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A Review of the Primary-Control Techniques for the Islanded Microgrids

Mohammad Jafar Hadidian Moghaddam[1], **Mehdi Bigdeli**[2*], **Mohammad Reza Miveh**[3]

*[1]Young Researchers and Elite Club, Zanjan Branch, **Islamic Azad University**, Zanjan, Iran*
*[2]Department of Electrical Engineering, Zanjan Branch, **Islamic Azad University**, Zanjan, Iran*
[3]Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia
**E-mail: mehdi.bigdeli@iauz.ac.ir*

Abstract. The growing interest in sharing the renewable-energy resources in power microgrids presents major challenge from the perspective of reliable operation and control of the power systems. The issue of the microgrids autonomous control has received a considerable attention in the last decade. As the architecture of the power system control, a hierarchical control scheme can be implemented for the islanded microgrids. So far, various concepts for the hierarchical control of the microgrids have been developed. In this paper, the most up-to-date primary control techniques for an autonomous operation of the microgrids are presented and droop-based and non-droop-based power-sharing approaches are comprehensively compared. The simulation results are used to improve and support the concept of the droop-based primary control in an islanded mode. Finally, a brief summary and a critical assessments of the findings are given.

Keywords: microgrid control, islanded mode, primary control, secondary control, droop control, distributed generation

Pregled primarnih krmilnih tehnik za otočne mikromreže

Naraščajoče zanimanje za skupne obnovljive vire električne energije ponuja nove izzive na področju zanesljivosti in nadzora električnega omrežja. Na tem področju je v zadnjem desetletju aktualen avtonomen nadzor mikromrež. Z upoštevanjem arhitekture električnih sistemov je mogoče zasnovati in izdelati hierarhični nadzor za mikromreže. V prispevku predstavljamo zadnje dosežke pri nadzoru delovanja mikromrež. Posamezni pristopi nadzora so predstavljeni z rezultati simulacij. V sklepu prispevka kritično podajamo ugotovitve.

1 INTRODUCTION

In the history of the power system development, distributed generations (DGs) have been a key factor in handling the environmental, technical and economic issues. The use of DGs based on renewable-energy resources has significantly reduced the climate-change concerns. Moreover, DGs stability near consumption points can supply some of the load from these resources, resulting in decreasing the loading and power of the power transmission system and losses [1-3]. However, researchers have soon realized that applying DGs of the low-voltage levels can jeopardize the stability and power quality of the power system. Hence, to deal with these aforementioned challenges a concept of the microgird is proposed [4-6].

A microgrid can be defined as a group of DGs, loads, power electronic devices and energy-storage systems acting as a controllable entity [7, 8]. It provides a superior reliability and power quality for the power system compared to individual DG units. Moreover, it has the ability to operate in both a grid-connected and an islanded mode [9]. Normally, the microgrids operate in conjunction the power system. Whenever a power quality event occurs the power system, they get disconnected from the rest of the distribution system activating a static switch and then they operate in an autonomous mode. In the grid-connected mode, the utility grid provides an accurate power-sharing strategy and proper electrical set-points for each DG unit. When in the islanded mode, the voltage source inverters (VSIs) continues the frequency and voltage of the microgrid to ensure a stable operation of the autonomous mode.

In the autonomous mode, the DG units provide an adequate power quality and reliability for the sensitive loads. Indeed, DGs should be maintained so that the value of the voltage and frequency of the microgrid is standardized. Also they should be able to share the active-reactive power among the loads proportionally to their power rating. Compensation issues such as the harmonic-current sharing, voltage and frequency restoration, voltage-profile control and reactive-power compensation need to be taken into account in the islanded mode [10-14]. Hence, a flexible control strategy should be implemented by using inverter-based

