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Article

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Research paper

Online optimal stationary reference frame controller for inverter interfaced distributed generation in a microgrid system



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ABSTRACT

This paper presents a novel optimal real-time controller for inverter-based distributed generation units in an islanded microgrid. With respect to the fact that the microgrid has a completely nonlinear structure and its dynamics is constantly changing, the linear controllers with constant and inflexible coefficients cannot maintain proper response in a wide range of operation conditions. Hence, an optimal nonlinear controller that their coefficient are adjusted in a real-time manner based on fuzzy logic is presented. To improve the performance of the proposed real-time controller, its fuzzy system parameters are determined using an offline particle swarm optimization algorithm for various operation conditions. In the proposed real-time controller, proportional-resonant controllers are used due to their advantage in the stationary reference frame for controlling the voltage and current of distributed generation units in the microgrid. Capability and efficiency of the proposed real-time controller are evaluated in different operation scenarios in MATLAB/Simulink environment. The simulation results shows that changing the control coefficients online with respect to operation condition leads to achievement of an optimum answer for voltage during the occurrence of islanding condition and also in case of load variation in the islanded microgrid.

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1. Introduction

In recent decades, the traditional structure of the power grid has fundamentally evolved due to tendency toward electricity generation by distributed generation (DG) units. Increased presence of DG sources in the distribution systems introduces a new concept, called microgrid, in the electrical energy system domain. A microgrid usually consists a set of DG sources, energy storage system and consumers, which should be able to (1) operate in grid-connected mode, (2) operate in autonomous-islanding mode and (3) change from the grid-connect to autonomous-islanding modes and vice versa. With respect to the ability of the microgrid in operating in autonomous-islanding mode and supplying all or a part of the loads in the microgrid after disconnecting from the main grid, the reliability of the microgrid is significantly increased that is the most important feature of the microgrids. Movement towards this form of power grids has many advantages, which include increased reliability, reduced transmission line and distribution feeder congestion and reduced grid losses. The DG units in the microgrid act as current source in grid-connected mode and

voltage source in autonomous-islanding mode (Gao and Irvani, 2008). In the grid-connected mode, the voltage and current in the point of common coupling (PCC) are dictated by the main grid and the available distributed generation units in the microgrid are operated to inject the predetermined active and reactive powers to the grid in the constant-power control mode (Blaabjerg et al., 2006). Under this condition, the injected power by the DG units is constant and it is usually tried to optimize the delivered power generated by the distributed generation units. In this operational condition, every load variation is responded to by the main grid. On the other hand, when the microgrid is disconnected from the main grid, the islanding mode occurs. Managing DG unit's power balance and stability in islanded microgrid is a challenging task since they depend on quite a number of variables. In island operation mode, the DG units control the voltage and frequency through changing the generated active and reactive powers. If the DG units continue to use the control algorithms prior to islanding in the island mode, because of imbalance between the generated and consumed powers in the microgrid, the voltage and frequency will deviate from their nominal values and the microgrid might even go toward instability (Katiraei and Irvani, 2005; Pogaku et al., 2007). In fact, the voltage and current control and power management are among the greatly challenging topics in the islanded microgrid operation context. This is because the

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main grid cannot intervene to regulate the voltage and current and the islanded system's dynamics extremely depends on local load variation. Hence, the DG units should be equipped with voltage and frequency controllers to prevent the voltage and current from deviating from the standard range in the island condition and track the load variation with high accuracy (De Brabandere et al., 2007; Cornforth et al., 2011; He et al., 2012). Various control techniques have been proposed for controlling the distributed generation units in the islanded microgrids (Karimi et al., 0000; Aghajani and Ghadimi, 2018; Liu et al., 2017; Gollou and Ghadimi, 2017). Also, many design theories have been developed for optimal disturbance rejection, most notably, H2 and H ∞ control. H2 control considers white noise disturbances and H ∞ control considers energy bounded L2 disturbances (Mirzapour et al., 2019; Hosseini Firouz and Ghadimi, 2016; Hamian et al., 2018). In reference Leng et al. (2018), a controller based on the classic control is proposed to control a distributed generation in islanded operation condition. In the proposed method, it is required to calculate the transfer function of the whole studied system to design and adjust the controller's parameters, which is one of the disadvantages of this method. In addition, as the studied system grows, calculation of the transfer function of the whole system gets more difficult and complicated. In references Akbary et al. (2019), small signal stability analysis method is used for analyzing the operation details of the control system and properly determining the controller's coefficients in the islanded microgrid. In the proposed method, the nonlinear system is linearized around the nominal operation point using the small signal analysis method and then, the stability and operation are analyzed under different controller coefficients. The small signal linearization method is a common technique for determining the controllers' parameters. However, this method has high intrinsic dependence on its working point. In addition, in case of quick or large change in the system, this method has low dynamic response and might even lead to instability. The most important challenge in optimal determination of control parameter in this method is the complexity of the whole system with respect to presence of states with large dimensions and nonlinear microgrid. To solve the problem in this paper, a simulated model of the microgrid in Matlab/Simulink software environment is used to determine the real-time controller's coefficients. In fact, the control problem in this work is formulated as an optimization problem. Hence, the controller's coefficients are directly applied to the nonlinear simulation model and the results of application of different coefficients on the cost function are determined. The final goal is optimization and optimal determination of parameters associated with real-time voltage controller under different operation conditions. The controller's coefficient are adjusted in real-time and with respect to operation condition in order to achieve microgrid voltage control with the shortest transient state when the islanding, distortion and load change occur in the islanded microgrid.

In general, the presented topics in the paper are in the following order. In the second section the studied microgrid is introduced. The thirds section explains the proposed control design structure of the distributed generation units under islanded microgrid condition and how the real-time voltage controller's parameters are adjusted. In the fourth section, the operation results of the proposed control design in different operation scenarios of the microgrid are shown. Finally, the conclusion is presented in the fifth section.

2. Microgrid system

Fig. 1 shows the single-line diagram of a microgrid simulation model that includes inverter based DGs and loads. The studied microgrid is able to operate in grid-connected and autonomous-islanding modes. The microgrid is connected to a main grid

Table 1
Parameters of the microgrid.

