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Belbic frequency control of provisional microgrid with hybrid AC/DC microgrid and renewable energy sources

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ABSTRACT
Nowadays, intelligent control methods play an important role in the advancement of technology and the human movement towards further evolution. The development of new frameworks for power generation and distribution systems by designing a microgrid structure with economic capabilities is one of these areas of progress. Therefore, this paper introduces a new practical method for controlling the frequency of provisional microgrid and is able to cover the following issues at the same time including (1) It considers the nonlinear model of provisional microgrid which has a hybrid structure (AC and DC) in addition to renewable energy sources; (2) Introduces a method for microgrid frequency control under different operational conditions that performs based on the brain emotional learning; (3) Ensures the operation and applicability of the control method for the provisional microgrid through implementation of FPGA for the first time; (4) Confirms the robustness of the proposed method under severe load changes and generation from renewable sources. So, the effects of wind turbines and solar energy are considered in the simulation scenario and under the influence of various changes in load and system uncertainties, the robustness and efficiency of the proposed method are well demonstrated.

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KEYWORDS
BELBIC method; provisional microgrid; solar energy; renewable energy; intelligent frequency control

Nomenclature

MG	Microgrid
DER	Distributed energy resource
RES	Renewable energy source
DG	Distributed generation
DEG	Diesel engine generator
FC	Frequency controller
AC	Alternating Current
DC	Direct Current
PI controller	Proportional integral controller
PID controller	Proportional integral derivative controller
BELBIC	Brain emotional learning based intelligent controller
FPGA	Field programmable gate array
BESS	Battery energy storage system
PV	Photovoltaic panel
WT	Wind turbine

1. Introduction

The appearance of microgrid (MG) concept has changed the nature of the energy industry from centralized generation and remote transmission to local production and distribution. Microgrids are local area networks that can be separated from the main system, and this option strengthens and enables them to perform flexible operations and provide more competitive services [1,2]. Reduction of network clutter and the possibility of faster network recovery in the event of a fault are other advantages of microgrids [3]. In addition, they support a flexible and efficient smart grid with the possibility of integrating distributed and renewable energy sources [4]. The use of local energy sources to supply microgrid loads reduces energy losses in transmission and distribution and further increases the efficiency of the distribution system. Due to the increasing penetration rate of renewable energy sources [5–7], microgrids can provide energy efficient, low cost, clean and flexible power with stable performance and the ability to service loads in emergencies.

The recent introduced provisional microgrids provide multiple economic capabilities with the potential for rapid integration of renewable energy sources [8,9], and are considered in this study to design frequency controller. The provisional microgrid consists of two master and slave parts. In this type of microgrid, the slave part is not able to connect directly to the main network for some reasons and the connection is made through the master microgrid. The master microgrid can be separated from the main network, and of course the slave microgrid cannot operate independently of the master microgrid. Provisional microgrids can use a high percentage of renewable energy sources to meet

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the island's needs, providing the flexibility required for economic needs and the reliability of consumers to handle more sensitive loads.

Microgrid frequency is a characteristic affecting the reliability and quality of power, and due to the supervision of microgrid frequency by the main network in the network-connected mode, this category is important in the islanded mode. In provisional microgrids, function mode and power management are in transmission mode, and as a result, microgrid frequency control will be more complex. In addition, any change in energy, wind speed, and in the intensity of solar radiation affecting renewable generation will have a severe impact on MG and its power quality and consumption. To ensure the optimal performance of the provisional microgrid system, it is necessary to reduce the frequency fluctuations, and to this end, the design of a control algorithm is a basic necessity for overcoming the adversities caused by low inertia of renewable energy sources, uncertainty between model and system, complex nonlinear dynamics and irregular power supplies. So far, various control methods have been used to regulate the microgrid frequency. Proportional Integral (PI) Method [10–12], Proportional Integral Derivative (PID) [13], $H\infty$ controller to minimize fluctuations [14], Internal Model controller [15], swarm-based approaches [16], genetic algorithms [17] and biographical optimization approaches [18] are just a limited number of methods designed to control microgrid frequency.

The use of intelligent control methods ability is the most important purpose of the study to cover the weakness of various controllers for regulating the frequency and ensuring the stability of the microgrid system. Intelligent control methods provide more efficient algorithms in the face of different operating modes and the effects of uncertainty, load disturbances and slow-fast dynamics of various components in the microgrid. By combining theoretical methods with artificial intelligence, they enable the management of complex dynamics and provide an efficient computational method for controlling a multidimensional system under imperfect specifications. Intelligent control methods can cover the lack of correct information as well as changes in environmental and parametric conditions with learning and have better overall performance with better accuracy and less variance compared to traditional methods [19].