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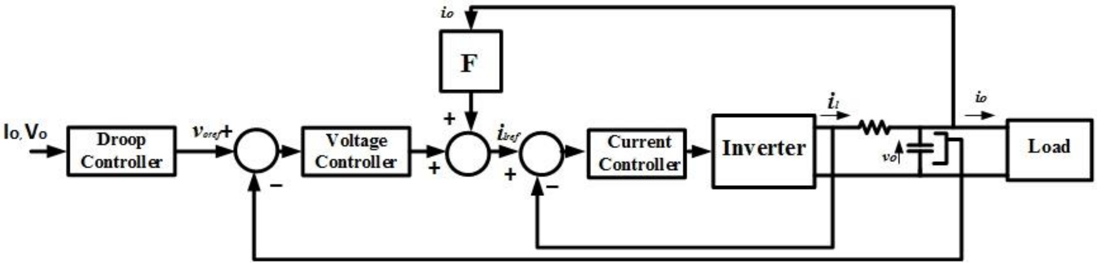

Figure 1. Structure of an inner-control loop and primary control

VSIs to meet all the power-quality demands during the island mode.

In this paper, a comprehensive review is made the recently used primary control strategies for the islanded microgrids. This paper is divided into four parts. In chapter 2 an overview is given of the recent primary control strategies in the islanded microgrids. In chapter3, two opposite approaches to power-sharing strategy are analyzed. In chapter 4 the basic simulation results are presented to improve and support the concept of the droop-based primary control. In chapter 5 a brief summary of the summary and an assessment of the findings are given.

2 CONTROL OF THE ISLANDED MICROGRIDS

Normally, for an islanded microgrid it is important to adapt an adequate control strategy to assure the system security, optimal operation, gas-emission reduction and proper transfer to the grid-connected mode. A microgrid should be able to continue its voltage and frequency within a certain reference value by means of VSIs. Furthermore, an adequate active and reactive-power-sharing strategy among the DG units is a significant challenge needing to be taken into account in the autonomous mode. Moreover, compensation issues, such as harmonic-current sharing, voltage and frequency restoration and reactive-power compensation consider off eat the performance of the islanded microgrids.

Basically, depending on the structure of a power system, to accomplish its control actions two different approaches, i.e. centralized and decentralized technique can be used. In a fully centralized technique, a central controller (CC) performs the control actions for all units based on the extensive communication links. On the other hand, in a fully decentralized approach, each control unit operates based on local measurements. For the microgrids, a fully centralized or a fully decentralized control is not possible due to the large number of the controller units and specific performance requirements. A possible solution to these limitations can be solution of a hierarchical control scheme [11]. It is a compromise between the fully decentralized and centralized approach which includes four different levels. Loading based on the infrastructure requirements and speed of response. They can be classified into the zero, primary, secondary and tertiary controllers [11].

The zero and primary levels, which operate based on the local controller, deal with the control and power-sharing issues (see Fig. 1). In VSIs, the voltages and currents are controlled by means of an outer voltage loop and an inner current loop, respectively. A power-sharing control is normally done using the droop-controlled methods.

Secondary control is also used to assure electric signals of the microgrids within the standard values. It is responsible for providing a reliable and economical operation of the microgrids. Compensation of the voltage and frequency deviations during the load-changing states can be done by using the secondary level. Note that sharing the active and reactive power according to the non-droop-based methods such as the master/slave and concentrated technique is a part of the secondary level. Lastly, the tertiary control which is the highest level, deals with the optimization issues based on the electricity market in the grid-connected mode. Hence, the secondary control is the highest level in the autonomous mode. More details about the tertiary and secondary levels are succeeded the scope of this paper. The rest of this section presents more detailed information and the recently available techniques for the primary level.

2.1 Primary Control with a Droop-Based Power-Sharing Strategy

Fig. 2 shows the structure of the primary level based on the droop power sharing strategy.