Parameters		Value
Distributed generation units	Active power of the DGs	80 kW
	DC voltage input of the inverter	800 V
	Switching frequency	2000 Hz
	L_{t1}	1.8 mH
	L_{t2}	3.6 mH
	K_p	30
	K_r	250
	ω_0	$2\pi \times 50$
Main grid	ω_c	4
	Main grid voltage	380 V _(L-L)
	Grid frequency	50 Hz
	R_s	1.5 m Ω
	L_s	0.2 mH
Local load	R_L	1.805 Ω
	L_L	3.192 mH
	C_L	3.174 mF

through circuit breaker (CB). The main grid in this study is modeled by a voltage source, a resistive and an inductive load and also the local load is modeled using an RLC load. The two inverter-interfaced DGs considered here have the same power and voltage ratings. In the simulations, the DG units in the microgrid are modeled as a constant DC voltage source which is connected to the main grid and local load through a power electronic inverter with a low-pass filter. The main role of inverter is controlling the injected active and reactive powers by the DG units to microgrid. When the CB opens and islanding condition occurs, with respect to imbalance in the generated and consumed powers inside the microgrid, the voltage and frequency of microgrid may deviated from their nominal values and the grid might move further toward instability. The voltage and frequency will be constant only when the consumed power in the local loads are equal to the generated power in the DG units. However, due to later change in the local load consumption, the microgrid might go toward instability again. Hence, the islanding condition should be detected and a controller suitable for the operation condition of the microgrid should be activated. Thus, the DG units should be equipped with controllers suitable for every operational condition of the microgrid. Constant-current control method is designed and implemented on distributed generation units in the studied microgrid in the grid-connected mode. The block diagram of the constant-current control system in the stationary reference frame is demonstrated in Fig. 2. However, because of losing the large and powerful upstream grid in the islanded operation condition, the microgrid will face problems and threats such as deviation and even instability of voltage and frequency due to sudden change in load and occurrence of error. In the next section of the paper the proposed control method for DG units in islanded operation mode will be stated with more details. It should be noted that the value of the associated parameters with the studied microgrid is presented in Table 1.

3. The proposed control scheme

This paper presents a novel intelligent control for autonomous operation of inverter-interfaced DG units and its local load after islanding from the main grid. The proposed control system of the DG units consists of active and reactive power droop controllers, proportional-resonant (PR) voltage and current controllers. For inverter-based autonomous microgrid, the droop control is widely used to regulate the power flow according to the local information with no need of communication (Ebrahimian et al., 2018). The design of the droop controllers is sufficiently studied in the literatures Khodaei et al. (2018), Mohamed and

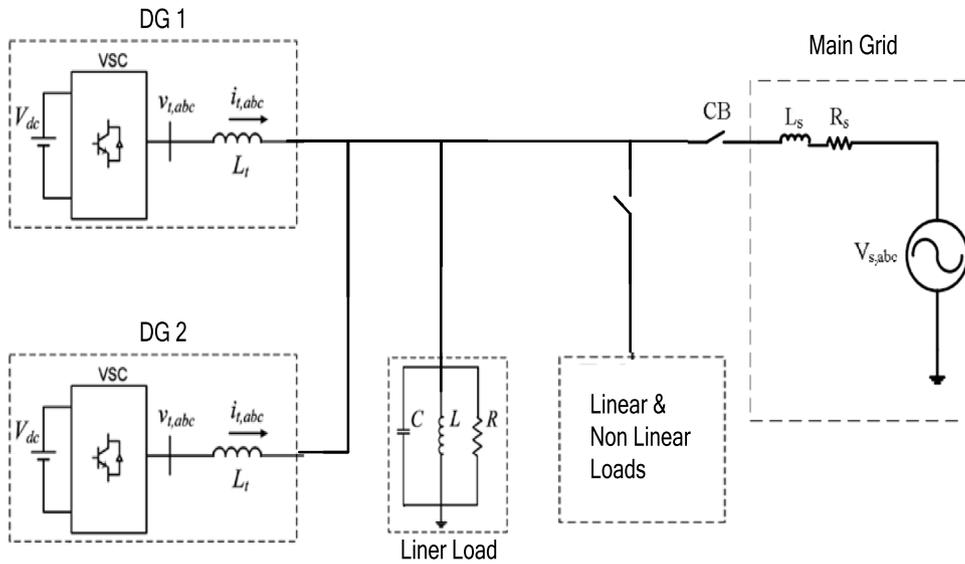


Fig. 1. Single-line diagram of the studied microgrid.

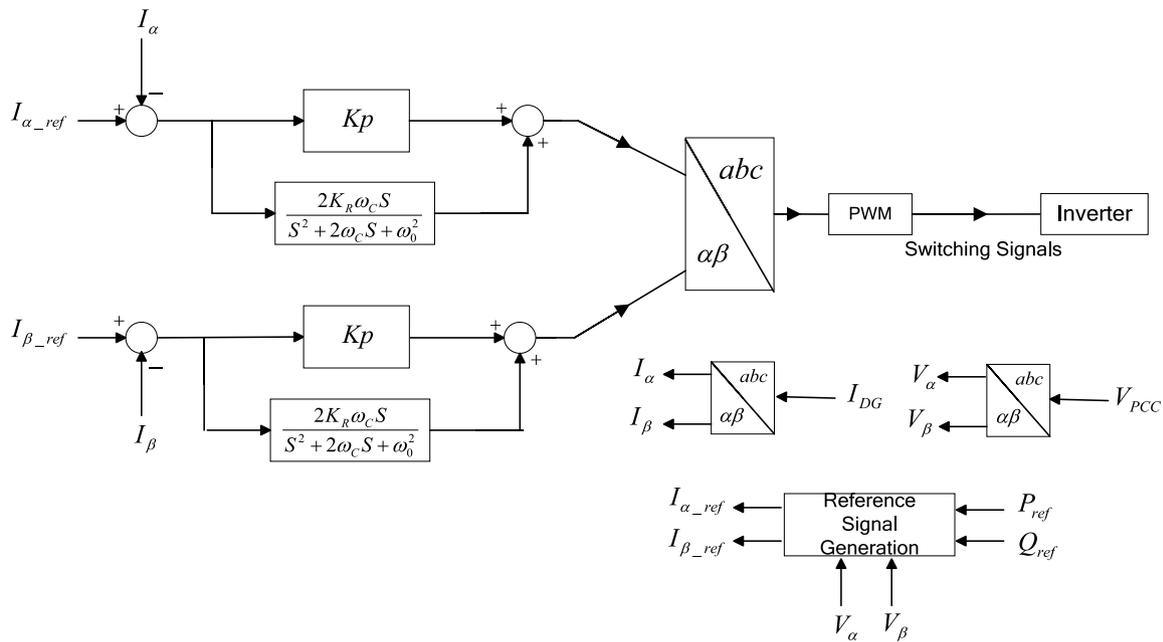


Fig. 2. The structure of the constant-current controller scheme for the DG units in stationary reference frame for grid connected mode.

