Journal of New Materials for Electrochemical Systems
Vol. 26, No.4, October 2023, pp. 304-311
Journal homepage: http://iieta.org/journals/jnmes

Robust Frequency Control of Additive Manufacturing Based Microgrid Considering Delayed Fuel Cell Dynamics

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https://doi.org/10.14447/jnmes.v26i4.a09

Received: August 05-2022
Accepted: August 15-2023

Keywords:
Provisional Microgrid, Additive Manufacturing, Fuel Cell, Frequency Control, Brain Emotional Learning Based Intelligent Controller, Robust Control, Renewable Energy

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 explains how to realize a microgrid with elements based on additive manufacturing technology; 2- It considers the nonlinear model of provisional microgrid which has a hybrid structure (AC and DC) in addition to renewable energy sources; 3- Introduces a method for microgrid frequency control under different operational conditions that performs based on the brain emotional learning; 4- Ensures the operation and applicability of the control method for the provisional microgrid through implementation of FPGA for the first time; 5- 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.

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 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.

Additive manufacturing (AM), also known as 3D printing, is a useful technology for manufacturing structural and energy devices. In this study, the promising nature of AM has been evaluated for the construction of different parts of microgrid. AM techniques are useful for manufacturing components of fuel cells, wind turbines, batteries, and solar cells, and provide low-cost geometrical structures, and hence wide opportunities of AM techniques are available to researchers and scientists. Therefore, the various techniques of making microgrid components and the current situation of additive manufacturing in relation to microgrid components and renewable energies are reviewed briefly.

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 behavior 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.

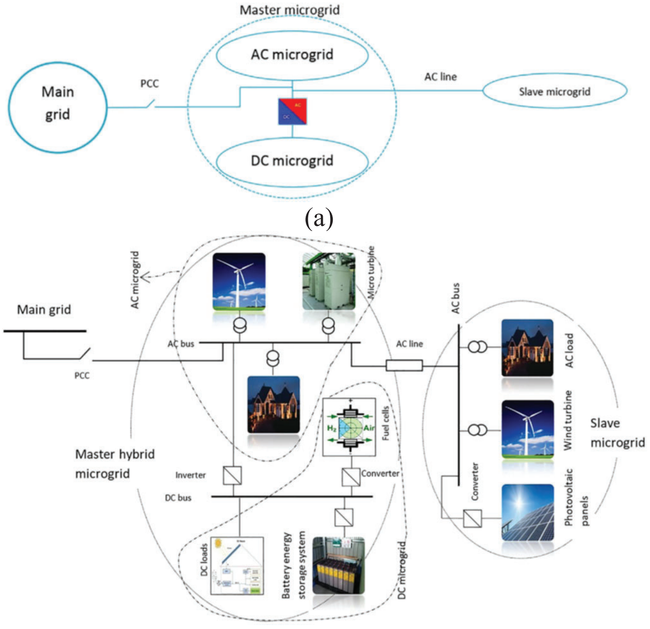
2. MICROGRID MODEL

This section describes the Provisional microgrid model. The general structure of the Provisional microgrid is shown in Figure 1. In the master part, the AC microgrid is directly connected to the mains and is connected to the DC microgrid through the converter. The Slave section is also an AC microgrid and is connected to the main section via the AC line. Renewable wind, solar and fuel cell sources are present in this structure, which due to their relatively slow dynamics and the impact of environmental changes, are rarely used for frequency control, and BESS, micro turbine and fuel cell have the largest share in providing the power needed to adjust the frequency. In this microgrid structure, the combined fuzzy reset frequency control technique carries out the adjusting duty in various operating situations.

Now, in the following, the important topics related to the additive manufacturing of each of the studied microgrid components are summarized

2.1 Micro Turbine

Higher temperature turbine operation for air/fuel Brayton turbines can be described as a key objective to achieve higher fuel efficiency [21-24]. This includes turbine blades, vanes and other components made of high temperature nickel alloys and the failure of these parts can create a significant risk and lead to significant costs, loss of power generating and human life, which requires a high level of quality assurance in the manufacture of these parts.