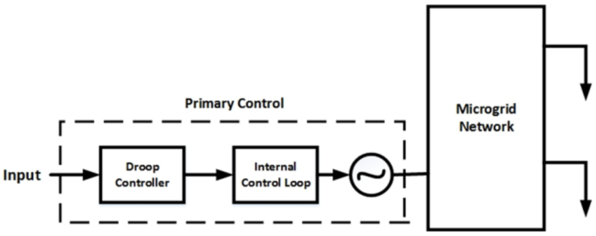

Figure 2. Structure of the primary level based on the droop power-sharing strategy

The construction includes an internal control loop for the voltage and current control. The droop concept is also used for the power-sharing control. The inverter output control and the power-sharing control belong to the primary level. In the following subsection, the most-up-to-date control methods for the primary control based on the droop power-sharing technique are presented.

[15], presents a Q -- G droop-control strategy based on the reactive power for an islanded microgrid. This strategy operates accurately in combination with the conventional droop-control technique. In addition, an external voltage loop and an internal current loop are employed to control the voltage and current values in the dq frame. The proposed controller shares the imbalance currents among the inverter-based DG units. The reference signals of the negative sequence compensate the negative sequence of voltages. It is noteworthy that integration of the positive- and negative-sequence currents forms the total commands of the current controller in the dq reference frame. This current is fed to the current controller and is then compared with the measured current to generate the voltage references of SVPWM. One of the limitations of this method is that it does not provide an acceptable performance when there is an exact value of the line impedance available.

Sao and Lehn [16] analyze a droop-based control strategy in the synchronous reference frame for the voltage-source converters (VSCs). The microgrid operates either independently or in the grid-connected mode. The voltage and frequency of the microgrid are controlled by means of the VSCs modules. Each module includes a voltage-power droop/frequency reactive power-boost- (VPD/FQB) control scheme which adjusts its current reference. The proposed strategy is implemented in the dq frame based on the conventional PI-type controllers. The power load is effectively shared in proportionally to the voltage and frequency-droop coefficients among VSCs.

In the study by Gustavo et al. [17], an improved droop-control-based technique is proposed for a single-phase islanded microgrid. As seen in Fig. 3, the suggested scheme consists of a droop unit, external voltage loop and internal current loop. To determine the average power components, a virtual quadrature reference frame is employed. They are compensated and power sharing between the DG units is accurate. However, the controller setting and circuit parameters effect the stability of the microgrid.

In [18], autonomous voltage imbalance compensation is proposed for the low-voltage islanded microgrid in the stationary reference frame. The main control loops consist of a voltage-current controller, virtual impedance compensator, active-reactive power controller and voltage imbalance compensator. The proposed method effectively compensates the imbalance voltages and also shares the active and reactive power among the DG units. The voltage and current loops are designed in the stationary reference frame by using the PR controllers. The output of the current loop is transformed to the abc frame and then divided by V_{dc} to provide three-phase reference voltages for the PWM.

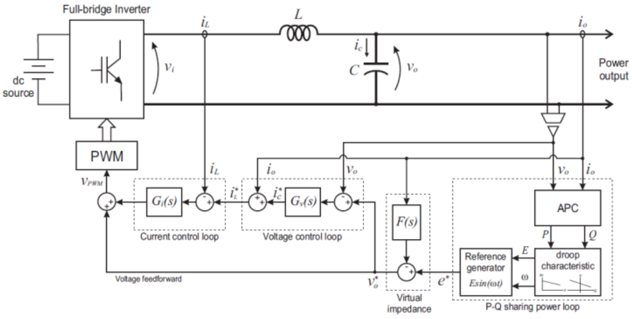

Figure 3. Power stage of a single-phase inverter and its control block diagram in [17]

[19] presents novel method based on the stationary reference frame in two levels. The primary-control structure contains a droop control, virtual impedance loop, external voltage loop and internal current loop. This level is designed to share the active and reactive powers and to control the output variables effectively. Both the voltage and current loops are implemented with the PR controllers in the stationary reference frame. Although such method is cost-effective to install, it suffers from the amplitude and frequency deviations.

