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Managing the Distributed Generation Units in a Microgrid using a Fuzzy-PI Controller

Abstract. *A power distribution system with distributed generations can operate as a microgrid under specific conditions. A microgrid can be operated under grid-connected and islanded modes seamlessly without disrupting the loads within the microgrid. This study analyzes the intelligent control of a microgrid with a pulse-width modulation-controlled voltage source inverter. Switching patterns are generated through a fuzzy proportional-integral (PI) controller. This study aims to develop a fuzzy-PI controller and compare its performance with that of a PI controller in controlling the voltage and frequency of a microgrid under disturbances in a Matlab/Simulink environment. Results show that the fuzzy-PI controller has higher capability, precision, and robustness than the PI controller in quickly restoring and stabilizing the microgrid. A simulation experiment is also performed to verify the greater validity and effectiveness of the microgrid equipped with the fuzzy-PI controller than with the PI controller. The developed fuzzy-PI controller can reduce the total harmonic distortion by 0.46%.*

Streszczenie. W artykule analizowano inteligentne sterowanie mikrosiecią z wykorzystaniem przekształtnika sterowanego metodą modulacji szerokości impulsu. Jako sterownik wykorzystano proporcjonalno całkujący układ z logika rozmytą. Zbadano pracę układu w sieci z zakłóceniami. Stwierdzon znaczące przewagi kontrolera pracującego z logika rozmytą w porównaniu do układów konwencjonalnvch. ***Zarządzanie rozproszonymi generatorami w mikrocieci z wykorzystaniem sterowników o logice rozmytej***

Keywords: microgrid, fuzzy proportional-integral, voltage-source inverter, voltage control, frequency control, pulse-width modulation, Matlab/Simulink
Słowakluczowe: mikrosieć, zarządzanie generatorami, sterowniki fuzzy logic

Introduction

A microgrid installed with distributed generations (DGs) is a new type of power system [1]. DGs, which include microturbines, photovoltaics, wind cells, and fuel cells, are small generation units of less than 100 kW. At present, power systems are experiencing a rapid growth in the connection of DG units. Integrating DGs in a distribution system offers technical, environmental, and economic benefits. Moreover, such integration allows distribution utilities to improve system performance by reducing power losses [2].Electric energy market reforms and developments in electronics and communication technology enable the advanced control of DGs [3].

DG units can be integrated and efficiently operated as a microgrid in grid-connected and islanded modes [4]. A microgrid system can strategically be placed on any site in a power system for grid reinforcement, thereby deferring or eliminating the need for system upgrades and improving system integrity, reliability, and efficiency of the existing power system [5,6]. Therefore, many efforts have been exerted to control power electronic converters and thus allow the grid connection of microgrids in a distribution system. This technique is necessary to maximize the potential of DGs to enhance power quality and reliability and provide auxiliary services, such as active reserve, load-following, interruptible loads, reactive reserve, and restoration [7]. A microgrid operated in islanded mode is controlled by several inverters connected in parallel and sharing load to maintain voltage and frequency. Among the various techniques applicable to parallel inverter control in islanded mode operation, voltage and frequency droop-based methods are appropriate to fulfill the requirements for communications control. Active power acts on voltage, and reactive power acts on frequency. That is, the active power output is dependent on local voltage. PI controllers have simple control structures and maintenance. However, the performance of these controllers degrades as the system operating conditions change. Fuzzy logic controllers are superior to conventional controllers because they can be easily adapted to different system structures, parameters, and operation points. In addition, they can be implemented in large-scale nonlinear systems. Thus, many researchers have attempted to combine conventional PI with fuzzy logic controllers to improve performance.

New droop-based decoupling fuzzy-PI techniques have been proposed to control microgrids. These techniques control the frequency and voltage in a microgrid under islanded operation depending on the performance of a voltage-source inverter (VSI). This fuzzy-PI controller consists of a fuzzy logic controller and a conventional PI connected in series. The fuzzy logic controller has two input signals, and the output signal of the fuzzy logic controller is the input signal to the conventional PI controller. The control performance of the fuzzy-PI controller is tested under load conditions using the MATLAB/SIMULINK simulation platform. In this study, fuzzy-PI controller algorithm, strategies, and modeling are developed and simulated in MATLAB/SIMULINK to develop an intelligent control technique for a microgrid in grid-connected and islanding modes. The main objective of the inverter control system is to generate and stabilize the 50 Hz sinusoidal-shape AC (alternating current) output voltage and frequency. With the grid synchronization algorithm, we can interconnect the inverter to the utility grid. The proposed fuzzy-PI control strategy has better robustness and adaptability with respect to the different parameters than the conventional strategy. The simulation results demonstrate that the model is potentially useful in studying the microgrid system. It is especially suitable for a microgrid operated in both grid-connected and islanded modes. The microgrid system simulation model is built in the MATLAB/Simulink environment and implemented using the SimPowerSystem toolbox.