(a)

(b)

Figure 1. (a) Configuration of provisional microgrid (b) Layout of Master and Slave microgrids

Various methods including highly advanced super alloy blades and turbine components, film cooling and internal cooling passages, and thermal barrier coating materials have been widely applied to the task [21-25]. All this demonstrates the commercial importance of reaching higher temperatures to improve thermal efficiency [21-25].

Additive manufacturing of turbine component cores as well as molds can significantly reduce the cost of developing turbine component cores and molds and significantly shorten the development time for testing new designs [25]. The combination of printed molds and cores for casting can in some cases lead to direct assembly of the mold and casting. AM stereolithography and binder jet printing techniques can provide high precision and good surface finish in prototype cores and molds. Advanced methods for additive manufacturing of cores may also allow grading of materials within the core to improve strength, reduce stresses, save cost, and facilitate better wash ability for core removal after casting [25]. Another important economic opportunity is dimensional control by the additive manufacturing process, whereby quality assurance can be applied to molds, cores, or finished parts.

2.2 Fuel Cell

AM technologies have been applied to fabricate fuel cell components, including biological fuel cells (BFCs), polymer electrolyte membrane (PEM) fuel cells, reversible fuel cells, and micro fuel cells. Microbial fuel cells (MFC) and enzymatic fuel cells (EFC) are typical BFCs that have been fabricated using AM for high performance chambers, membranes [26] and electrodes with large reaction area, high conductivity, biocompatibility and multi-scale porous structure [27-28]. AM techniques simplify MFC design and assembly by eliminating clips, screws, clamps, washers, or sealants. AM is suitable for the fabrication of biocompatible components and thus has been considered for implantable or wearable BFC applications [29-30].

Consistent with the general principles of additive manufacturing (ISO/ASTM 52900:2015), AM technologies can be categorized into seven groups, including binder jetting, material extrusion, material jetting, direct energy deposition (DED), sheet lamination, vat polymerization and powder bed fusion (PFB) [31]. In fuel cell applications, AM technologies that have been used include material extrusion, powder bed fusion, vat polymerization, and binder jetting. Other AM technologies, such as DED, material jetting and sheet lamination, are still under investigation.

2.3 Wind Turbine

Additive manufacturing wind turbines can significantly reduce machining, enable complex geometries, and minimize material waste. In addition, AM can provide better magnetic performance of wind turbine in terms of remanence, coercivity, temperature stability, and etc. without relying heavily on rare materials such as Dy, Tb, or Pr. The expensive and time-consuming tooling process for a wind turbine prototype is eliminated with AM, as the product can be created directly from the computer model. Wasteful processes such as cutting, machining, and polishing are mostly eliminated through AM because it is not a subtractive process, but rather the object is built layer by layer directly into the final shape desired by the program. Reducing the cost of manufacturing permanent magnets is one of the advantages of AM, because it reduces the use of precious and expensive materials through the reduction of waste. Additional advantages include savings in capital and time associated with machining and tooling, as well as lower energy consumption compared to traditional methods [32]. Another application of AM that can significantly reduce the waste of permanent magnets is the recycling of used and discarded permanent magnets [33]. The five main AM-based technologies commonly used for PM wind turbine manufacturing are: Binder Jet Technology (BJT), Material Extrusion (MEX), Cold Spray (CS), Directed Energy Deposition (DED), Powder Bed Fusion (PBF).

2.4 Battery Energy Storage System

Compared to conventional technologies, additive manufacturing offers several significant advantages for making batteries, including: 1) The possibility of building complex desired architectures; 2) Precise control of the shape and thickness of electrodes; 3) Solid-state electrolyte printing with high structure stability and safer performance; 4) the potential for low-cost, environmentally friendly manufacturing, and ease of operation; 5) The possibility of eliminating the assembly and packaging steps of the device through direct integration of batteries and other electronic devices. Also, 3D printing is able to make new electrodes with 3D architecture with larger surface area to improve the energy density of the battery. It should also be noted that 3D printing can significantly reduce material waste and save time due to less complex manufacturing processes. The most important 3D printing techniques for producing batteries are: 3D printing based on lithography, direct ink writing (DIW), inkjet printing (IJP), 3D printing based on template-assisted exfoliation (TAE), fused deposition modeling (FDM) and Aerosol Jet Printing (AJP). Figure 2 shows the manufacturing methods, electrode materials and electrolyte materials in batteries based on AM technology.