El-Saadany (2008), Guerrero et al. (2007, 2011) and will not be discussed in this paper. In the island mode, the DG voltage may vary with a certain amount of uncertainties because the droop controllers adjust them to compensate the instant power mismatch. This paper focuses on controller design for individual power inverters that accommodates variations in the voltages of microgrid. Despite the possibility of designing the microgrid with island functionality, transition from the grid-connected mode to islanded mode can be very challenging. For this purpose, safe and proper operation of the islanded microgrid requires making fundamental changes in the tasks and goals of the DG unit's controller in the islanded microgrid. Because of ability to operate in both grid-connected and autonomous-island modes, the DG units should be equipped with controllers suitable for the mentioned conditions. In addition, the controller should have a proper performance during the transition between these two modes. Therefore, the DG units and the local loads of Fig. 1

must remain in service in both grid-connected and islanded modes. It should be noted that control of inverter-based DG units has been implemented in synchronous (dq), stationary ($\alpha\beta$), or natural (abc) reference frames and depending on the reference frame used, the adopted control structures can be chosen from linear or nonlinear algorithms such as proportional integral (PI), proportional resonant (PR), vector control, hysteresis control, etc. The synchronous reference frame which has received more attention uses a Park transformation to convert three-phase rotating quantities to direct and quadrature dc variables. These dc quantities can be regulated by using PI controllers. Despite good performance in controlling dc variables, PI controllers have the well-known drawback of a nonzero steady state error; furthermore they fail to operate well in case of load changes and high penetration of DGs in microgrids. Poor compensation capability for low-order harmonics has also been reported. Application of PR controllers in the stationary reference frame eliminates

the steady state error, however, it is accompanied with other drawbacks such as sensitivity to grid frequency variations, poor transient response during step changes, and low stability margins. Therefore, in order to control DG units in the proposed method a proportional-resonant (PR) controller is used.

This paper focuses on how to design and to determine the voltage controller parameters for the inverter-based DGs in microgrid. The goal of the proposed control scheme is controlling the islanded microgrid's voltage in the nominal state with the shortest transient state when the islanding condition, disturbance and load change occur in the microgrid. The block diagram of the proposed control scheme for the DG units in islanded operation mode of the microgrid is shown in Fig. 3. The DG units and the local load form an island and operate as an autonomous system by opening switch CB, Fig. 1. To maintain uninterruptible operation after an islanding event, the event must be detected and a new control strategy that can regulate voltage magnitude of the island should be activated. In the presented studies, it is assumed that the islanding event is detected based on an existing method in Hashemi et al. (2016) and upon detection, the control is changed from the grid connected control mode to the proposed control mode.

For the purpose of controlling the DG units in the islanded microgrid and assure the proper performance of the proposed scheme in presence of imbalanced and nonlinear loads, current inner control loop and voltage outer control loops are designed. In the proposed control method, the DG terminal voltage (V_{PCC}) and output current of the DG (I_{DG}) are converted from abc space to $\alpha\beta$ using the Clarke transformation. Based on reference Akagi et al. (1984), the instantaneous active and reactive powers can be calculated using Eqs. (1) and (2) and voltage and current components in $\alpha\beta$ space.

$$P = v_{\alpha}i_{\alpha} + v_{\beta}i_{\beta} \quad (1)$$

$$Q = v_{\beta}i_{\alpha} - v_{\alpha}i_{\beta} \quad (2)$$

Using two first-order low-pass filters, the DC component of the active and reactive powers are extracted and applied to the droop power controller. Cutoff frequency (ω_c) of the low-pass filter is assumed to be 10 rad/s. In the proposed control method, a droop controller is used for controlling the active and reactive powers and a proportional-resonant (PR) controllers in stationary reference frame ($\alpha\beta$) are used for voltage outer loop and current inner loop of the DG units in the islanded microgrid. Generation of reference output active and reactive power in each DG unit of the microgrid is determined using the droop characteristics of the voltage and current according to the following equations:

$$P_{ref} = P_0 + K_{pf}(f_0 - f) \quad (3)$$

$$Q_{ref} = Q_0 + K_{qv}(V_0 - V) \quad (4)$$

where, P_0 and Q_0 are assumed values of active and reactive powers in each DG unit in grid-connected mode, respectively. Parameters f_0 and V_0 are nominal frequency and voltage, respectively. f and V are frequency and voltage of point of common coupling, and coefficients K_{pf} and K_{qv} are associated with droop controller. P_{ref} and Q_{ref} are reference modified active and reactive powers in each DG unit in islanded condition. The output of the droop controller of the active and reactive power include reference values for frequency and voltage amplitude of the three-phase system. The three-phase reference voltage signal generation is transferred from abc space to $\alpha\beta$ using Clarke transformation. The reference parameters V_{α}^* and V_{β}^* are constantly compared to distributed generation voltage terminal, i.e. V_{α} and V_{β} , and the error is applied to the real-time fuzzy proportional-resonant controller. The coefficients of the PR controller are changed with respect to the error amount (e) and error change (Δe) in two

axis of α and β to achieve the desired reference value. With respect to the inaccurate performance of the integrator section of the resonant controller due to factors such as input signal frequency variation and difference between the input signal and resonant frequency of the controller and to solve the problem in the proposed scheme, the generated reference frequency by the droop power controller is considered as an input for the voltage and current PR controller. The current controller is included as a PR controller with constant coefficients in the proposed scheme. Finally, the output of the current controller is again converted from $\alpha\beta$ space to abc and switching frequency is prepared and sent to the DG unit's inverter.

3.1. Structure of real-time proportional-resonant voltage controller

This paper proposed a method to determine the voltage controller parameters for the inverter-based DGs in microgrid. The most critical problem for control parameter optimization is the complexity of overall systems due to the high state dimensions and nonlinearity of microgrids. Common approaches are based on small signal linearization but small-signal models intrinsically depend on specific operating points. In the proposed method, given that the microgrid has a completely nonlinear structure and its dynamics is constantly changing. And also, usual uncertainties in power systems cause the classic controllers to be unable to provide a proper performance over a wide range of operating conditions. In response to this challenge, the present paper addresses a new online intelligent approach by using a combination of the fuzzy logic and the particle swarm optimization (PSO) techniques for optimal tuning of the PR voltage controllers. With respect to the fact that the microgrid has a completely nonlinear structure and its dynamic is constantly changing, the classic linear controllers with constant coefficients cannot maintain their proper response in a wide range of operation points. Hence, using the real-time nonlinear controller whose coefficients change with respect to operation condition is an essential measure. In fact, the main purpose of the proposed controller is real-time adjustment of the voltage controller's coefficients to maintain the nominal voltage level and improve the transient response during the occurrence of islanding condition and load variation in the islanded microgrid. In the proposed control method, the controller's coefficients change with respect to conditions and based on an optimized fuzzy logic. Despite the classic controllers, the fuzzy controller controls the system using a series of rules, which are stated in fuzzy if-then form without needing the mathematical model. It is necessary to mention the fact that optimum operation of the fuzzy controllers depends on the proper adjustment of their parameters. Scale coefficient, membership function (MF), fuzzy rules, weighted coefficients of the rules, fuzzification and defuzzification inference algorithms are some of the adjustable parameters in a fuzzy system. Adjusting all of these parameters requires a lot of trial and errors. For accurate adjustment of the parameters in this paper, it is stated in form of an optimization problem. However, because of large number of parameters, only scale coefficients are chosen to be adjusted by the PSO algorithm to decrease the computational burden. Fig. 4 shows the voltage controller's parameter adjustment strategy based on fuzzy logic by the optimization algorithm. Inputs of the real time PR controller based on fuzzy logic (FL) are including error, error change.