The method proposed by Hamzeh et al. [20] suggests a novel decentralized control scheme for an autonomous microgrid based on a droop controller (see Fig. 4). To effectively share the power among the DG units in the presence of imbalanced loads, it also compensates the negative sequence currents to improve the overall power quality of the microgrid. To achieve an adequate negative-sequence current compensation, the phasor of the negative sequence current of each load is measured and transmitted by low-bandwidth communication links. Not using MGCC, the main responsibility of the control scheme is with MCs. Each MC is equipped with a droop controller, internal current loop and external voltage loop to deal with the power sharing and control issues. Indeed, the droop control shares the active and reactive power among the DG units, and the cascaded voltage-current loops control the magnitude of electrical variables.

[21] Proposes an autonomous microgrid power-sharing technique using an enhanced virtual impedance control scheme. It is designed with a central controller based on low-bandwidth communication links. An adequate sharing and improved point of the common-coupling (PCC) voltage quality are accomplished by controlling the DGs equivalent impedance. Where using such method which is based on the grid impedance variations, the poor power quality at PCC results from shifting the voltage.

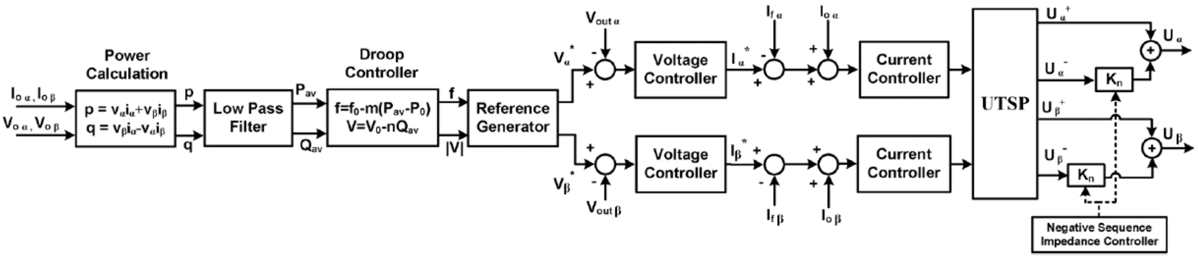

Figure 4. Structure of the proposed control system in [20]

2.2 Primary Control using the Active Load Sharing Methods

Fig. 5 shows the structure of the primary level based on the non-droop power-sharing methods. The structure includes an internal controller for the voltage and current control. The power is shared by using the communication-based methods, such as concentrated control, master/slave, instantaneous current sharing and circular-chain control method. The power sharing control is part of the secondary control [11]. In the following subsection, the most-up-to-date control techniques for the primary control based on the non-droop power sharing methods are presented.

Using the centralized limit-control method, Siri et al. [22] propose a novel control strategy for parallel-connected converters. A multi-loop controller is employed to control the electric signals of the parallel converters. CC provides an accurate voltage control and adequate power sharing through communication links. The authors also present result of an analytical comparison between the master-slave control and the centralized-limit-control method. It is showed that using the central-limit control method pursues both the performance in case of flexibility, transient response and maintainability and the transient response of the output currents. The main drawback of the method is the necessity of using the inter-unit communication links.

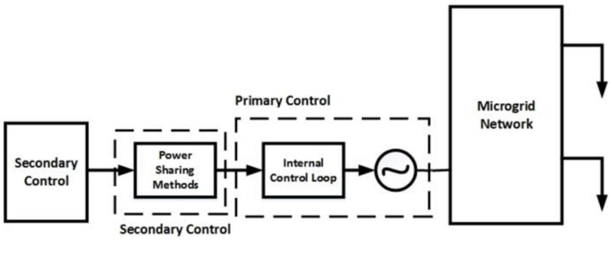

Figure 5. Structure of the primary level based on the non-droop power-sharing strategy.