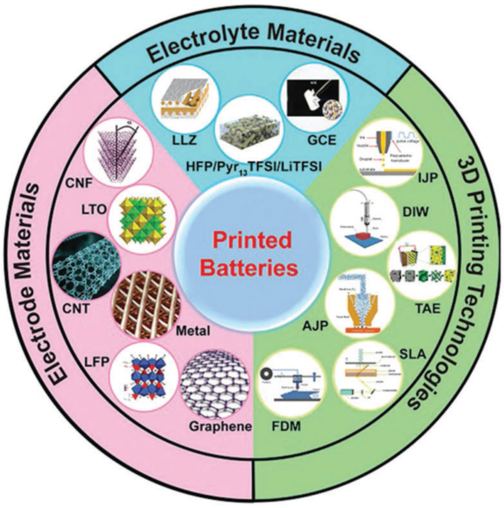


Figure 2. the manufacturing methods, electrode materials and electrolyte materials in batteries based on AM technology

2.5 Solar Cells

3D structures with proper design have the potential to increase the performance of photovoltaic cells. Self-supporting 3D photovoltaic (3DPV) structures achieved by AM technology can produce energy densities by a factor of 2–20 higher than fixed flat PV panels [34].

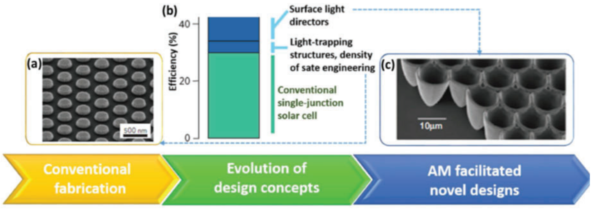


Figure 3. AM technology for solar energy conversion. a) Hexagonal array of Ag nanoparticles deposited using SCIL. b) Thermodynamic losses in solar-energy conversion, c) 3D micrometer-sized parabolic mirror arrays fabricated via 2PP

One way to increase the efficiency of solar cells is to create light-trapping structures, such as the one shown in Fig. 3a, where silver (Ag) nanopatterns were fabricated using substrate coherent printing lithography (SCIL). To achieve efficiencies beyond the typical Shockley-Queisser limit, light guides must be integrated into the solar cell surface (Fig. 3b). Kosten et al. have recently fabricated parabolic mirror arrays via 2PP (two-photon polymerization AM technology), which have the potential to increase the power conversion efficiency of a single-junction GaAs solar cell above 38% [35].

Considering AM's extraordinary ability to reduce material waste, optimize geometries and produce lightweight components, and of course produce parts locally, it will definitely be the most important technology for producing solar cells.

The dynamic model of the controller mechanism is shown in Figure 4. As it is known, environmental influences lead to changes in the output power of solar and wind generation sources, and due to their uncertain behavior, 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.

