A Novel Grid Current Compensator for Grid-Connected Distributed Generation under Nonlinear Loads with Fuzzy Logic Controller

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Abstract- **This paper introduces an advanced current control strategy for grid-connected operations of distributed generation (DG), which supports the DG to transfer a sinusoidal current into the utility grid despite the distorted grid voltage and nonlinear local load conditions. The proposed fuzzy logic controller based current controller is designed in the synchronous reference frame and compared with conventional PI controller and with combination of a proportional–integral (PI) controller and a repetitive controller (RC). An RC serves as a bank of resonant controllers, which can compensate a large number of harmonic components with a simple delay function. Hence, the control strategy can be greatly simplified. In addition, the proposed control method does not require the local load current measurement or harmonic analysis of the grid voltage. Therefore, the proposed control method can be easily adopted into the traditional DG control system without installation of extra hardware. Despite the reduced number of sensors, the grid current quality is significantly improved compared with the traditional methods with the PI controller and PI-RC controller. The operation principle of the proposed control method is analyzed in detail, and its effectiveness is validated through simulation results.**

Index Terms- Distributed generation (DG), grid-connected inverter, harmonic compensation, nonlinear load, repetitive control performance.

I. INTRODUCTION

The use of renewable energy sources, such as wind turbines, Photovoltaic, and fuel cells, has greatly increased in recent decades to address concerns about the global energy crisis, Depletion of fossil fuels, and environmental pollution problems. As a result, a large number of renewable energy sources have been integrated in power distribution systems in the formof distributed generation (DG) [1]. DG systems can offer many advantages over traditional power generation, such as small size, low cost, high efficiency, and clean electric power generation. A DG system is typically operated in a grid-connected mode where the maximum available power is extracted from energy sources and transferred to the utility grid [2]–[8]. In addition, to exploit full advantages of a DG system, the DG can be also equipped and operated with local loads, where the DG supplies power to the local load and transfers surplus power to the grid [9]–[14]. In both configurations, i.e., with and without the local load, the prime objective of the DG system is to transfer a high-quality current (grid current) into the utility grid with the limited total harmonic distortion (THD) of the grid current at 5%, as recommended in the IEEE 1547 standards [15]. To produce a high-quality grid current, various current control strategies have been introduced, such as hysteresis, predictive, proportional–integral (PI), and proportional-resonant (PR) controllers. Hysteresis control is simple and offers rapid responses; however, it regularly produces high and variable switching frequencies, which results in high current ripples and difficulties in the output filter design [3]. Meanwhile, predictive control is a viable solution for current regulation of the grid-connected DG. However, despite its rapid response, the control performance of the predictive controller strongly relies on system parameters [4]. Therefore, system uncertainty is an important issue affecting the grid current quality. The PI controller in the synchronously rotating (d–q) reference frame and the PR controller in the stationary (α–β) reference frame are effective solutions that are commonly adopted to achieve a high-quality grid current [2],

[5], [10], [11], [16]. However, these current controllers are only effective when the grid voltage is ideally balanced and sinusoidal. Unfortunately, due to the popular use of nonlinear loads such as diode rectifiers and adjustable-speed ac motor drives in power systems, the grid voltage at the point of common coupling (PCC) is typically not pure sinusoidal, but instead can be unbalanced or distorted. These abnormal grid voltage conditions can strongly deteriorate the performance of the regulating grid current [17].To eliminate the adverse effect of the distorted grid voltage on the grid current quality, several harmonic compensation methods have been introduced [6]–[8]. A novel compensation approach for reducing the THD of the grid current under distorted grid voltage is introduced. In this method, the harmonic components in the grid voltage are extracted, and the Cauchy–Schwarz inequality theory is adopted to find the minimum point of the grid current THD.