In the study by Wu et al. [23], a current-sharing method based on the central-limit control in various design options is proposed. It endures sharing the currents excellently in both the steady and transient states. Moreover, it controls the output voltage. Its main limitation is for the necessity of using the high-bandwidth communication links to deal with the unit synchronization.

The proposed approach in [24] is basically the same as in [22]. An improved central-limit control is suggested for parallel-connected DC-DC converters. The method solves the sensitivity issues of the feed-back loop control and enhances the reliability of the central-limit control techniques, even during the parameter-changing states.

Martins et al. [25] introduce a current control method for parallel operation of standard UPSs. The instantaneous load and the harmonic currents are shared based on the capacity of the output filter. A common-phase reference is used. Its advantage is its simplicity; and has cost installation. However, using the communication links, the method is not reliable.

In [26], a master-slave control method for parallel operation of UPS is suggested. The master functions as a grid-forming unit to control the voltage, whereas the salve controls the current in the grid-following mode. Unlike the decentralized master-slave technique, the reference signals have provided by the central controller. Since in the grid-connected mode, the utility grid operates as a master unit, the approach was the same strategy for both the islanded and the grid-connected mode. However, this method has a number of limitations such as difficulty of expanding of the system because of using the communication links.

Ramos et al. [27] present a master-slave control scheme based on the sliding-mode control scheme. In the decentralized master-slave technique, the master unit controls the load voltage and determines the reference values of the currents as a grid-forming inverter while the slave units follow the orders of the master unit in the grid-following mode. An adequate voltage recovery is achieved by the current and voltage control loops.

In the study by Moradi et al. [28], a decentralized servomechanism controller based on robust approach for the islanding operation of the microgrid is proposed. Each DG unit adjusts its voltage independently. To achieve an adequate power sharing, an internal oscillator is employed in the control system to extract the phase angle used to transmit it to each DG units through the communication links. Although the study shows an acceptable power sharing, it is difficult to implement it in a large system.

A recent study by Etemadi et al. [29] suggests a decentralized control strategy for the islanded microgrid. The authors propose a power-management system to determine the set points of the active and reactive power and an internal oscillator in each unit to determine the frequency system. The employed distributed energy resources operate either in the voltage-controlled or power-controlled mode. The reference values of the active and reactive power determined by the power-management unit are transmitted through a low-bandwidth communication system. Furthermore, to synchronize the oscillators by a common time-reference signal, a global positioning system is employed. A good performance is shown in the sharing power among the DG units as well as setting the frequency.

3 A COMPARATIVE ANALYSIS OF THE POWER-SHARING METHODS

A power sharing strategy either using or not using the control scheme, either the concept of droop is droop-based or non-droop-based. When using the controllers as well analyzing control techniques, the power-sharing techniques to the used should be assessed critically. There are a number of differences and similarities between them. Table 1 provides a comparative analysis of the most important evaluation criteria after the controller performance. As observed, each method has its advantages and disadvantages.

The non-droop-based power-sharing scheme offers numerous good features, such as simplicity and robustness against to controller setting and circuit parameters. Yet leaning implemented with communication links, it is neither reliable nor cost-effective. And it is difficult to have the system expanded.

Unlike the non-droop-based power-sharing control scheme, the droop-based needs communication links. As it can be locally implemented based on the droop-control technique, it provides numerous desirable characteristics for the local controller such as flexibility, reliability and expandability. Furthermore, it is highly cost-effective because of the local operation of the control unit. However, it has some weaknesses, such as slow transient response because of the average values of the active/reactive power over a cycle and current flowing among the DG units resulting from the impedance mismatching between the DG outputs. Another weakness is the deviation in the amplitude and frequency due to the high load-dependency or the control scheme.