Because of being effective in vague environments and using human knowledge, Mamdani fuzzy inference system is used in the proposed controller. Triangular and symmetrical functions are considered for membership functions for input and output variables to decrease the computational burden and required memory. The input and output variables of the fuzzy system in

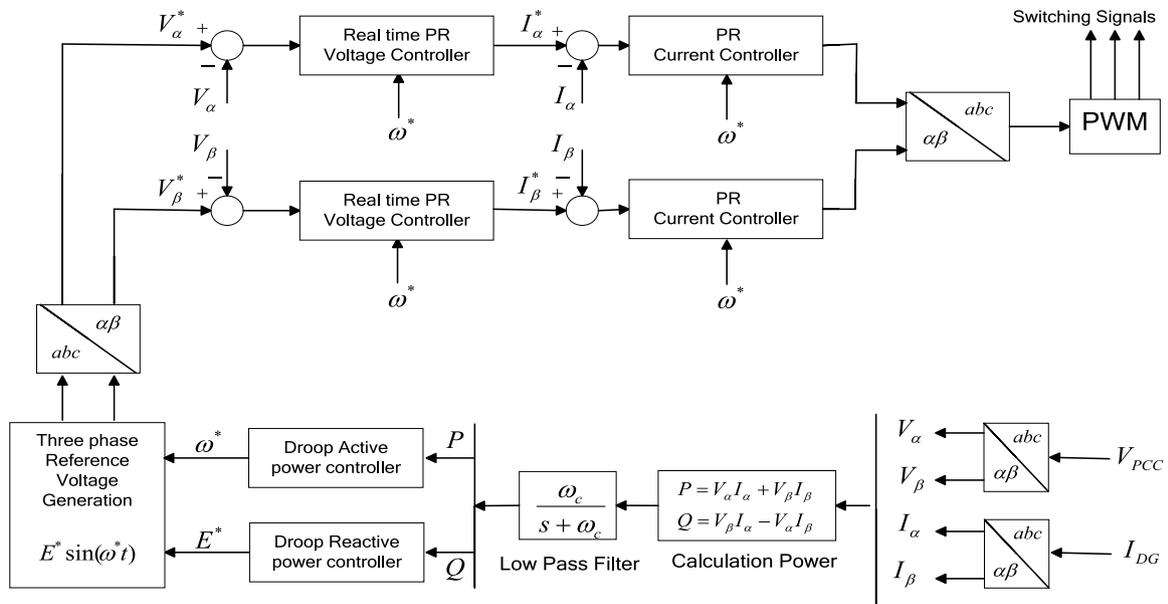


Fig. 3. The structure of the proposed controller scheme for the DG units of the islanded microgrid.

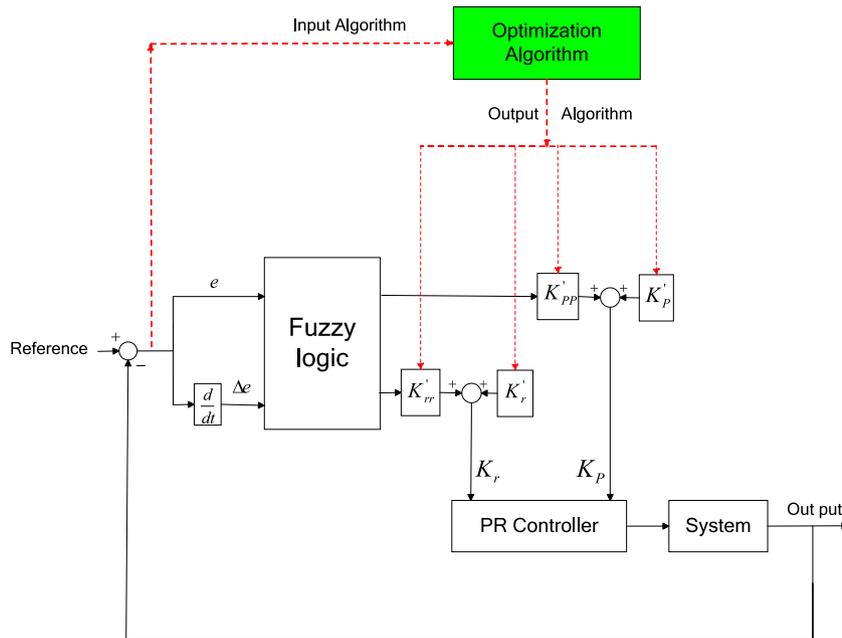


Fig. 4. Proportional-resonant voltage controller's parameter adjustment strategy using PSO algorithm.

the proposed controller are defined by seven linguistic variables. The label of these variables are Positive Big (PB), Positive Medium (PM), Positive Small (PS), Zero (Z), Negative Small (NS), Negative Medium (NM) and Negative Big (NB), which have 50% Overlap. The considered membership function for input and output signals in the range of $[-1 \ 1]$ are shown in Fig. 5. In the proposed fuzzy system, the AND fuzzy operator is min type and the numerical value of the fuzzy system output is obtained using the centroid of area method in the defuzzification stage. The rules of the fuzzy system inference and membership function are determined based on the qualitative assessment of the studied power system and conducting different simulations on different scenarios of the microgrid, which are shown in Tables 2 and 3, respectively.

Table 2
Fuzzy inference system rules for the proportional coefficients.

e(k)	$\Delta e(k)$						
	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PM	PM	PS	PS	ZE
NM	PB	PB	PM	PM	PS	ZE	ZE
NS	PM	PM	PM	PS	ZE	NS	NM
ZE	PM	PS	PS	ZE	NS	NM	NM
PS	PS	PS	ZE	NS	NS	NM	NM
PM	ZE	ZE	NS	NM	NM	NM	NB
PB	ZE	NS	NS	NM	NM	NB	NB

3.2. Particle swarm optimization algorithm

Recently, computational intelligence algorithms such as particle swarm optimization (PSO) have been applied to different

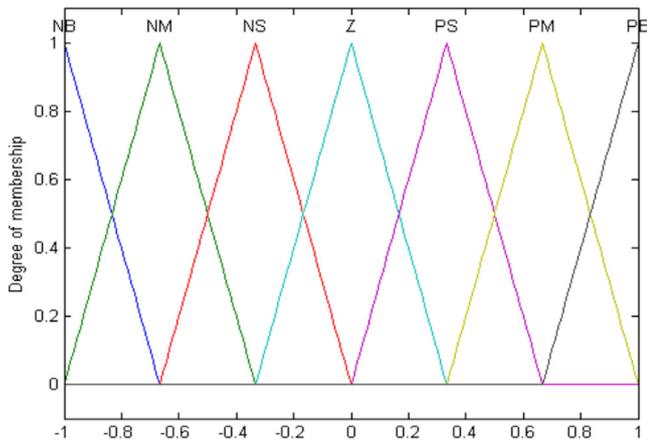


Fig. 5. Membership function of the input and output signals.

