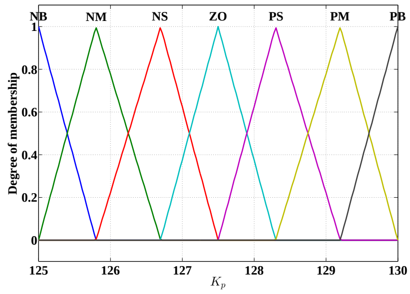
Once the FLPID controller results are obtained, the values of λ and μ have been considered equal to 1 and for obtaining the results FFOPID, the values of parameters λ and μ are obtained with the PSO algorithm and the results of minimization of objective functions in Table 7 have been presented for 50 iterations and number of 25 initial populations. PSO algorithm is presented in Algorithm 1 in order to find the optimal coefficient for FFOPID controller.



(a) K_i variable



(b) K_d variable



(c) K_p variable

Figure 10: outputs of fuzzy membership functions

Table 6: set values for the PID, FLPID and FFOPID controller coefficients

Controller	PID	FLPID	FFOPID
K_p	125	125.9208	125.9092
K_i	9	9.3584	9.4816
K_d	12	12.6151	12.7144
μ	-	1	0.893122
λ	-	1	0.819054

7. MG case study

The system structure of the case study MG, which includes: wind turbine (WT), energy storage (ES), diesel operated microturbine (MT) and loads coupled to the utility grid is shown in Figure 11. Generally speaking, the simulation system has two parts, the AC three-phase and DC parts which are centrally controlled by a power controller.

Assuming the system is in operation and a fault occurs on the grid system, the MG goes to islanded mode by the power switch. When there is excess or shortage of power is in the AC part, amount of P_{ref} is compared with this power. In this direction, switching is done from AC to DC or vice versa by ES. ES is able to save energy (during excess of production) and energy production resource (during power

Table 7: Comparison of the controllers performance with the specified criteria functions

Controller	ISE	IAE	Best cost
FLPID	4.7223	4.6196	4.67095
FFOPID	2.9593	2.2732	2.616277

Algorithm 1 PSO ALGORITHM FOR FFOPID CONTROLLER

Require: specifying criteria functions (IAE and ISE)

Set *the number of parameters μ and λ, min/max range of μ, Λ and particles velocity, PSO parameters and the constraints handled*

1. Create the best present position;
2. Repeat the initial position;
3. Update velocity;
4. Determine velocity boundaries;
5. Update positions;
6. Determine position boundaries;
7. Update best local particle.

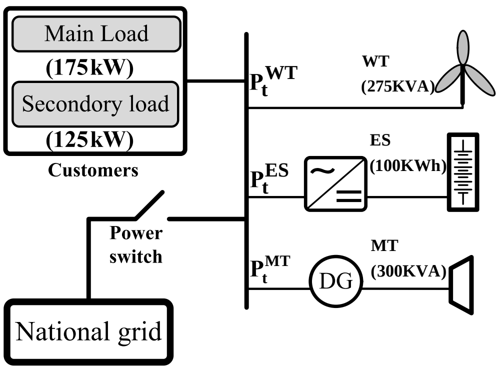


Figure 11: Outline of case study grid connected MG

shortage) in the system. The second load is used to show accurate performance of control and energy storage systems in transferring power in AC and DC forms. Two scenarios are considered in this study:

1. Scenario ♯1: fault occurring at system and system islanding;
2. Scenario ♯2: load changing at time period of system performance.

8. Simulation results

MG stimulation results have been considered for the conventional PID as well as for FLPID and FFOPID controllers. The effectiveness of the Three controllers is measured using overshoot and settling time of the responses.

8.1. The grid-connected operating mode

In this case, MG system power and frequency are controlled by main network and all DG units can be exchanged active power with the network.

8.2. The islanding operating mode (scenario ♯1)

A three-phase fault was initiated on the utility grid at t=3s. This fault results in the islanding operation of the MG by disconnecting from the utility grid. Clearing of the fault was achieved by opening the circuit breaker after 5 cycles. The frequency deviation due to the sudden change in the loading condition during islanding of the system is shown in Figure 12. FFOPID controller was applied and its performance based on energy storage shows appropriate responses to the mentioned criteria. The results show that FFOPID is able to reduce the fluctuation and improve the transient stability. Before the fault occurrence (t=3s), MG is operating under a certain voltage and frequency in the predefined range in order to maintain a balance between production and consumption. After fault occurring, active power change causes the frequency decrease and is diagnosed by controller; then battery storage system compensates power through injecting power form DC to AC part. When system is operating in islanding mode, power flow from grid to MG is interrupted and frequency of the MG starts fluctuating. Based on FFOPID, ES unit starts to inject active power to control frequency through maintaining the balance between production and consumption.