Microgrid System Description

Fig. 1 illustrates a block diagram of the proposed microgrid system with VSI. As illustrated, this system consists of the control system and an inverter with filter that interfaces the DGs with the grid. The DGs generally used in a microgrid are photovoltaic, fuel cell, and microturbine generators. The configuration and utilization of a set of DGs usually depend on customer needs and load criticality. The DC power sources can either be directly interfaced to the AC system through an inverter or be first set to an inverter-compatible DC voltage level using a DC–DC converter and then converted into three phases using an inverter. AC power sources (e.g.,microturbines) that produce power at high frequencies are first rectified and then converted to three-phase.

The loads within a microgrid can either be electrical and/or thermal in nature. They can be further classified into critical and non-critical loads. During islanding, load shedding of non-critical loads can be performed to maintain the power balance and hence stability of the microgrid system. Therefore, the critical loads can be continued to operate in a normal manner through load shedding.

The control system shown in Fig. 1 consists of several subsystems, including voltage and current control functions, grid synchronization function, and a pulse-width modulation (PWM) generator.

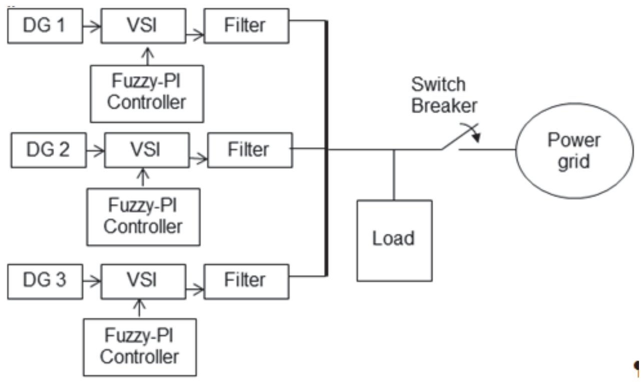

Fig.1. Block diagram of the microgrid system

Proposed Control Strategy

In dealing with power flow issues, a conventional PI control scheme would lead to a high overshoot and a long response time when the load demand sharply increases. Under the transient response, overshoot and long settling time negatively affect power systems. Specifically, they influence the frequency in the utility grid and thus the stability of power systems. To control the power flow, this study proposes a fuzzy-PI controller for a PWM inverter. Specific P and Q references are given. The references of voltage magnitude and phase angle at the inverter side can be calculated using Equations (1) and (2). The calculated voltage magnitude and phase angle references are in the three-phase abc-frame. Thus, the controller should be transformed into the voltage reference in the dq0-frame. The voltage references in the dq0-frame are compared with the actual voltages in the dq0-frame. The errors are the input to the fuzzy-PI controller, and the output is sent to the inner current loop. The inner current loop contains a conventional PI controller because using a fuzzy-PI controller in the outer loop alone is enough to improve performance. The generated controlled signals are transformed to the three-phase abc-frame of the PWM generator to produce a PWM wave. The difference between the fuzzy-PI control scheme and the conventional PI control scheme is the presence of a fuzzy-PI controller in the outer voltage loop. The fuzzy-PI controller scheme greatly reduces the overshoot and yields faster response in the transient load. The fuzzy-PI controller can also follow a non-linear load better than the conventional one because it can adjust the control parameters according to different operational scenarios. Fig. 2 shows the basic structure of the fuzzy-PI controller, which is the two input arguments of fuzzy controller error and the derivative of error. According to the fuzzy rules, the fuzzy logic adjusts the PI parameters and sends it to the PI controller. With the real-time update of PI gains, the fuzzy-PI control process can perform much better than a conventional PI controller with fixed parameters.