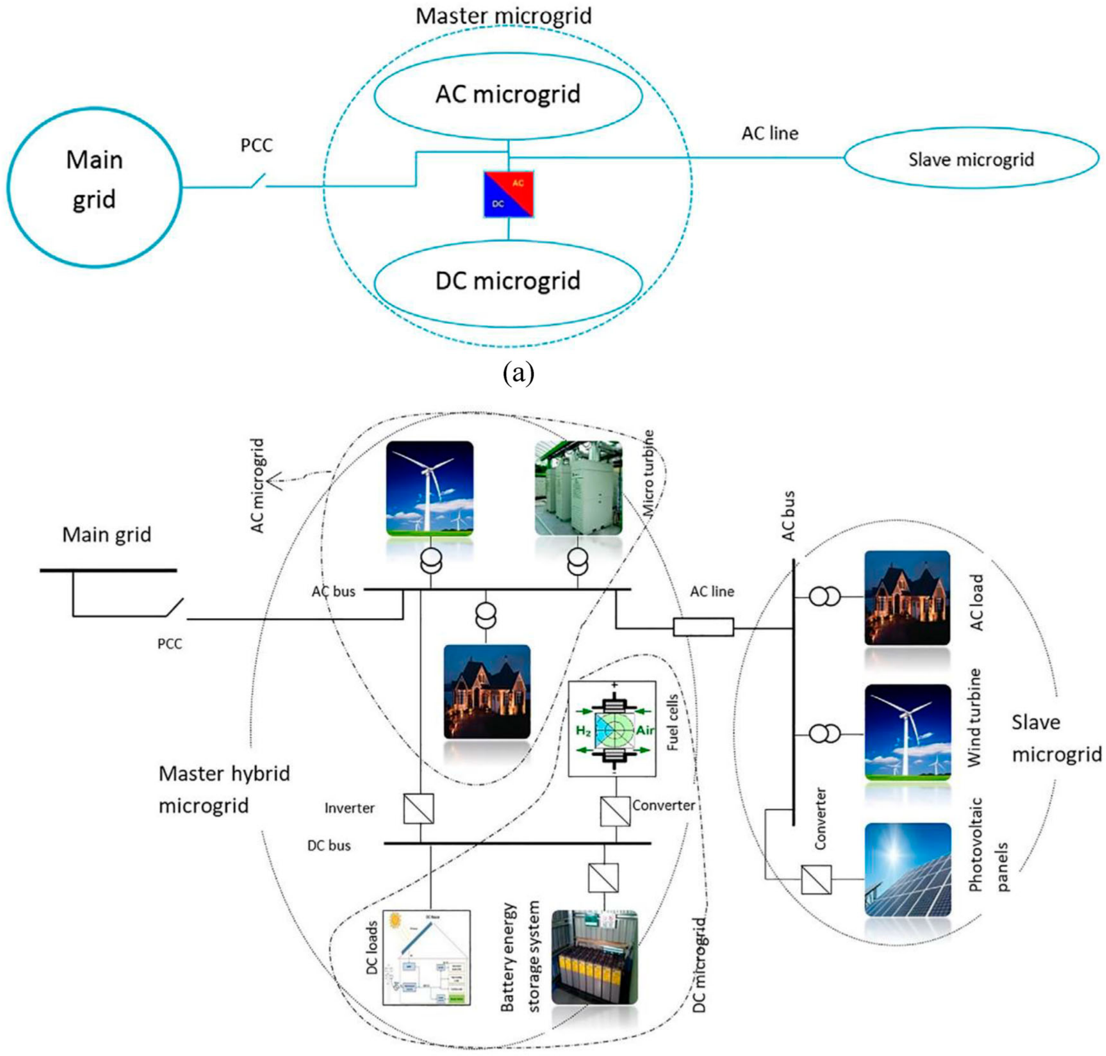
Setting up the controller structure and implementing its hardware with the ability to respond quickly and in a timely manner is another point considered in designing frequency control for microgrids. Many existing control methods are only theoretical and often not applicable to existing microgrid systems, or at least not suitable for existing structures due to economic and technical issues. To achieve the practical implementation of the proposed frequency control method with multiple scheduling capabilities and high flexibility, the innovative tactic of this study is to pay attention to the capabilities of Field Programmable Gate Array (FPGA) [20]. FPGA-based controller design allows achieving practical goals with flexible scheduling and configuration of operations without worrying about how the microcontroller communicates to the existing microgrid structure. FPGA allows the controller to be executed and reconfigured at runtime, and such a powerful mechanism increases overall performance by reconfiguring various parts of the controller system.