As shown in Figure 12, during fault occurring, frequency of MG deviates to about 1.02 per unit by PID controller but this amount is fluctuate between 0.992 to 1 per unit by using FLPID. During t=3s and t=5s, amount of output power of generation units is increased to maintain a balance between the power produced and load demand. When system works in islanding mode at (t=3s), power flow from distribution network to MG is interrupted and MG frequency starts fluctuating. By contribution of FFOPID controller to maintain the balance between generation-consumption and control frequency, ES started to inject active power according to frequency droop. Figure 12 shows MG frequency response and ES output power at shortage/surplus mode in MG at the scenarios under study.

At time t=3s, the system will operate in island mode and frequency dropped to 0.992 value. Due to the amount of frequency tolerance $\pm1\%$, the proposed controller begins to change the control parameters to achieve an acceptable level of frequency. In period t= 3-5s, despite of the action of FLPID, frequency has small oscillations caused by the sudden arrival of resource reservation to provide a balance between production and consumption after islanding. As seen in Figure 12, the proposed controller has maintained oscillations in an acceptable range.

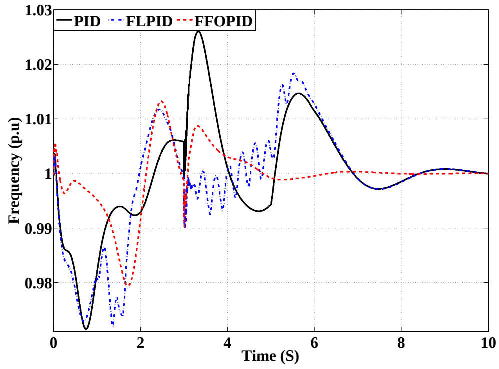


Figure 12: Islanded MG frequency deviation

The FFOPID controller frequency variations graph at time t=3s shows that controller has much less fluctuation than the PID and FLPID controllers. During the time between t=3-5s its completely obvious that the FFOPID controller dampens the fluctuations and tries to reduce the frequency transient error to zero, such that at this time, PID and FLPID controllers have serve and fast fluctuations, but such conditions are not established in FFOPID and with similar trend but much smaller fluctuation amount tries to reduce transient error. At time t=5s very negligible fluctuation (about zero) in the FFOPID controller output is observed, such that this fact is not true in other controllers and at this time the PD and FLPID controllers have server fluctuations and more than the value 1.01 per unit. But under FFOPID the fluctuation is %0.1 which shows performance accuracy much better relative to other presented controllers. Also this fact in the overshoot, undershoot, settlement time, response speed to the created fluctuations and damping speed, has FFOPID controller absolute advantage relative to the PID and FFPID controllers. A small time after the time of occurrence of scenario #2, because of the fast diagnosis of FFOPID controller in reducing the MG consumed power and establishing the generation-consumption balance by reducing the generated power of generation resources, the grid frequency remains at the value of 1 per unit, this is while the values of this deviation in the PID and FLPID controllers are respectively equal to 1.011 and 1.014 per unit. According to Figure 12, after applying the scenario #2, because of the reduction of load demand (resulting from the exist of secondary load) and also supplying part of the need of the consumers by the energy storage system, three no need for generating power from the MT resource. In other word, faster response for supplying the load need has been done by the ES system and there no need to generate high power by MT. in other words, faster response has been applied for supplying load requirement by the ES system and there is no need for generating high power by MT. As it is observed from the figure, the fluctuations of generated power in the FFOPID controller has become much less relative to other controllers after applying scenario #2.