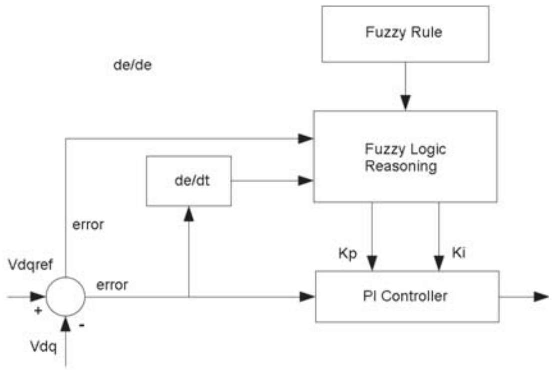

Fig.2. Structure of fuzzy PI controller

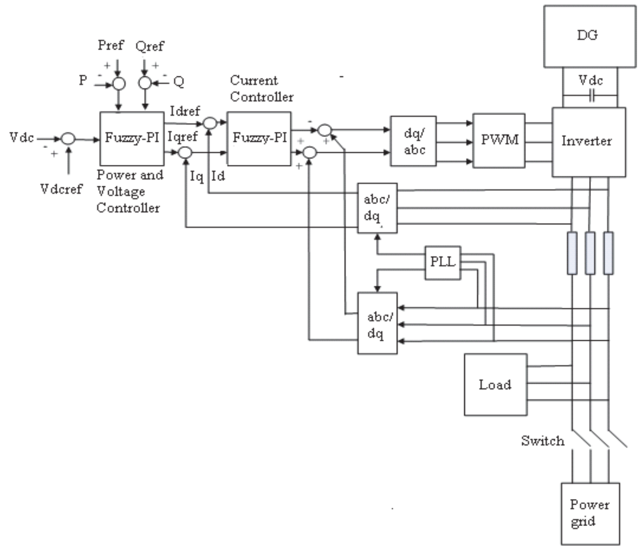

Fig.3. Fuzzy-PI controller during grid connected operation

A. Grid Connected Mode Operation

The PQ control scheme is shown in Fig.3, in which the single controllable inverter interfaced DGs is operated with a PQ control strategy in grid-connected. Using Park's transformation the three-phase voltages and currents are converted to dq components. The advantage of doing so is that in dq frame the quantities are DC in nature and hence easy to control using Fuzzy-PI controllers. The currents in the rotating reference frame are proportional to the active power (P) and reactive power (Q) as the PCC side direct axis component voltage, V_d is constant and the quadrature voltage component, V_q is equal to zero due to the reference frame being synchronized with the grid voltage. Therefore by controlling the direct and quadrature axis components of current, I_d and I_q the active and reactive power through an inverter can be controlled. Hence the power equations at the grid side can be modified as P_{ref} and Q_{ref} can be used to determine the reference currents for a current controlled inverter:

(1) $I_{dref} = \frac{P_{ref}}{P} I_d$

(2) $I_{qref} = \frac{Q_{ref}}{Q} I_q$

Using standard decoupling and feed-forward control loops, we derive the following current dynamics to obtain the reference dq frame voltages as

(3) $V_{dref} = K_p(I_{dref} - I_d) + K_i \int_0^t (I_{dref} - I_d) dt - \omega L I_q + V_d$

(4) $V_{qref} = K_p(I_{qref} - I_q) + K_i \int_0^t (I_{qref} - I_q) dt - \omega L I_d + V_q$

where Vd, Vq, Id,and Iq are the instantaneous values of the rotating reference frame voltages and currents; L is the inductance connecting the inverter to the grid; and Kp and Ki arethe PI controller coefficients. Using the dq-frame reference voltages Vdref and Vqref, we obtain and convert the modulation signals to three-phase signals by using Clarke's transformation. The three-phase modulation signals are compared with a unity triangular wave signal using the PWM to obtain the switching pulses for the inverter switches.

B. Islanded Mode Operation

In islanded mode, the microgrid system is disconnected from the main grid. The rest of the DGs could either be operated at the same or different set points depending on the supply and demand. The V/f control scheme is shown in Fig. 4. The V/f control strategy is a tightly closed loop control in which the reference values Vref and Iref are compared with the DC bus values and the error is minimized using PI controllers. The frequency of the DC bus is measured using a Phase-Locked Loop.