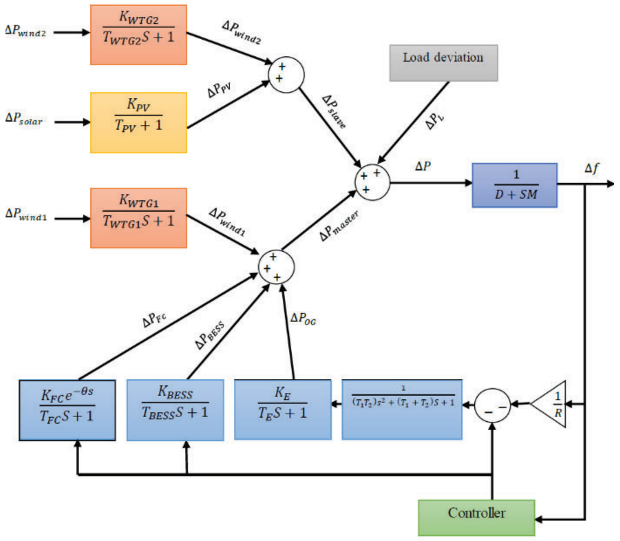


Figure 4. The proposed controller in provisional microgrid structure

3. THE ROBUST CONTROL CONFIGURATION

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 behavior and other factors. Therefore, the designed controller must be able to overcome the effects of the changes, worries and excitements on the microgrid frequency and minimize frequency deviations as much as possible. Figure 5 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.

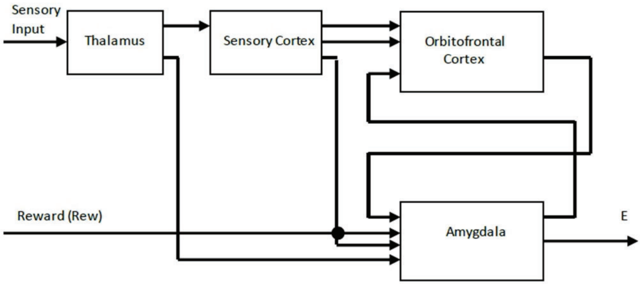


Figure 5. Structure of BELBIC intelligent technique [36]

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

$$A_i = s_i v_i \qquad (1)$$
$$O_i = s_i w_i$$

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 [37-38].

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

$$\Delta w_i = \beta s_i\left(rew - \sum A_i - \sum O_i - max(s_i)\right)$$

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)

$$\dot{v_i} = \alpha s_i(rew - A_i) \tag{4}$$

$$\dot{w_i} = \beta s_i(rew + s_i + O_i - A_i)$$

Figure 6 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.

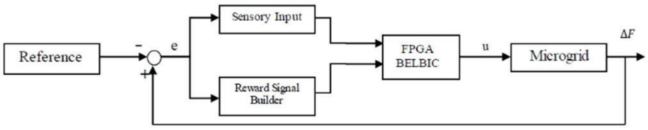


Figure 6. The proposed FPGA-based intelligent control for provisional microgrid frequency control

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 reprogram. Figure 7 shows how to implement the BELBIC intelligent control method through FPGA. In Figure 7, 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 7.

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 8.