Therefore, considering the importance of microgrids and especially the provisional type, the effect of frequency on reliability and power quality, the need to use the benefits of intelligent control methods and finally the practicality of realizing the control method, this paper presents a new method for tuning the provisional microgrid frequency established on the brain emotional learning based intelligent controller (BELBIC) technique. To describe the microgrid behaviour more accurately, its nonlinear model is considered, which is able to provide complete and precise information of system dynamics and prevent data loss without linearization around the operating point or elimination of nonlinear terms. Combining intelligent control technique that use the brain's emotional intelligence to make decisions and ultimately regulate frequency, with FPGAs that provide a realistic and operational environment with appropriate processing speeds and, of course, a flexible and implementable computational framework with re-programmability, forms the most important innovation of this study. To evaluate the robustness of the proposed technique, variations in renewable sources, the most severe load changes along with the maximum possible uncertainty are considered and the ability of the intelligent controller is shown in the simulation scenarios.

As a result, the body of the article is as follows. In the second part, the provisional microgrid model is presented. The third section describes the structure of the intelligent BELBIC control technique in full, and the fourth section presents the simulation results under the most severe environmental and load changes in different scenarios. Finally, conclusions and suggestions for future studies are provided in Section Five.

2. Modelling of provisional microgrid

In this section, the provisional microgrid model under study is fully explained. The general schematic of the hybrid provisional microgrid is shown in Figure 1. In the master part, the AC microgrid is directly connected to the main network on one side and is connected to the DC microgrid on the other side through the converter. The slave part, which is an AC microgrid, is connected to the master part via the AC line. There are different types of loads and resources in this structure including renewable wind, solar and fuel cell sources with



(a)

(b)

Figure 1. (a) Structure of provisional microgrids (b) Arrangement of master hybrid and slave microgrids.

relatively slow dynamics which due to the impact of environmental changes, the first two renewable sources cannot be used to control the frequency.

Due to the hybrid structure of the microgrid, the presence of converters and inverters in different parts is obvious, but to avoid the complexity of the overall model, the effect of these elements is embedded in the transfer function model of each subsystem. In this microgrid structure, the intelligent frequency control method performs the regulatory task in different operating conditions by adjusting the generation of micro turbine and fuel cell.

The dynamic model of the controller mechanism is shown in Figure 2. As it is known, environmental influences lead to changes in the output power of solar and wind generation sources, and due to their uncertain behaviour, they are not used in any way to apply the control signal. The change in battery mode is also determined by the microgrid frequency characteristic, and of course the proposed intelligent controller will use the fuel cell and micro turbine to adjust the frequency.

The transfer function of each of the subsystems is given in Figure 2, and as it is clear, in the case of microgrid islanded operation, the proposed controller seeks to eliminate and minimize frequency deviations by balancing the generation and consumption power.

3. The proposed intelligent frequency control for provisional microgrid

This section describes an intelligent approach to control microgrid frequency based on the brain's emotional intelligence. In this scheme, the learning is based on emotional factors such as excitement and anxiety, and due to the provisional microgrid structure under study, these emotions and worries are primarily due to environmental variations such as changes in sunlight, wind speed and the rest that affect the amount of power generation and secondly because of the amount of load change that affects consumer behaviour and other factors. Therefore, the designed controller must be able to overcome the effects of the changes, worries