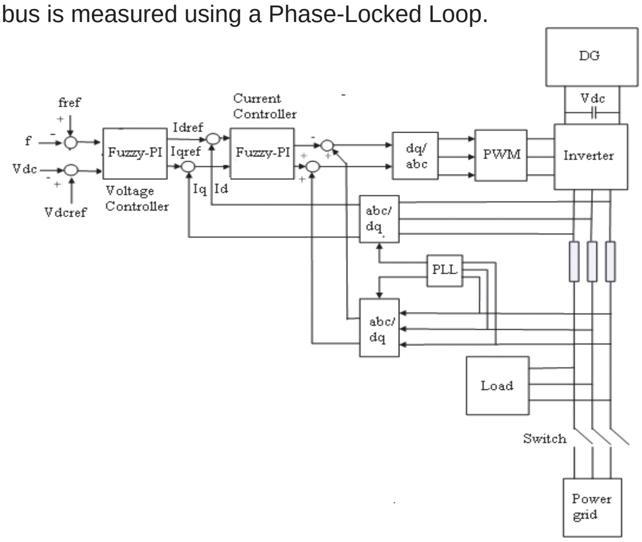

Fig.4. Fuzzy-PI controller during islanded mode operation

In the proposed work, the fuzzy-PI control technique is used to generate the gating signals. After proper amplification and isolation, the switching signals obtained are given to the switching devices of the PWM converter. The DC link capacitor voltage is remained constant by a fuzzy logic controller. The schematic of the proposed fuzzy-PI is shown in Fig. 2. Fuzzy logic is characterized by five fuzzy sets [Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB)] for each input and output variables. (2) The triangular membership function is used for simplicity. (3) Implication is performed using Mamdani-type min-operator. (4) Defuzzification is employed using the centroid method.

Fuzzification: Fuzzy logic uses linguistic variables instead of numerical variables. In a control system, the error between the reference signal and the output signal can be assigned as NB, NS, Z, PS, and PB. The processes of fuzzification convert numerical variables (real number) into linguistic variables (fuzzy number).

Defuzzification: The rules of fuzzy logic are followed to generate required output in linguistic variables according to real-time requirements. The linguistic variables must be transformed to crisp number. This selection of strategy is a compromise between accuracy and computational intensity.

The DC side of the inverter is connected to a capacitor. The DC capacitor provides a constant DC voltage and the real power necessary to cover the losses of the system. In the steady state, the real power supplied by the source should be equal to the real power demand of the load plus a small power to compensate for the losses in the active filter. Thus, the DC capacitor voltage is maintained at a reference value. A fuzzy logic controller is applied to maintain the constant voltage across the capacitor by minimizing the error between the capacitor voltage and the reference voltage.

The fuzzy logic control has two input signals, namely, error and change of error. Five membership functions are assigned for both input and output. Fig. 5 shows the membership functions for the input and output variables. A triangular membership function is used to represent the input and output variables. The two input variables with five labels for each variable produce 25 input label pairs. The relations of the 25 input pairs to the respective output label are listed in Table 1. The fuzzy IF-THEN rules formed for controlling the DC voltage are provided in Fig.6.

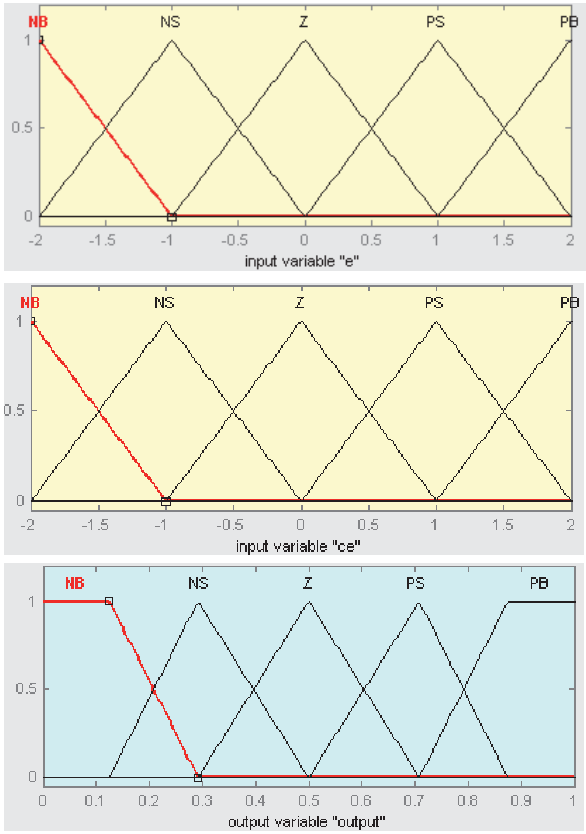

Fig.5. Membership functions for input and output variables

Table 1. Fuzzy rule base

Error (e)	Change of error (de)				
	NB	**NS**	**Z**	**PS**	**PB**
NB	NB	NB	NB	PS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