As demonstrated in Figure 12, FFOPID decreases frequency deviation and furthermore, response speed is short and fewer fluctuations occur. During islanding operation, output power of MT (master unit) is changed from initial amount to others which is determined by FFOPID. In Figure 13, the generated power of MT is shown. In time of fault occurrence t=3s, MT unit tries to increase production power,

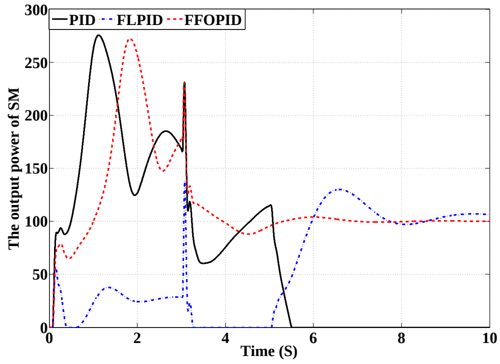


Figure 13: MT output power

but it needs a relatively long time. To cope this problem, ES is used to compensate active power. This task is continuing till the time that generation units increase their output powers. Between t=3s and t=5s, MT unit increases amount of output power to maintain balance between generation and consumption. As shown in Figure 13, PID controller does not show appropriate performance in this time interval, due to having lower generated power. After separating auxiliary load, ES and WT units are responsible to supply load power and MT unit generates a low amount of power. According to the load in the MG and production amount of WT unit, the remaining amount of power is supplied by the energy storage system, and so there is no need to MT needs. In other words, the total power supplied from the battery and that WT unit are sufficient to supply the MG load.

Figure 13 shows MT power production under specific scenarios. In the start of scenario ♯1 (at t= 3s), MT power production will begin to decrease due to slow dynamic reaction in response of power changes. While entering MT to the service, ES tries to maintain power system frequency and stability within the allowable range and maintain power balance with rapid injection of active power to the MG. During periods t = 3-5s, fluctuations in power production unit are due to MT slow dynamic in response to the decline of measured power by FLPID.

Variations of power generated by WT unit after system islanding and sudden change of load is shown in Figure 14. After the occurrence of the fault, lack of sufficient active power results in a decrease in the system frequency. However, this problem has been detected by controller, then ES compensate lack of system power by injecting power from DC part to AC. But, role of WT unit should not be ignored, because it is responsible to supply the power demand of MG until entrance of MT unit. FLPID responds to disturbance faster than PID one and tries to increase the power generation of WT to the mentioned amount. Also, between t=3s and t=5s, amount of fluctuation by using PID controllers is more than the case of applying FLPID. It is also true about overshoot value. In scenario ♯1 (t=3s), WT power production starts to decrease due to its slow dynamic reaction in response to power changes by using each of the studied controllers. At the first moments of fault occurrence (MG transient) ES systems with fast response to load changes can inject power into the MG. During periods t=3-5s, fluctuations in power production due to WT slow dynamic reaction are in response to decrease of measured power by FLPID. Slight fluctuations in the production of WT can be viewed in the case of applying fuzzy controller. The reason is faster detection of fuzzy controller in comparison

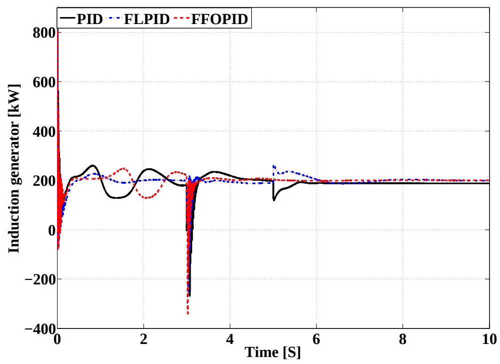


Figure 14: WT output power

with the PID controller in changes of MG system.

Under the FFOPID controller at time t=3s the fluctuation in generation is much less than other PID and FLPID controllers. At this time in the FLPID controller the amount of generated power is equal to zero which this is an undesired fact because it is expected with the occurrence of islanded state, MG has little generation, not that all of power injection load is carried out by ES system. At this time the performance time of PID controllers and FFOPID controller are much better than FLPID controller, but the amount of fluctuation of generated power in the FFOPID controller is much less than PID controller.

During the time interval t=3-5s, this trend continues under the FFOPID controller and the amount of generation has stayed at a small limit, although at this time, ES system has role as strong support in generating power but is completely obvious that MT by overcoming its slow dynamic can generate power and can play the generating role of master unit. During this time, the amount of generation fluctuation in the fractional fuzzy controller is very negligible, such that this fact in other applied controllers (that is PID controllers and FLPID) has been much more.

Load changes in islanding mode are shown in Figure 15. At scenario ♯1, FFOPID has less fluctuation compared to PID controller and is trying to decrease power swing for the least possible amount of power to the nominal values of MG. Between t=3s and t=5s, amount of fluctuation using PID controller is more than the case with the proposed controller which has negligible overshoot compared to PID controller. In scenario ♯2, power fluctuation using FLPID is near zero and this amount is negligible compared to PID controller and in addition, damping of fuzzy controller is done with high speed and low fluctuation. Overshoot of FLPID is negligible relative to the PID controller′s. The proposed controller has efficient performance in improving settling time, minimizing fluctuations and increasing response speed to the disturbance.