4 SIMULATION RESULTS

Based on the simulation results the basic features of the islanded microgrid based on the primary control are evaluated. Fig. 6 depicts the diagram of the case-study system. It is a two-DG inverter-based autonomous microgrid. Both DG units are equipped with a droop control strategy. Moreover, each DG controls independently. The parameters of the inverter-based DG units are defined as follows: L_s = 3.5mH, R_s = 1.15Ω, f= 60Hz, and the filter capacitance C= 15µf., the switching frequency for PWM is set at 10 kHz. The test-system parameters are given in Table 2. The simulations are conducted in Matlab/Simulink.

In the islanding operation, DGs supply the sensitive load according to their power rating. In fact, the DG units the power dispatch and control the islanding operation. This includes an adequate voltage and frequency control as well as an appropriate power sharing. To assess the performance of the local controllers load change is used. The sensitive load is set to 20kW of the active and 3kVar of the reactive power in the initial operating point. At 0.6s, the load increases to 27kW of the active and 8kVar of the reactive power. After 0.6s, the balanced power is supplied through the DG units.

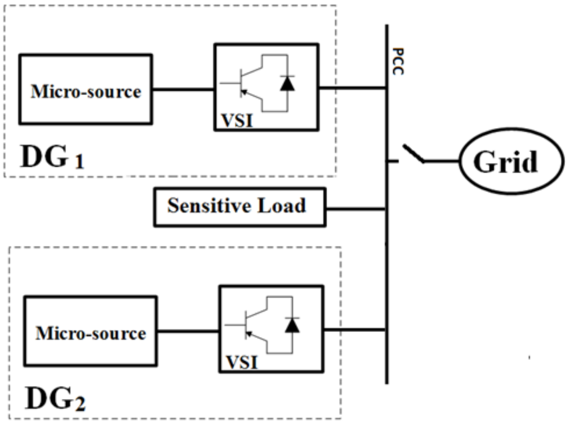

Figure 6. Test system used in our simulations

Figure 7 and Figure 8 show variation of the active and reactive power of two DG units during the load-changing states. As seems, there is a sharp increase in both the active and reactive power of the DG units after 0.6s. Assaulting from showing the active and reactive power for the sensitive load is shared between the DG units proportionally to their droop coefficients. Since the droop coefficient of DG1 is half of that of DG2, DG2 provides twice as much of the active and reactive power. The frequency and voltage of the islanded microgrid at PCC during a load-change state are shown in Figure 9 and 10 respectively. As seen, both the frequency and voltage are controlled perfectly with no deviations.

To assess the basic characteristics of the islanded microgrid, the behavior of the autonomous microgrid during a load-changing states simulated. The simulation results show that the local controllers assure an adequate power quality and reliability for the islanding operation. This is achieved by independent controlling the DG units.