Table 3
Fuzzy inference system rules for resonant coefficients.

e(k)	$\Delta e(k)$						
	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NM	ZE	ZE
NM	NB	NB	NM	NM	NS	ZE	ZE
NS	NM	NM	NS	NS	ZE	PS	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	NS	ZE	PS	PS	PM	PM
PM	ZE	ZE	PS	PM	PM	PB	PB
PB	ZE	ZE	PS	PM	PB	PB	PB

power system problems with impressive successes. The PSO algorithm is a type of evolutionary algorithms and is able to explore wide search spaces with large dimensions. PSO has been widely implemented and stamped as one of the promising optimization technique due to its simplicity, computational efficiency, high convergence speed and low probability of getting trapped in the local minimums (Kennedy and Eberhart, 1995; Liu et al., 2008; Al-Rashidi and El-Hawary, 2008; Robinson and Rahmat-Samii, 2004; Shi and Eberhart, 1998). Unlike the other heuristic techniques, PSO has a flexible and well-balanced mechanism to enhance the global and local exploration abilities. The performance of this evolutionary algorithm is based on the intelligent movement of each particle and collaboration of the swarm. In the standard version of the PSO, each particle starts from a random location and searches the space with its own best knowledge and the swarm’s collective experience. The search rule can be expressed by simple equations with respect to the position vector $X^i = (x_1^i, x_2^i, \dots, x_m^i)$ and the velocity vector $V^i = (v_1^i, v_2^i, \dots, v_m^i)$ in the n-dimensional search space:

$$V_i^{k+1} = \omega V_i^k + c_1 \cdot rand_1 \cdot (X_{pbest_i}^k - X_i^k) + c_2 \cdot rand_2 \cdot (X_{gbest}^k - X_i^k) \quad (5)$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (6)$$

$$\omega = \omega_{max} - (\omega_{max} - \omega_{min}) \cdot (k/N) \quad (7)$$

where V_i^k is the velocity of particle i at iteration k , X_i^k is the position of particle i at iteration k , ω is the weight inertia, c_1 and c_2 are acceleration constant, $rand_1$ and $rand_2$ are random numbers between [0, 1], $X_{pbest_i}^k$ and X_{gbest}^k are the best positions that particle i has achieved so far based on its own experience and the best position so far based on overall swarm’s experience, respectively.

3.3. Objective function

The controller optimization can be done by minimizing objective function, which can yield a stable system with small

Table 4
Different operation scenario of the microgrid.

Scenario	Quantity	Variation range
Islanding condition occurrence	50	$S_{Local\ load} = [10-160]$ kVA
		$S_{DC1} = [10-80]$ kVA
		$S_{DC2} = [10-80]$ kVA
Load variation in the islanded microgrid	50	$S_{Local\ load} = [10-160]$ kVA
		$S_{Motor} = [20-100]$ kVA
		$P_{Nonlinear} = [50-100]$ kW

steady-state errors. Choosing a proper objective function plays an important role in the optimization process. One of the important goals of designing a controller is improving the response time of the system. Decreasing the steady-state error of the system and properly reducing the overshoot and undershoot are factors that affect the system response. In this paper, to achieve these goals, the objective function is considered in form of integral of the multiplication of time and absolute error (ITAE) of DG unit’s voltage, which is formulated as Eq. (8):

$$Fitness_function = \int_0^{T_s} t(|V_{ref\alpha\beta} - V_{o\alpha\beta}|) \quad (8)$$

The parameter T_s is the time taken for calculations after the occurrence of islanding condition or load variation in the islanded microgrid. The ITAE technique allocates far more weight to the error that has been existing for a long time compared to the errors occurred in the beginning of the solution. Existence of time multiplication implies more penalty for steady-state errors and, hence, effectively decreases the settling time. In addition, because of presence of absolute error in the objective function, the overshoot percentage is minimized.

3.4. Different operation scenarios

For optimum adjustment of the fuzzy system coefficients of the proportional-resonant voltage controller using the optimization algorithm, the studied microgrid is operated in different scenarios. Table 4 shows the different simulated operation scenarios of the studied microgrid for optimum adjustment of the fuzzy system coefficients in the voltage controller.

3.5. Application to control parameter tuning

In this paper, in order to determine the control parameters for fuzzy system coefficients in the proposed real-time PR controllers, an optimization method based on cost function is proposed. The objective function is calculated for all of the mentioned scenarios in Table 4 for each member of the optimization algorithm. This process is conducted continuously for the determined iterations for the optimization algorithm and finally the optimum values for coefficients K_p' , K_{pp}' , K_r' and K_{rr}' are determined through minimization of the objective function by PSO algorithm. It should be noted that, with respect to stability considerations and maintenance of proper function of the controller during different simulation, the variation range for controller’s range are obtained to be [0.1–100]. In addition, the total iterations for the PSO algorithm and initial populations are 200 and 50, respectively. The obtained parameters from the optimization algorithm associated with the proportional-resonant PR voltage controller’s coefficients and the considered coefficients for the proportional-resonant current controller, cutoff frequency of the proportional-resonant controllers, frequency-active power droop control coefficient and voltage-reactive power droop control coefficient, which are shown in Fig. 3, are presented in Table 5.

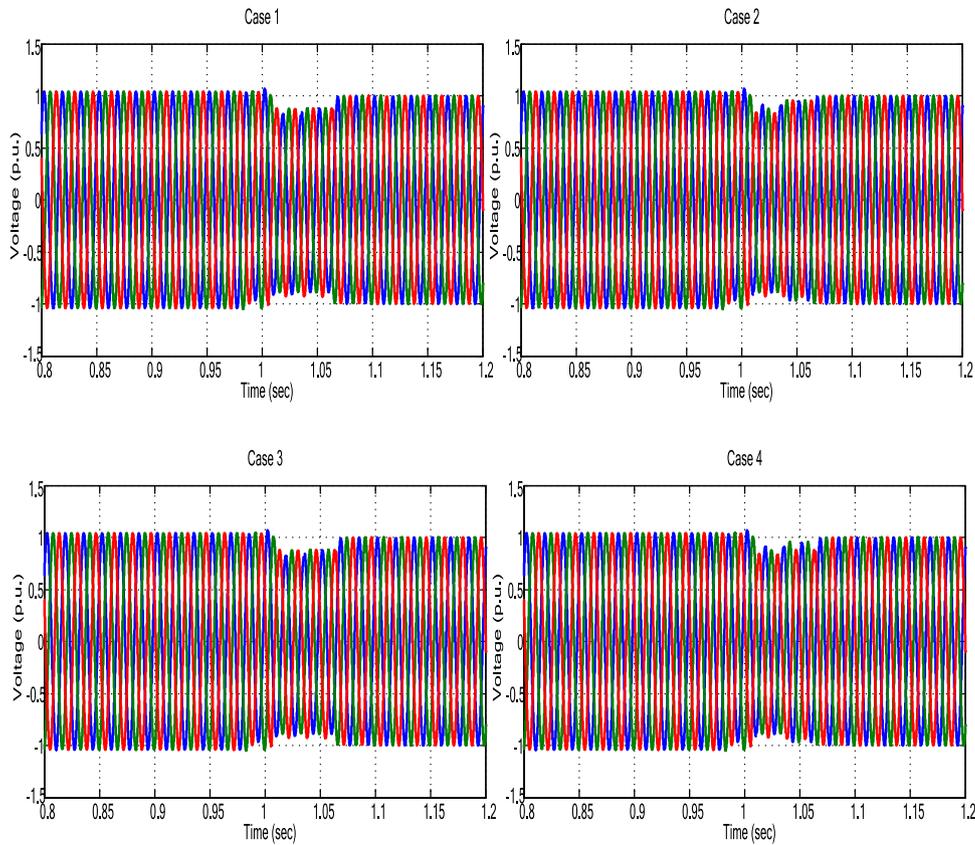


Fig. 6. The three-phase voltage of DG1 terminal for the occurrence of islanding condition.