On the basis of the descriptions of the input and output variables defined by the FIS Editor, the Rule Editor automatically constructs the rule statements by selecting one item in each input variable box, one item in each output box, and one connection item. Choosing name as one of the variable qualities will exclude that variable from a given rule. Choosing not under any variable name will negate the associated quality. Rules may be changed, deleted, or added by clicking the appropriate button. Fig. 6 shows the rule editor, and Fig. 7 shows the surface viewer.

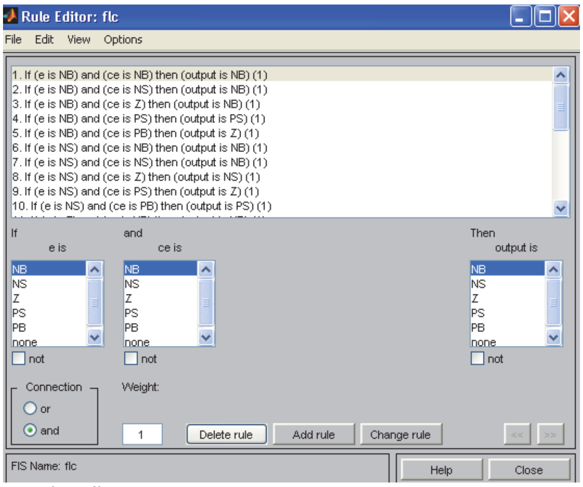

Fig.6.Rule editor

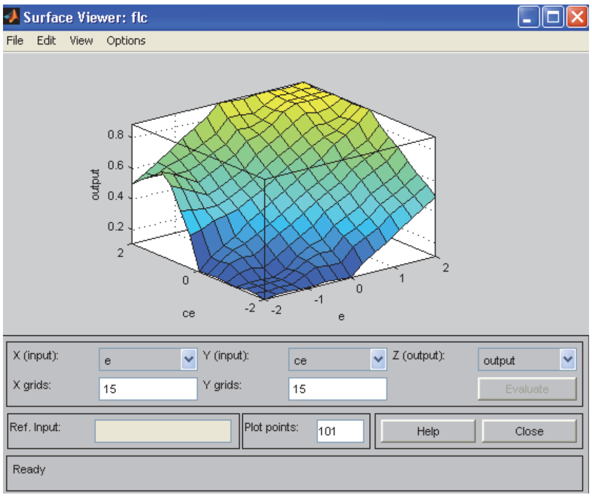

Fig.7.Surface viewer

Result and Discussion

A simulation in MATLAB/Simulink is conducted to investigate the effectiveness of the developed fuzzy-PI controller algorithm for the microgrid control system. The simulation is carried out on a test system connected with the power grid. The test system used in the model is shown in Fig. 8.

The proposed control strategy is incorporated in the fuzzy-PI controller. The SimPowerSystem toolbox is used to simulate the test system and the proposed fuzzy-PI controller algorithm. The microgrid performance is evaluated under steady-state and transient system conditions. In this case, the switch represented by the circuit breaker is closed and opened. The three-phase inverter waveform with microgrid is shown in Fig. 9.

The performance of the microgrid with the proposed fuzzy-PI controller algorithm is excellent. Figs. 10 and 11 compare the performances of the fuzzy-PI controller and the PI controller. The voltage waveform is exactly maintained at the reference value by the fuzzy-PI controller, whereas some deviations are present within the PI controller. A step change in load voltage and current is applied to observe the transient characteristics of the proposed control strategy. The load is connected to the source through a circuit breaker after being disconnected from the power grid of the source. It initially has 2kW at 0.15 s. A step change to 3kW occurs until 0.2 s. Figs. 12 and 13 compare the current waveform using the PI and fuzzy-PI controllers, respectively.