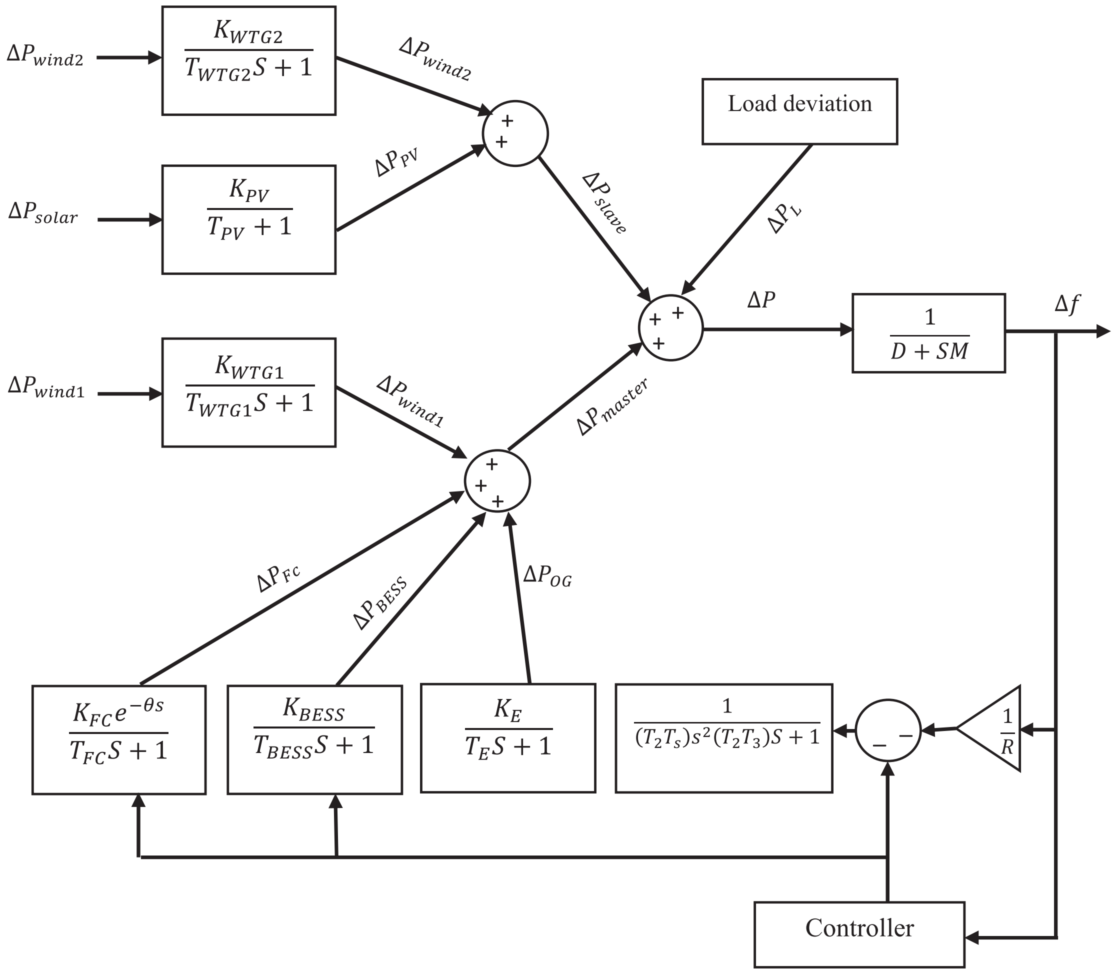


Figure 2. The dynamic model of provisional microgrid for controller design.

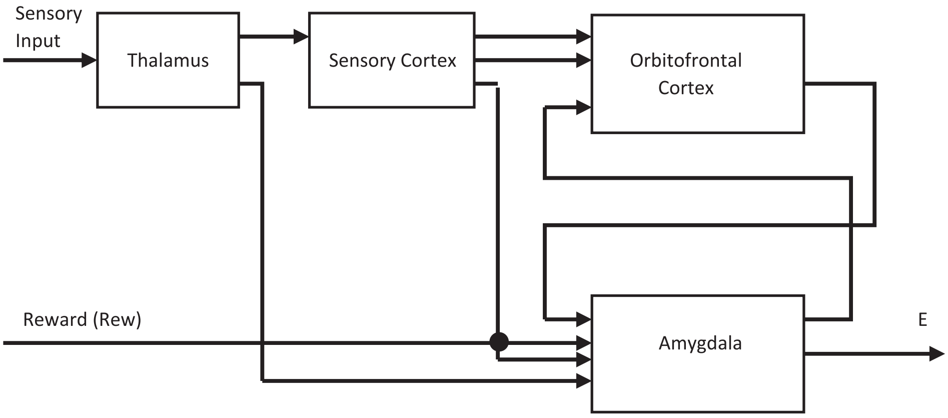


Figure 3. Structure of BELBIC intelligent technique [21].

and excitements on the microgrid frequency and minimize frequency deviations as much as possible. Figure 3 shows the structure of the proposed BELBIC control method, and there are two main components for intelligent control based on brain emotional learning, which take account of the amygdala and the orbitofrontal. The former receives input from the thalamus and cortical regions, while the latter receives input only from the cortex and amygdala along with the reward signal.

The designer selects the input sensors for the BELBIC controller, which have two different states as follows.

$$A_i = s_i v_i$$
$$O_i = s_i w_i \tag{1}$$

where v, w are states reliant on the input sensor s and the i indicates the ith sensor.

Updating the control states is with the following equations [22,23].

$$\Delta v_i = \alpha s_i max\left(0.rew - \sum A_i\right)$$
$$\Delta w_i = \beta s_i\left(rew - \sum A_i - \sum O_i - max(s_i)\right) \tag{2}$$

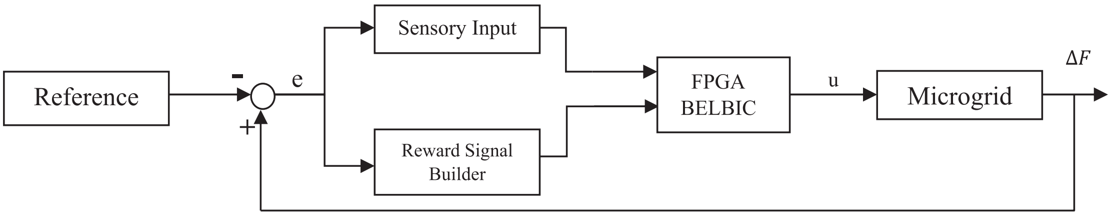


Figure 4. The proposed FPGA-based intelligent control for provisional microgrid frequency control.