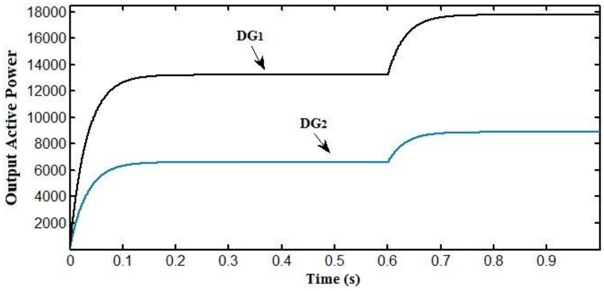

Figure 7. DG1 and DG2 output active powers

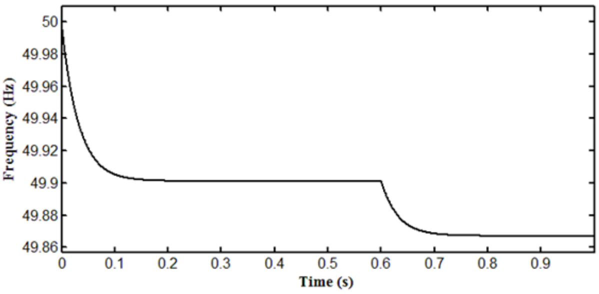

Figure 9. Frequency of the islanded microgrid at PCC

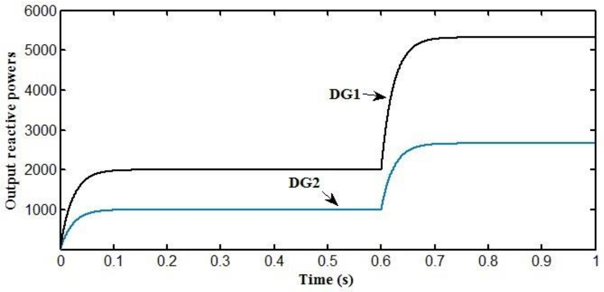

Figure 8. DG1 and DG2 output reactive powers

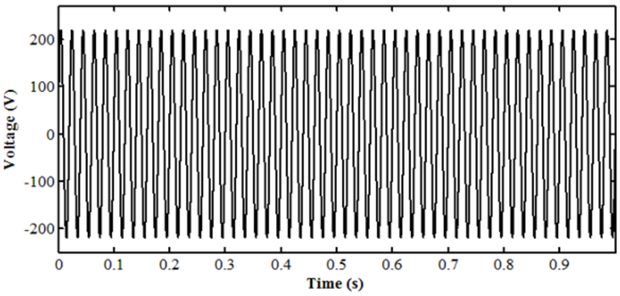

Figure 10. Voltage of the islanded microgrid at PCC

Table 1. Performance comparison

Power-sharing method	**Advantages**	**Disadvantages**
Non-droop-based method	Simple control algorithm. Robust to the controller setting and circuit parameter.	The need for communication links. Difficult to expand. Costly to implement.
Droop-based method	No need for communication links. Less costly to install. The effect of the grid impedance on the power-sharing ratio in the P/V droop. More flexibility, reliability and expandability.	Amplitude and frequency deviation. Poor transient response. Circulating current among the DG units. Coupling between the active and reactive power. Unsuitability for nonlinear loads.

Table 2. The microgrid system parameters

Parameter	**DG1**				**DG2**			
	m_1	n_1	f_n	V_n	m_2	n_2	f_n	V_n
Value	4.7×10^{-5}	0.65×10^{-3}	50Hz	$220\sqrt{2}$	9.4×10^{-5}	1.3×10^{-3}	50Hz	$220\sqrt{2}$
Parameter	Z_1		Z_2		Load		V_{rms}	
Value	$0.03+j1.1$		$0.06+j2.2$		20kW, 3kVar		$220\sqrt{3}$	

5 CONCLUSIONS

For economic, technical and environmental reasons, there is today a trend towards using of microgrids in the power distribution networks. However, the increasing interest in sharing the renewable-energy resources in the microgrids presents a major challenge in terms of reliable operation and control. The main goal of the paper is to analyze the most up-to-date primary control techniques and classify the different power-sharing methods based on whether or not the power-sharing unit employs the concept. A case-study simulation conducted to assess the microgrid operation in the islanding mode. The most important finding drawn from this simulation is that microgrid enhances the reliability of the distribution system by providing power for the sensitive load even when there is no supply from the utility grid.

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Mohammad Jafar Hadidian Moghaddam received his M.Sc. degree from Islamic Azad University, Science and Research Branch, in 2014. His research interests are in renewable energy and migrogrids.

Mehdi Bigdeli received his M.Sc. and Ph.D. degrees from the Faculty of Engineering of the Zanjan University and Islamic Azad University, Sciences and Research Branch, in 2006 and 2012, respectively. His research interests are in fault detection, modeling and application of power systems.

Mohammad Reza Miveh received his B.Sc. (Electronics Engineering) and M.Sc. (Electrical Engineering) in 2009 and 2012, respectively. Currently, he is pursuing the Ph.D. degree (Electrical Engineering) at Universiti Teknologi Malaysia (UTM). His research interest includes microgrid control and protection, smart grid, and power system stability.