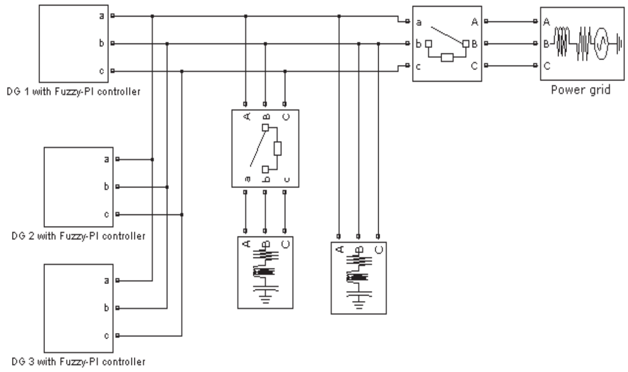

Fig. 8. Simulation model of the microgrid system

The following section presents the simulation results to validate the effectiveness of the developed inverter control system algorithm. Fig. 9 presents the three-phase grid voltage waveforms, va, vb, and vc in p.u.

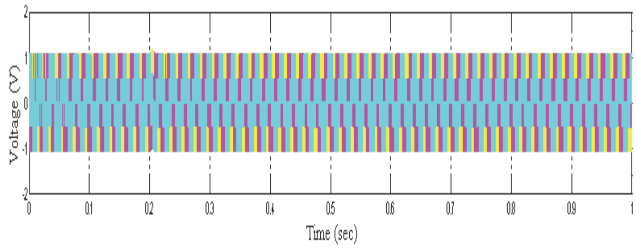

Fig. 9. Three phase inverter voltages, v_a,v_b and v_c

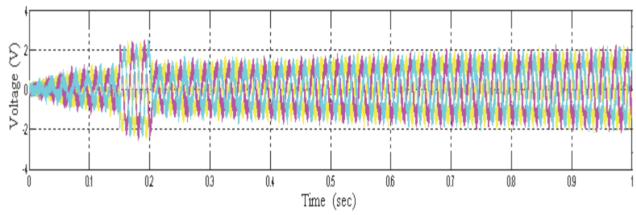

Fig. 10. Three phase load voltage using PI controller

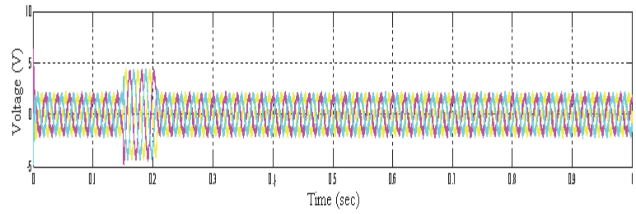

Fig. 11. Three phase load voltage using Fuzzy-PI controller

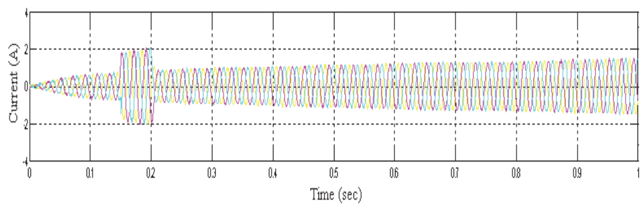

Fig. 12. Three phase load current using PI controller

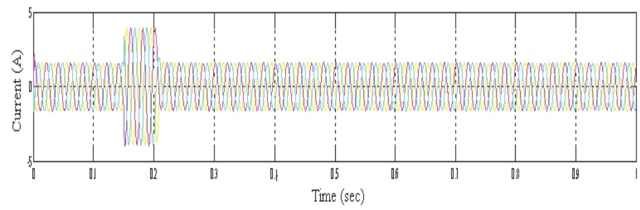

Fig. 13. Three phase load current using Fuzzy-PI controller

When the microgrid imports active and reactive powers, the amounts of active and reactive powers generated from the DGs are adjusted to make the microgrid import real and reactive power from the main grid. In this study,the load rating is 10 kW. The disconnection from the main grid is simulated at t = 4 s. As shown the sequence of the events before t = 4 s, the microgrid is at steady state with a nominal frequency (50 Hz). The microgrid imports active and reactive powers from the main grid. At t = 4 s, islanding occurs, and the microgrid loads are larger than the power generated by DGs so that the frequency drops to approximately 49.98 Hz using the fuzzy-PI controller. The stability frequency deviation is much better in the response waveform result of the fuzzy-PI controller than in that of the PI controller is shown in Fig. 14.