FFOPID controller has much less fluctuation against the occurred disturbances relative to other controllers, under the application of scenario #1 and tries to bring the value of MG consumed power with the least possible fluctuation close to its nominal values. In scenario #2 also the amount of power fluctuation in the controller FFOPID and controller FLPID is very negligible compared with the PID controller and furthermore, the damping speed in the FLPID controller has been performed with greater speed and less fluctuation.

After entering the islanding mode, ES output power change from zero to a cer-

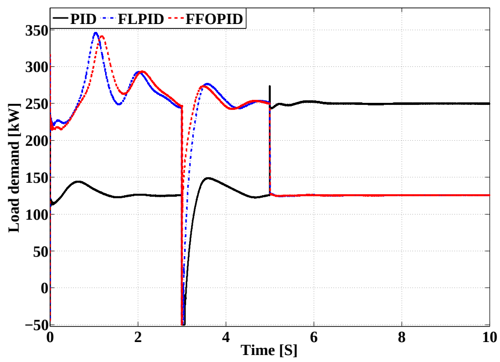


Figure 15: Load demand power profile

tain amount in order to control fluctuation caused by fault occurring. Figure 16 shows active power response of ES system in permanent islanding mode and occurrence of three phase fault. During fault occurring, ES tries to supply the load power of MG, until production units increase output power amount. Also, settling time and overshoot amount is decreased by proposed controller and dynamic response is fast. Using PID controller, overshoot and fluctuation amount is high. In scenario ♯2 which contains addition of active load to MG and occurs in t=5s, ES could inject active power to MG in order to balances power at the system, because there is sufficient storage at ES system. As shown in Figure 12, frequency could be near to nominal amount by using this controller. According to loads and outputs of RES units, battery energy storage helps to improve stability and reduces the fluctuations.

In scenario ♯1 (t= 3s), the maximum amount of power is being produced by ES. Due to fast dynamic response of ES systems to changes and fluctuations in transient time in comparison with slow dynamic reaction of MT units and WT, ES systems can inject part of required power to load of MG. After a short time (about 5 cycles) the amount to be injected by ES to MG is decreased and from this time reserve unit (MT in this study) increases the amount of active power production to with ES unit generation. Because of fast dynamic response and faster response to power changes, ES are applied in initial and transient time of system, to help MG system stability, maintain frequency in acceptable range and provide balance between production and consumption. This applies till the time that MT and WT unit start to service. After entering the MT and WT to service, ES systems are applied to maintain charge balance to supply power under next faults or scenarios. The power fluctuation are observed in t= 3-5s, because MT and WT units are in the initial moments of re-entering to service after scenario ♯1, to provide MG load without using ES.

After the units MT and WT enter service, in case of need and when the sum of generated powers cannot satisfy the amount of consumed load demand, the energy storage system by keeping the remaining charge tries to supply and inject power under errors or next applied scenarios. During the periods t=3-5s, the MT and WT units after the occurrence of scenario #1 at initial moments try to again enter the grid so they can supply the MG consumed load without the presence of energy storing system, so power fluctuations in the ES system have been observed. During this time interval the response speed to the variations in the FFOPID controller has been more than the other controllers. That is power injection to MG has been performed with greater speed and much smaller transient time exists relative to

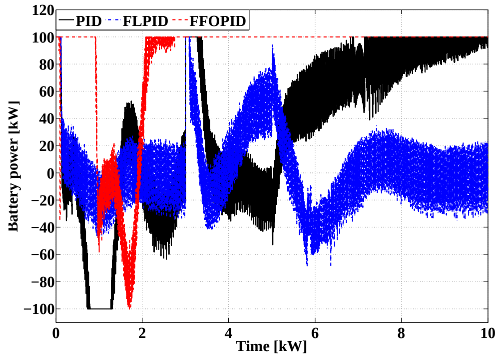


Figure 16: Battery power

other controllers and also has transient stability which is much better and faster.