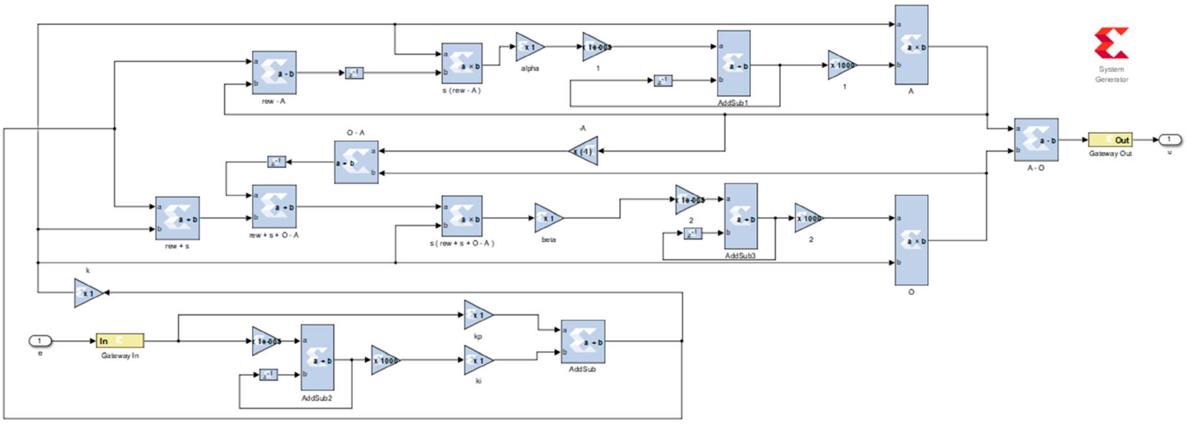


Figure 5. The implementation of the BELBIC intelligent control method through FPGA interface.

where α and β are training constants and *rew* signifies the reward signal. As the amygdala is the actuator and the orbitofrontal is the preventer, the control signal is obtained from the following equation

$$u = \sum A_i - \sum O_i \tag{3}$$

The dynamics of the continuous-time BELBIC controller follows Equation (4)

$$\begin{aligned} \dot{v}_i &= \alpha s_i(rew - A_i) \\ \dot{w}_i &= \beta s_i(rew + s_i + O_i - A_i) \end{aligned} \tag{4}$$

Figure 4 shows a schematic of the proposed FPGA-based intelligent control system that uses a traction force sensory input as follows.

$$s_i = k\left(k_p e + k_I \int e\right) \tag{5}$$

where k_p, k_I and k indicate the coefficients of gains and e specifies the error.

To demonstrate the feasibility of operation, the proposed intelligent control method has been implemented using FPGA, and for this reason, its interface has been used in MATLAB Simulink. Using FPGA capabilities, firstly, the innovative controller can be easily implemented on existing microgrid hardware, and secondly, it allows the development and upgrade of the controller structure without the need for additional investment and cost because of the ability to reprogramme. Figure 5 shows how to implement the BELBIC intelligent control method through FPGA. In Figure 5, the gateway-in and gateway-out blocks are responsible for exchanging data between the MATLAB Simulink environment and the FPGA user interface, how to design a PI controller with proportional coefficient k_p and integral coefficient k_I through input e which actually acts as a *rew* signal, and how to accurately design the BELBIC controller structure and update its states are all shown in Figure 5.

4. Simulation results

This section is intended to evaluate the performance of the proposed intelligent method in controlling the provisional microgrid frequency. In the simulation scenario, disturbances in the sources of renewable generation and changes in the amount of load are all considered simultaneously to provide the strongest possible case for evaluating the robustness of the controller. Changes in the generation of renewable resources include changes in both wind turbines located in the master and slave microgrids. The disturbance profile of the wind turbine 1 located in the master microgrid, together with the disturbance profile in the generation of the wind turbine 2 located in the slave microgrid, are shown in Figure 6. In addition, the disturbance intended for sunlight as well as changes in load are also shown in Figure 7. What emerges from Figures 6 and 7 is the simultaneous occurrence of load changes and generation disturbances in the master and slave microgrids which the performance of the controller must be evaluated at the same time.