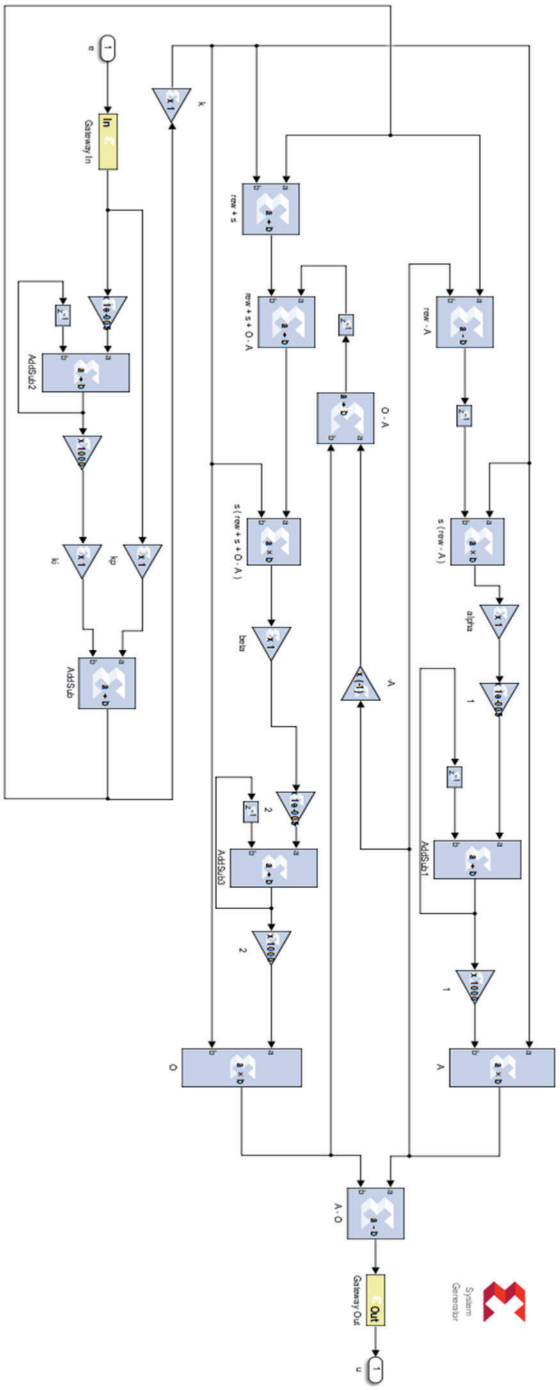


Figure 7. The implementation of the BELBIC intelligent control method through FPGA interface

In addition, the disturbance intended for sunlight as well as changes in load are also shown in Figure 9. What emerges from Figures 8 and 9 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.

To better understand the performance of the proposed intelligent controller, two conventional PID and robust reset methods have been used for comparison [13, 39]. 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.

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	$k_p = 2 . k_i = 1 . k = 10 . \alpha = 10^3 . \beta = -10^3$

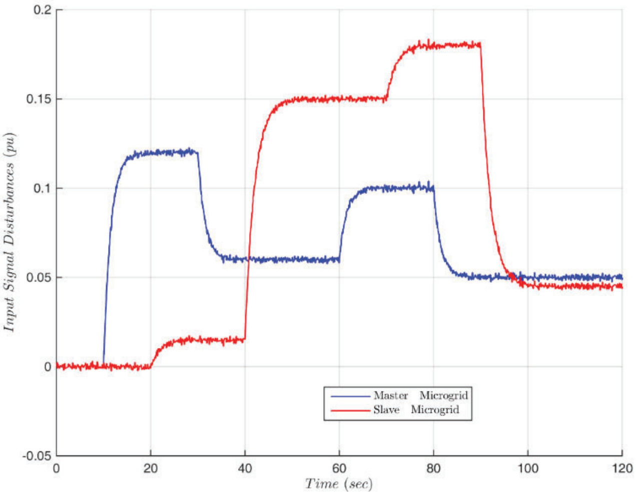


Figure 8. The disturbance profile of the wind turbines in the master and slave microgrids

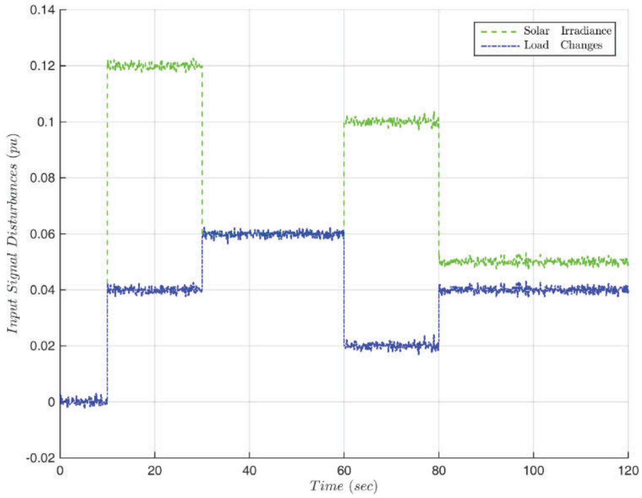


Figure 9. The disturbance of the sunlight and changes in load

The rate of frequency deviation under the three mentioned methods is shown in Figure 10 in the time interval of 0 to 120 seconds. As can be seen from Figure 10, the 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 11. 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 11(b).

For a more detailed review of the results obtained in Figure 10, the rate of frequency deviation under the ISE, ITSE, IAE, ITAE, and RMSE error criteria is given in Table 4. The values obtained in Table 4 show the same behavior 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 4, which confirms the superiority of the proposed intelligent control technique in this field.