8.3. Secondary load exit operating mode (scenario ♯2)

During the occurrence of scenario #2 (t=5s), the system frequency (according to Figure 12 has increased significantly under the PID and FLPID controllers, because of the elimination of secondary load in MG and as long as the controller doesn′t understand the occurrence of this amount of fluctuation is much less in the proposed controller. In scenario ♯2, the level of fluctuation is less using FFOPID compared to the conventional PID controller. It is observed that FFOPID is more effective in the sense that it has short settling time, minimizes oscillation and response time to disturbance. During the scenario ♯2 at (t=5s), the system frequency has increased substantially due to MG secondary load shedding and until the controller does not understand these changes in the system, the frequency will increase. Upon leaving the secondary load, FFOPID tries to reduced power from production resources to preserve the balance between production and consumption and the increase in frequency to the desired point reversed. Shortly after the occurring of scenario ♯2, FFOPID reduces the power consumption of MG due to the rapid diagnosis and establishes the balance of generation- consumption by reducing the power of productive resources, the value of the network frequency is 1 p.u. After applying scenario ♯2 at (t=5s), because of reducing the load demand (due to the secondary load shedding) and the needs to provide part of consumers by ES, it is not very necessary to apply MT. In other words, the need to faster response to provide demand of loads by ES is fulfilled and so MT servicing is not very necessary. As can be seen in the figure, a fluctuation in power production at FFOPID after applying scenario ♯2 is much less. After t=5s, because of reducing the load demand (due to secondary load shedding), and demand of part of consumers can be supplied by ES in order to establish the balance of production-consumption and also reduce WT generation. Since the proposed fuzzy controller can detect the changes in MG faster, power oscillations can be significantly lower volatility compared to FLPID and PID controllers case. After applying scenario ♯2, WT generation levels can be maintained in an acceptable range. After applying scenario ♯2 (t=5s), because of reducing the load demand (due to secondary load shedding) and in order to establish the balance of production-consumption, the ES injected power is decreased. In scenario ♯2, ES is not required to remain in service, because of no change in the MG power and stability of production-consumption. In this case, ES is trying to

Table 8: Nominal characteristic of ES

Nominal Capacity (kW)	Max. Constant Current (A)	$\overline{SOC}(\%)$	$\underline{SOC}(\%)$
100	66	100	20

charge itself to be ready for proper cover of the next faults or scenarios. ES application led to smooth the fluctuations frequency/power WT unit and controller tried to compensates these fluctuations by fast operation.

FFOPID have a good efficiency and performance to improve settling time and minimize frequency deviation. Amount of frequency deviation is decreased in frequency control by ES cooperation.

Because of supplying power to MG for maintaining generation-consumption balance, there is need for discharging ES and injecting power from its amount of controller generated power and ES system causes the generation-consumption balance maintenance in the system which this fact causes the reduction of the fluctuations of frequency-power in the MG under study. One of the advantages of this fact can be pointed to this case that using ES system and generation resources simultaneously, increase the system reliability in the case of occurrence of next error or next unwanted scenarios which finally loads to system reliability increase in supporting sensitive load at the time of error occurrence.

9. Conclusions

This paper has proposed a controller based on PID, fuzzy logic and fuzzy fractional order to evaluate the performance of MGs in both isolated and grid connected mode. The proposed controller operation, which takes into account the "plug and play" capability of the system is investigated during the transient time under both operating modes considering the medium voltage fault or generation units overhaul. The study focused on the following issues:

The results obtained in the study can be summarized as follows:

1. The available power by MG including the proposed controller has been increased significantly in comparison to the classic controller;
2. Efficiency of MG has increased in each of the DG;
3. DG resources capacity can be reduced with adequate control of these resources; especially ES capacity has significantly reduced;
4. MG frequency is set in allowable limit using auxiliary load control and ES assets in the proposed algorithm. The proposed controller has shown a good response to maintain the frequency in proper range of MG in both of surplus and shortage of energy;
5. Frequency stability issues arising from the active power imbalance between generation and consumption can be managed in best possible way by the proposed controller. The result proves that the MG frequencies can be dumped in a narrow band of transient disturbances, during a few seconds;
6. The capability of the proposed algorithm for fast responding and appropriately achieving overshoot stabilization has been proved;
7. The proposed controller with the help of ES has been configured properly in overload, short-term reduction in productivity and tolerable frequency and voltage deviation limits;
8. The proposed controller is well suited to implement an effective energy management within MG systems under both operating modes;

9. Determining IAE and ISE criterion functions and the optimum determination of FFOPID operator orders by the PSO algorithm;
10. Comparing the output obtained from classic controller, FLPID and FFOPID in reducing the frequency fluctuations resulting from error occurrence in the system under study.

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