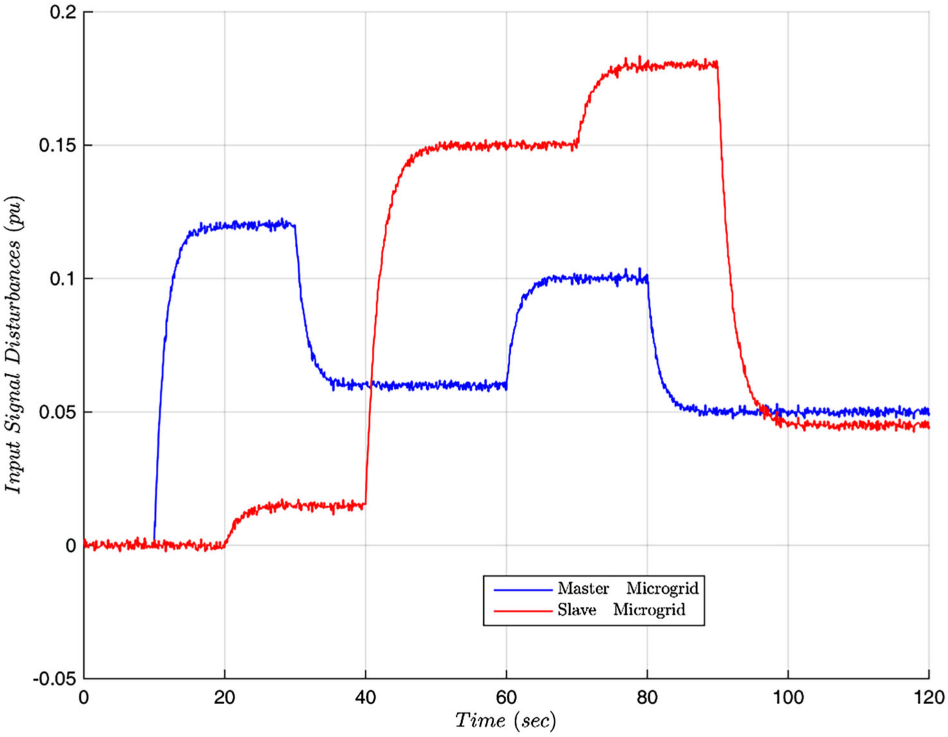


Figure 6. The disturbance profile of the wind turbines in the master and slave microgrids.

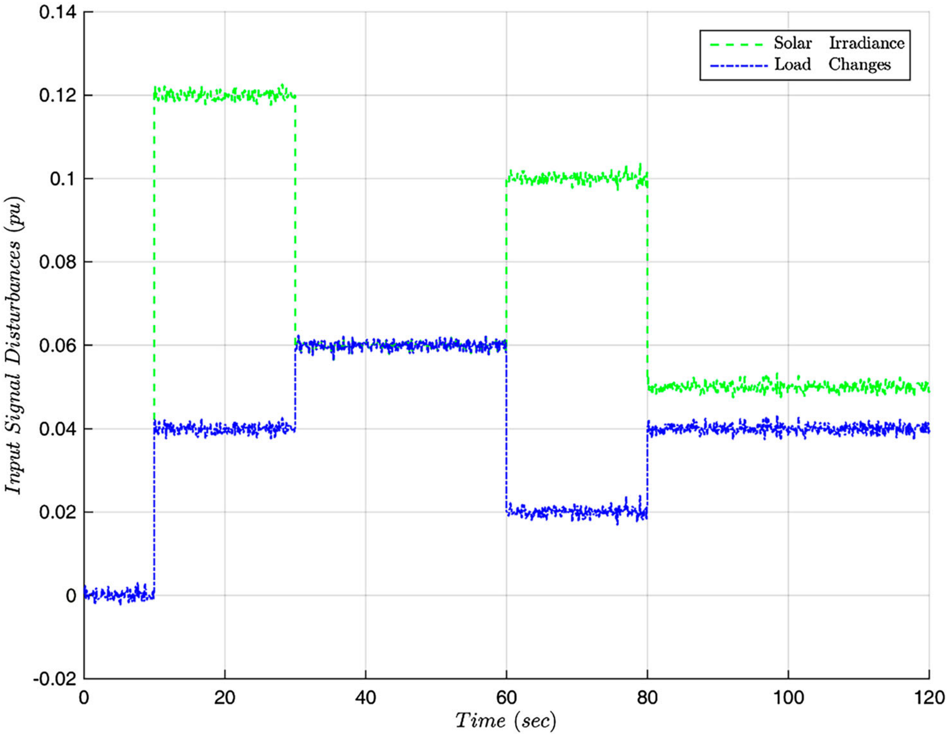


Figure 7. The disturbance of the sunlight and changes in load.

To better understand the performance of the proposed intelligent controller, two conventional PID and robust reset methods have been used for comparison [13,24]. PID is one of the most common control methods and reset method, in addition to being robust, is able to overcome the weakness of linear controllers. The parameters related to the different parts of the provisional microgrid and the proposed FPGA BELBIC controller are given in Tables 1 and 2, respectively.