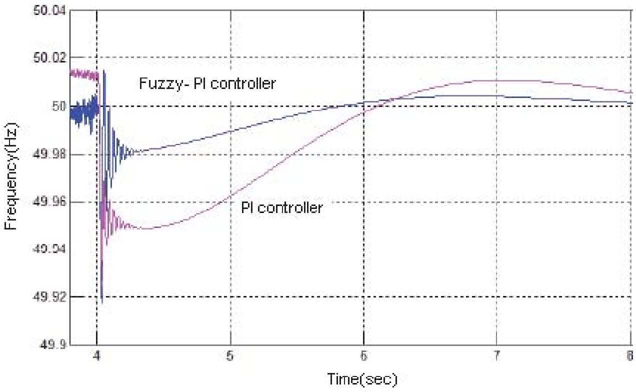

Fig. 14. Frequency response during import powers from the grid

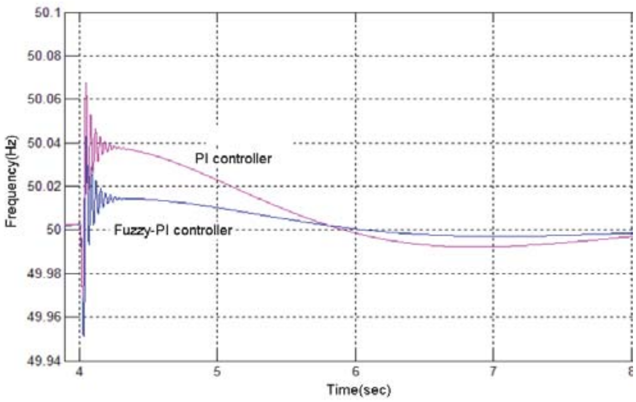

Fig. 15. Frequency response during export powers to the grid.

When microgrid exports active and reactive powers to the main grid, the amounts of active and reactive powers generated by the DG become greater than the demand. The load rating is 5 kW. The simulation results of the disconnection from the main grid at t = 4 sare shown in the following figures. Before islanding, the microgrid operates at its steady state and exports active and reactive powers to the main grid. The frequency of the microgrid is at its nominal value (50 Hz). During Islanding at t = 4 s, the microgrid load is less than the power generated by DG, which increases the frequency. The frequency rises to some extent and restores to its nominal value after a short time by the controller. The fuzzy-PI and PI controllers are compared. Thus the controlled grid frequency is shown in Fig.15.

Fig. 16 shows the variation of the active and reactive power outputs due to the disconnection from the main distribution network. At t = 0s, the microgrid and the grid are connected and supplied to the load. After power grid disconnection at t = 2.5s, the microgrid system still shares the local load proportionally to the rated power. Specifically, the active power is equal to approximately 1p.u.Fig. 17 shows the variation of the active and reactive power outputs due to the connection to the main distribution network. In this case, at t =0 s, the microgrid initially supplies the load. After utility grid connection at t = 2.5s, the microgrid system still shares the local load to the rated power.