Table 5

Parameters of the proposed control scheme.

Proportional-resonant voltage controller	K_p'	5
	K_{pp}	25
	K_r'	50
	K_{rr}	8
	ω_c	4
Proportional-resonant current controller	K_p	10
	K_r	25
	ω_c	4
Droop power controller	K_{pf}	0.0002
	K_{QV}	0.004

Table 6

Power generation in distributed generation units and local load for islanding occurrence condition.

	Case 1		Case 2	
	DG1	DG2	DG1	DG2
Active power	30	50	80	40
Reactive power	zero	zero	zero	zero
	Case 3		Case 4	
	DG1	DG2	DG1	DG2
Active power	20	50	80	20
Reactive power	40	30	zero	20

4. Simulation results

This section evaluates performance of the studied microgrid system of Fig. 1 after an islanding event, based on the proposed novel intelligent controller. To show the superiority of the proposed control scheme, its performance and efficiency in islanding occurrence scenarios in different conditions of the DG units and local load variation in island condition are assessed in this section.

4.1. The occurrence of the islanding condition

In this section, the performance of the proposed control scheme for occurrence of the islanding condition for studied microgrid is analyzed. The system in Fig. 1 initially operates in a grid connected mode. In all of the analyzed conditions, the islanding occurs at $t = 1$ s and the local load is considered to be $R = 1/805$ (Ω), $L = 3.192$ (mH) and $C = 3.174$ (mF). Table 6 describes the amount of power generation of DG units for testing the occurrence of islanding condition.

To show the robustness of the proposed control method, the size of local loads chosen for the case studies in Table 6 are such that the imbalance in active power is maximum after islanding condition occurrence, which is in order to impose a difficult condition for the microgrid controller. The waveform of the three-phase voltage in the point of common coupling (PCC) and frequency of DG1 for each of the studied conditions are shown in Figs. 6 and 7, respectively. In the grid-connected mode, the bus voltage and system frequency are well maintained around the nominal values (1.0 p.u. and 50 Hz). After analyzing the waveform of the three-phase voltage in the common coupling point, it is suggested that the proposed controller has a proper response for regulating the microgrid voltage and is able to obtain the final response after a short transient time with low harmonic distortion during and after islanding condition occurrence.

4.2. Load variation in the islanded condition

In this section, the performance of the proposed control method for load variation in islanded microgrid is analyzed.

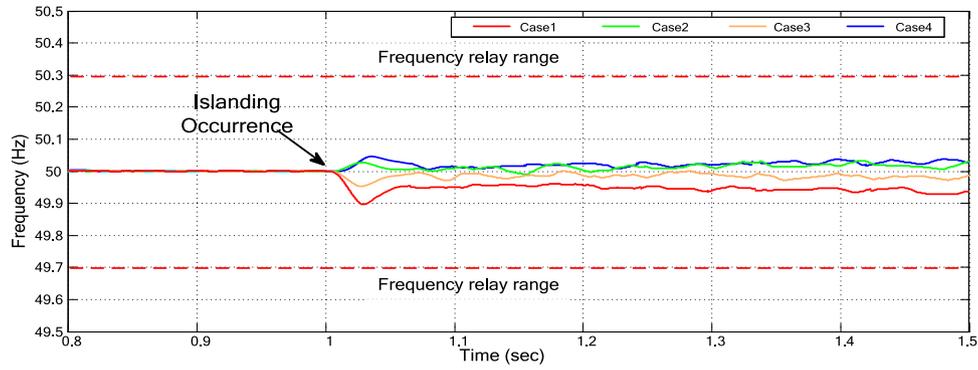


Fig. 7. Frequency signal of DG1 for the occurrence islanding condition.

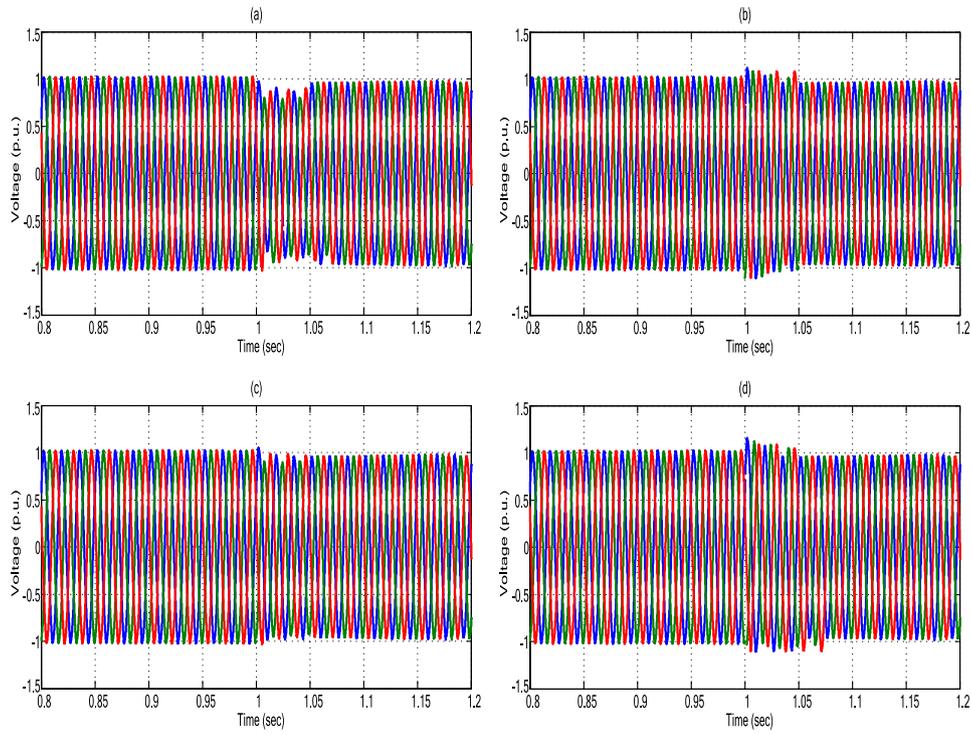


Fig. 8. The three-phase voltage of DG1 terminal for load variation condition.