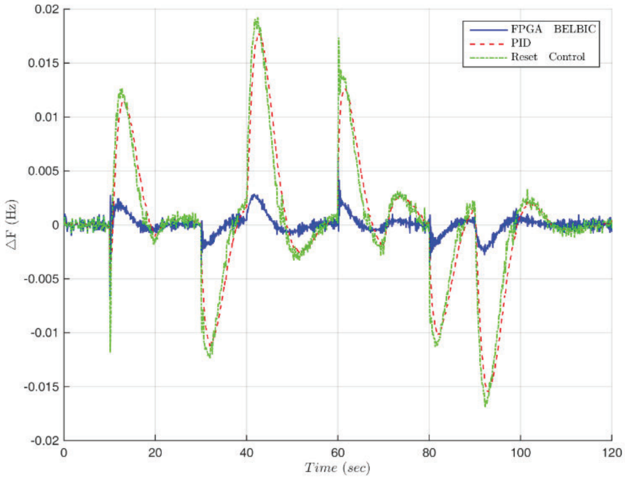
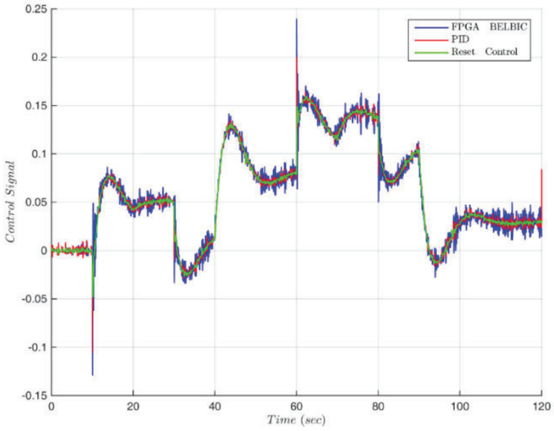


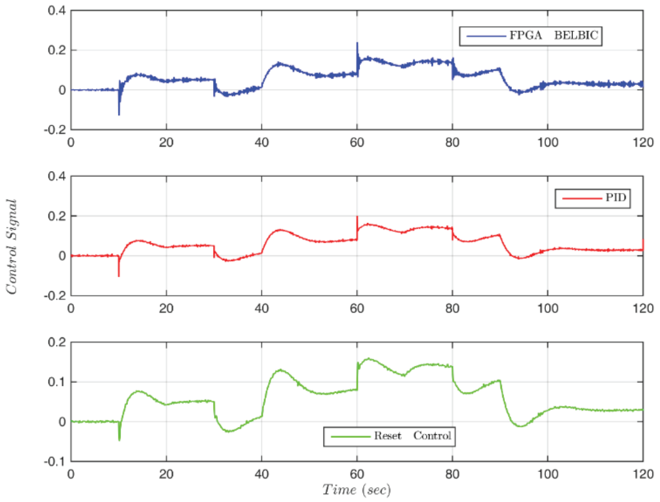
Figure 10. The frequency deviation under the three PID, reset and BELBIC approaches

Table 3. Performance index comparison of the simulation scenario

Controller	ISE	ITSE	IAE	ITAE	RMSE	Over-shoot
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	9.18e-5	0.0049	0.0701	3.9729	8.6307e-4	0.6507



(a)



(b)

Figure 11. The control signals under the three PID, reset and BELBIC approaches

5. CONCLUSIONS

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 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.

ACKNOWLEDGMENT

This work was financially supported by 2023 Jiangsu Province Higher Education Excellent Science and Technology Innovation Team Supported Project: Laser Processing and Metal Additive Manufacturing Technology and Application, the funding for key research and cultivation projects of Nantong Institute of Technology (XKYPY202309, XKYPY202312), the Top Talent Project of Nantong Institute of Technology (XBJRC2021003), Key disciplines of the 14th five year plan in Jiangsu Province: Mechanical Engineering (2022-2), First-class specialty and industry education integration brand specialty in Jiangsu Province: Mechanical Design, Manufacturing and Automation (2020-9,2022-7).

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