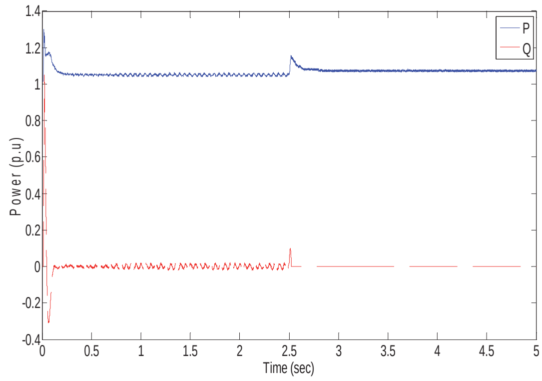

Fig. 16. Power variations from grid connected to island mode

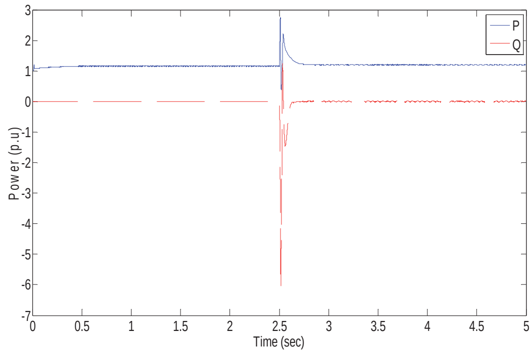

Fig. 17. Power variations from island to grid connected mode

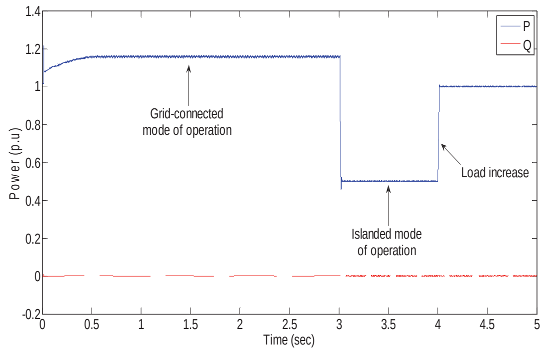

Fig. 18.Power variations due to load increase at the islanded mode of operation

Fig. 18 shows the variation inactive power supplied by the microgrid system. In this case, the microgrid system is initially connected to the grid and operated in power mode control. At 3s, the system is operated in islanded mode. In this condition, the microgrid is initially operated with a load of 15kW connected to the generator bus up to t = 5s. Then, another load of 15kW is operated at t = 4s. At 4 s, the load on the system is increased, the active power reaches 1.0p.u system, and the reactive power remains at 0. The microgrid system is configured to operate in parallel for providing power to critical loads of the main utility grid system. In these cases, the microgrid can rapidly take up the critical loads when faults arise in the main grid.

The total harmonic distortion (THD) is calculated using the FFT analysis tool provided in Matlab/Simulink software. The nominal THD value is <5%. By using PI controller, the THD is calculated as 12.64% in Fig. 19. The Harmonic Distortion is higher in PI controller and hence it can be reduced the THD value by using FLC to 0.46% in Fig. 20.

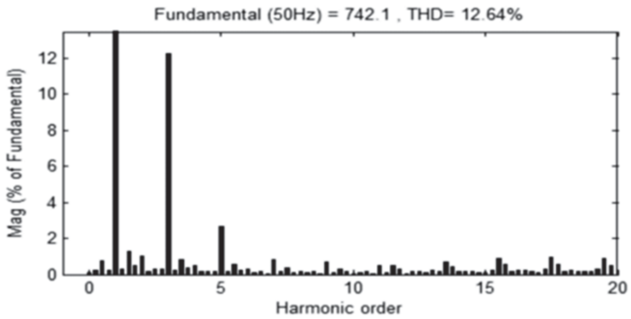

Fig. 19. THD waveform using PI controller

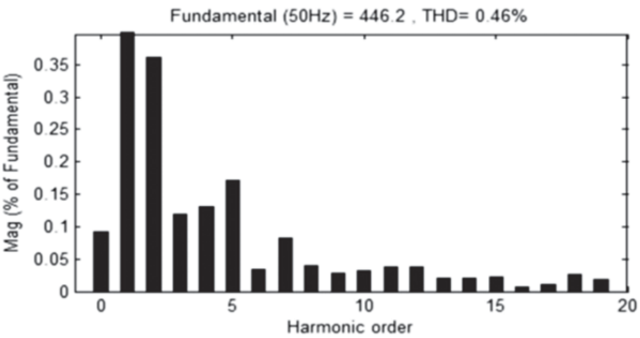

Fig. 20. THD waveform using fuzzy-PI controller

Conclusion

This paper presents the modeling and simulation of microgrid controlled by using fuzzy-PI controller. The simulation is performed in MATLAB/SIMULINK. The proposed controller has good response and can compensate the harmonics in the source. The test system is constructed to verify the validity and effectiveness of the fuzzy-PI controller. The fuzzy-PI controller retains the nominal voltage and frequency of the microgrid. By this control, the unbalance between the generation and the load ire satisfied, and the stable operation of microgrid is realized. Voltage magnitude, frequency, and active and reactive power results are obtained with acceptable accuracy. and the comparison result is made between The performances of the fuzzy-PI and PI controllers are also compared. The models for the microgrid are simulated and verified by showing that it can be controlled at 1.0p.u. The microgrid model is simulated in grid-connected and islanded operation modes. The load following characteristics is also observed and analyzed from the simulation. FFT analysis shows that the fuzzy-PI controller can reduce the THD value by 0.46%. In future works, adaptability intelligent control schemes will be proposed to improve performances in terms of power management, particularly power compensation and load balancing, without generating instability problems.

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