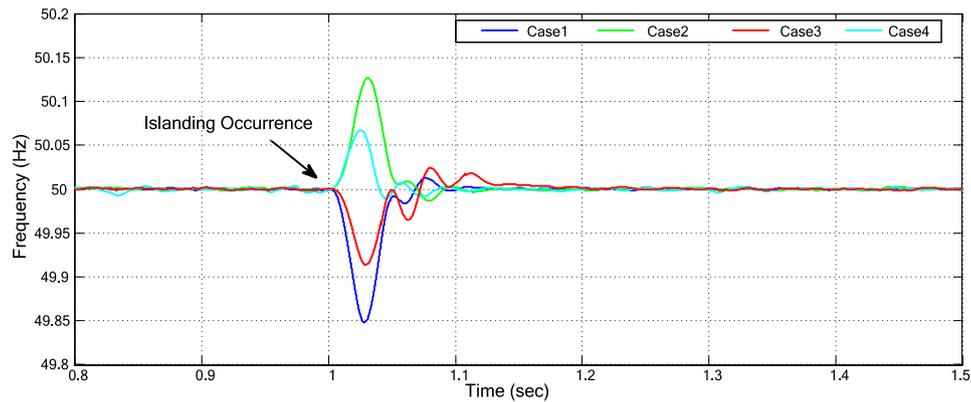


Fig. 9. Frequency signal of DG1 for the load variation condition.

Different tests under various local load conditions are shown in Table 7. To show the robustness of the proposed method, all of the considered tests are accompanied with the highest variation.

In all of the analyzed cases in Table 7, the changes occur at $t = 1$ s. Waveform of the three-phase voltage in the common coupling point and frequency of distributed generation units under each

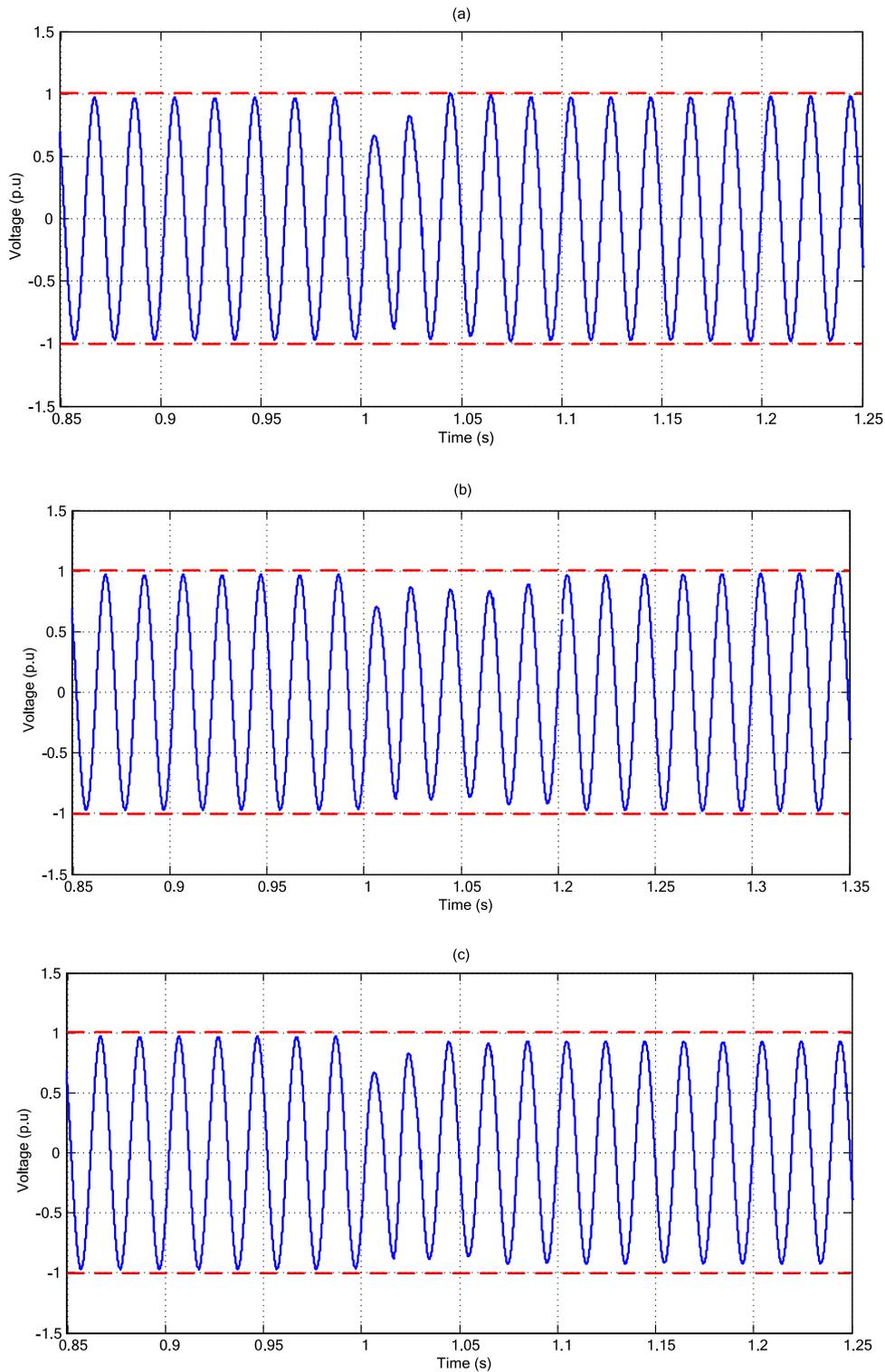


Fig. 10. The voltage of DG1 terminal, (a) with proposed controller, (b) with the controller in Ref. [Khorramabadi and Bakhshai \(2015\)](#), (c) with the controller in Ref. [Aghajani and Ghadimi \(2018\)](#).

analyzed condition are shown in [Figs. 8 and 9](#), respectively. After analyzing the waveform of the three-phase voltage in the common coupling point, it is suggested that the proposed controller has a proper response for regulating the microgrid voltage and is able to obtain the final response after a short transient time with low harmonic distortion during and after load variation.

4.3. Comparison between the proposed control method and other methods

This section evaluates performance of the proposed intelligent control with other control method. To show the robustness of the proposed controller, its performance is compared to the proposed control method in reference [Aghajani and Ghadimi \(2018\)](#) and [Khorramabadi and Bakhshai \(2015\)](#).