The rate of frequency deviation under the three mentioned methods is shown in Figure 8 in the time interval of 0–120 s. As can be seen from Figure 8, the

Table 1. Parameters of the provisional microgrid

Wind turbine parameters	$K_{WTG1} = 1.\ T_{WTG1} = 1.5$
$K_{WTG2} = 1.5.\ T_{WTG2} = 2$	
Solar PV system parameters	$K_{PV} = 0.0075.\ T_{PV} = 0.03$
BESS	$K_{BES} = 1.\ T_{BES} = 0.1$
Valve Actuator	$T_1 = 0.025.\ T_2 = 2.\ T_3 = 3$
Diesel Engine	$K_E = 1.\ T_E = 3$
Speed Regulation Constant	$R_{1.2} = 5\frac{Hz}{P.U.MW}$
Synchronizing power coefficient	$T_{12} = 0.225$
Rotor Swing-1	$K_{P1} = 60.\ T_{P1} = 18$
Rotor Swing-2	$K_{P2} = 60.\ T_{P2} = 18$

Table 2. The parameters of the controllers.

Controllers	Parameters
FPGA BELBIC	$k_p = 2\ .\ k_i = 1\ .\ k = 10\ .\ \alpha = 10^3\ .\ \beta = -10^3$

Table 3. Performance index comparison of the simulation scenario.

Controllers	ISE	ITSE	IAE	ITAE	RMSE	Overshoot
PID	0.004	0.2293	0.4353	25.0701	0.0057	1.7746
Reset Control	0.004	0.2359	0.4313	24.5696	0.0058	1.9217
FPGA BELBIC	9.1897e-5	0.0049	0.0701	3.9729	8.6307e-4	0.6507

least amount of deviations during the occurrence of the adversities is obtained under the proposed intelligent BELBIC control method. Fast frequency recovery and fast error elimination are obtained by the proposed method, while the reset and PID techniques show almost the same response. The control signal obtained from the three approaches is also shown in Figure 9. Due to the severe changes and disturbances in the simulation scenario, large fluctuations occur in all three control signals, which are shown separately in Figure 9(b).

For a more detailed review of the results obtained in Figure 8, the rate of frequency deviation under the ISE, ITSE, IAE, ITAE, and RMSE error criteria is given in Table 3. The values obtained in Table 3 show the same behaviour of the PID and reset controllers, while the FPGA BELBIC technique gives much lower error values in terms of all five criteria mentioned. This means a much smaller provisional microgrid frequency deviation under the proposed intelligent control technique. The amount of overshoot obtained for the three control methods is given in Table 3, which confirms the superiority of the proposed intelligent control technique in this field.

5. Conclusion

This paper presented a new intelligent approach for controlling the provisional microgrid frequency. First, the provisional microgrid structure was presented by considering master and slave hybrid microgrids in the presence of different types of renewable energy sources. Considering the transfer functions of micro turbine, fuel cell, wind turbine, battery and solar cell in the hybrid provisional microgrid structure, a nonlinear model was offered for the whole set. A robust and optimal control method based on the emotional sense of the brain was suggested to regulate the microgrid frequency and the possibility of its practical implementation was confirmed by the FPGA user interface. To