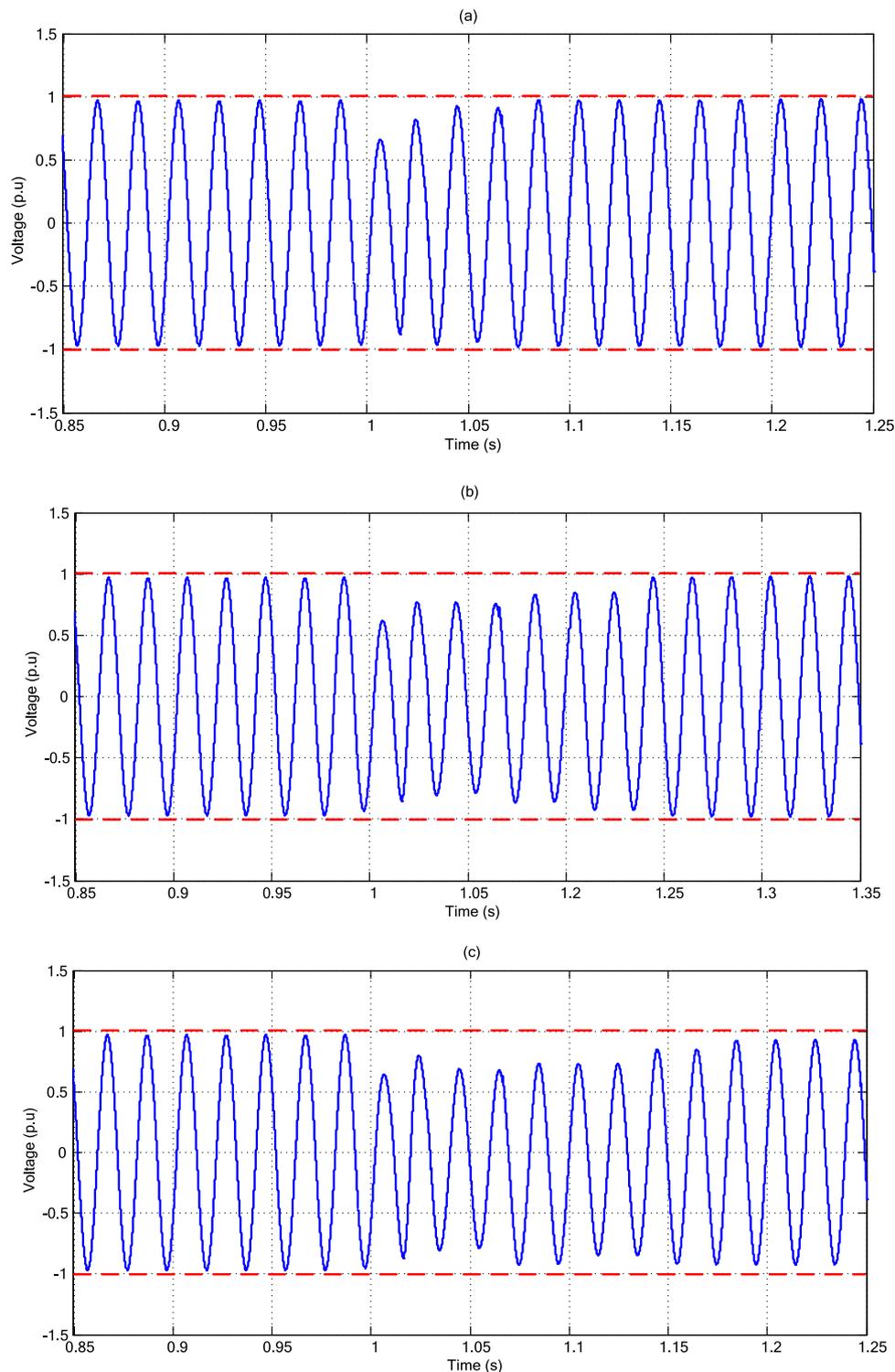


Fig. 11. The voltage of DG1 terminal, (a) with the proposed controller, (b) with the controller in Ref. [Khorramabadi and Bakhshai \(2015\)](#), (c) with the controller in Ref. [Aghajani and Ghadimi \(2018\)](#).

4.3.1. Load condition 1

This case study demonstrates performance of the designed controller for islanding condition. In this condition, the system is islanded at $t = 1$ s by opening CB of [Fig. 1](#). Upon this event is detected by islanding detection method the DG control strategy is changed to proposed method. The each DG unit power is set to generate 80 kW and the local load power amount is 200 kW. The terminal voltage of DG1 for this scenario with the considered controller is demonstrated in [Fig. 10](#). It is observed that after two

cycles of transients, the load voltage is regulated at the desired reference value of 1.0 p.u. by the proposed optimal real-time controller.

4.3.2. Load condition 2

This subsection demonstrates performance of the designed controller under load change in islanded microgrid. While the system in [Fig. 1](#) is operating in the islanded mode with initial local load of 65 kW, another load with the size of 100 kW is connected

Table 7
Variation type and size of the local load in the local microgrid.

Test	Case 1		Case 2	
Variation type	Linear load connection		Linear load disconnection	
Local load size	Local load 1	Local load 2	Local load 1	Local load 2
	R (Ω) = 1.805	R (Ω) = 1.805	R (Ω) = 1.805	R (Ω) = 1.805
	L (mH) = 3.192	L (mH) = 3.192	L (mH) = 3.192	L (mH) = 3.192
	C (mF) = 3.174	C (mF) = 3.174	C (mF) = 3.174	C (mF) = 3.174
Test	Case 3		Case 4	
Variation type	Nonlinear load connection		Nonlinear load disconnection	
Local load size	Local load 1	Local load 2	Local load 1	Local load 2
	R (Ω) = 1.805	55 kW	R (Ω) = 1.805	45 kW
	L (mH) = 3.192		L (mH) = 3.192	
	C (mF) = 3.174		C (mF) = 3.174	

to the network at $t = 1$ s. The terminal voltage of DG1 for this scenario with the considered controller is demonstrated in Fig. 11. It is observed that after very short transient time the load voltage is regulated at the desired reference value of 1.0 p.u.

The reported case studies demonstrate that the designed optimal real-time controller is capable of maintaining the magnitude of the PCC voltage at 1 p.u. after a short transient time, whereas, the proposed controller in Ref. Khorramabadi and Bakhshai (2015) takes longer transient time to reach 1 p.u. and the proposed controller in Ref. Aghajani and Ghadimi (2018) has a small steady state error.

5. Conclusion

This paper present an optimal real-time controller design for inverter-based DGs in island operation mode of microgrid. Because of nonlinear nature of the microgrid structure and constant changes in the microgrid topology, it is impossible to obtain an optimum solution for all of the microgrid operation conditions by constant-coefficient controllers. Proper design of the distributed generation unit controller in the microgrid with the purpose of improving the transient response, maintaining the essential parameters of the microgrid close to their nominal values and minimizing their fluctuations in the transient state and load variation in the islanded microgrid is one of the important and essential priorities in correct operation of microgrids. In this study, the challenge of microgrid voltage control is stated as an optimization problem and the particle swarm optimization (PSO) algorithm is used for determining the parameters of the real-time voltage controller. The obtained results from the proposed method shows that the changing the control coefficients in a real-time manner with respect to the operation condition results in achievement of the optimum solution for the voltage during the occurrence of islanding condition and load variation in the islanded microgrid.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit authorship contribution statement

Xiao-yan Jiang: Conceptualization, Data curation, Writing - original draft, Writing - review & editing. **Chuan He:** Conceptualization, Data curation, Writing - original draft, Writing - review & editing. **Kittisak Jermsittiparsert:** Conceptualization, Data curation, Writing - original draft, Writing - review & editing.

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