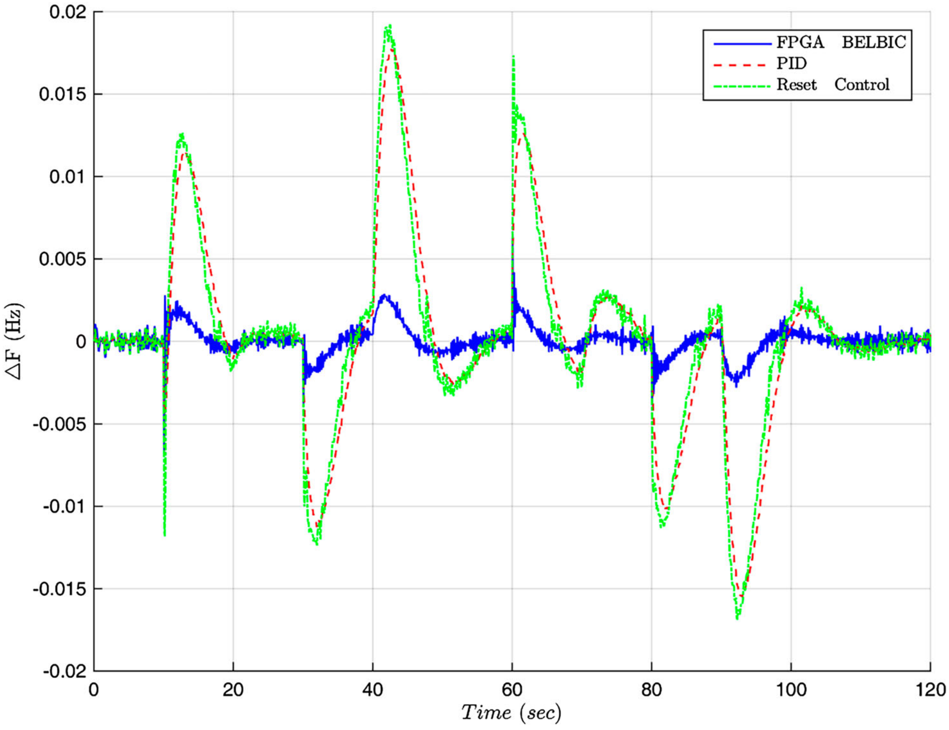
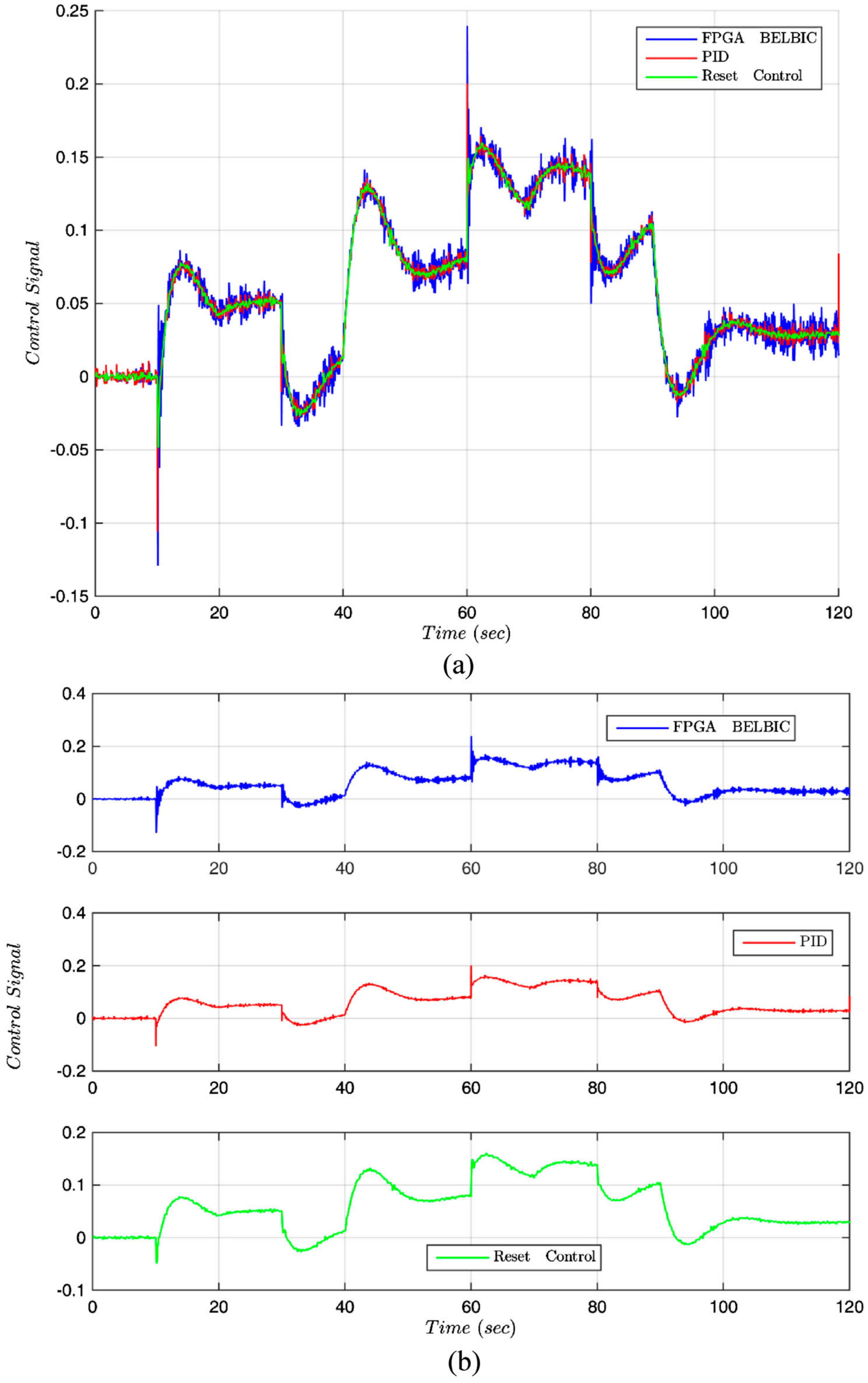


Figure 8. The frequency deviation under the three PID, reset and BELBIC approaches.



(a)

(b)

Figure 9. The control signals under the three PID, reset and BELBIC approaches.

evaluate the performance of the controller, by applying disturbances in the sources of renewable generation as well as drastic changes in the amount of load, the most difficult working conditions were considered in the simulation scenario and the simulation results all showed the ability and efficiency of the proposed BELBIC method in quickly adjusting the frequency with the least error and overshoot.

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Disclosure statement

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