The grid current quality therefore relies heavily on the accuracy of the grid voltage harmonic analysis; if the harmonic components in the grid voltage are varied, it is difficult to maintain a good grid current quality. Moreover, the searching algorithm requires a large calculation time and can operate only offline. In [6]–[8] and [18], several selective harmonic compensators are developed using a resonant controller, in which the resonant controller tuned at the sixth multiple of the fundamental frequency is added to eliminate the effect of fifth and seventh harmonic grid voltages on the grid current quality. The grid current quality can be improved, due to the additional resonant controllers. However, if higher order harmonics are taken into account, more resonant controllers should be added because a single resonant controller can regulate only one specific harmonic component [7], [8]. Unfortunately, adding more controllers increases the complexity of the control system. To improve the grid current quality with a simplified control scheme, the repetitive control technique has been adopted [12]. A repetitive controller (RC) serves as a bank of resonant controllers to compensate a large number of harmonic components with a simple delay structure. However, despite the effectiveness of the RC in harmonic compensation, the traditional RC has a long delay time, which regularly limits the dynamic response of the current controller. For example, as reported in [12], the dynamic response of the grid current under a step change of the current reference is approximately 150 ms, which is extremely slow compared with other control methods. In addition, even with the utilization of the RC, this method is unable to bring the THD of the grid current lower than the limited value 5% in the IEEE 1547 standards.

Along with grid voltage distortion, the presence of nonlinear loads in the local load of the DG also causes a negative impact on the grid current quality [13]. To address this problem, the local load current measurement and a load current feed forward loop are regularly adopted [13].Although these compensation methods are effective in improving grid current quality, the requirement of additional hardware, specifically the current sensor for measuring the local load current, is the main drawback of this control method. Furthermore, most aforementioned studies consider and separately tackle the impact of distorted grid voltage or the nonlinear local load; none of them simultaneously takes into account those issues. To overcome the limitations of aforementioned studies, this paper proposes an advanced current control strategy for the grid-connected DG, which makes the grid current sinusoidal by simultaneously eliminating the effect of nonlinear local load and grid voltage distortions. First, the influence of the grid voltage distortions and nonlinear local load on the grid current is determined. Then, an advanced control strategy is introduced to address those issues. The proposed current controller is

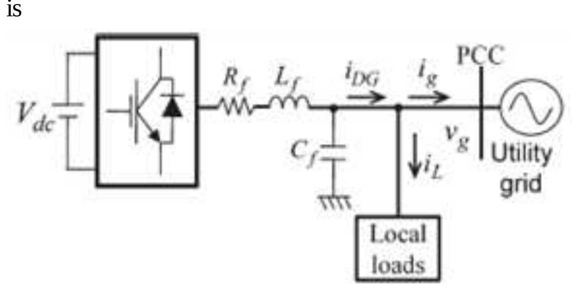


Fig.1. System configuration of a grid-connected DG system with local load

designed in the d–q reference frame and is composed of a PI and an RC. One single RC can compensate a large number of harmonic components with a simple delay function. Hence, the control strategy can be greatly simplified. Another advantage of the proposed control method is that it does not demand the local load current measurement and the harmonic analysis of the grid voltage. Therefore, the proposed control method can be easily adopted into the traditional DG control system without the installation of extra hardware. Despite the reduced number of sensors, the performance of the proposed grid current controller is significantly improved compared with that of the traditional PI current controller. In addition, with the combination of the PI and RC, the dynamic response of the proposed current controller is also greatly enhanced compared with that of the traditional RC. The feasibility of the proposed control strategy is completely verified by simulation results.

II. SYSTEM CONFIGURATION AND ANALYSIS OF GRID VOLTAGE DISTORTION AND NONLINEAR LOCAL LOAD

Fig. 1 shows the system configuration of a three-phase DG operating in grid-connected mode. The system consists of a dc power source, a voltage-source inverter (VSI), an output LC filter, local loads, and the utility grid. The purpose of the DG system is to supply power to its local load and to transfer surplus power to the utility grid at the PCC. To guarantee high-quality power, the current that the DG transfers to grid (ig) should be balanced, sinusoidal, and have a low THD value. However, because of the distorted grid voltage and nonlinear local loads that typically exist in the power system, it is not easy to satisfy these requirements.

A. Effect of Grid Voltage Distortion

To assess the impact of grid voltage distortion on the grid current performance of the DG, a model of the grid-connected DG system is developed, as shown in Fig. 2. In this model, the VSI of the DG is simplified as voltage source (vi). The inverter transfers a grid current (ig) to the utility grid (vg). For simplification purpose, it is assumed that the local load is not connected into the system. In Fig. 2(a), the voltage equation of the system is given as

$$v_i - v_g - L_f \frac{di_g}{dt} - R_f i_g = 0 \qquad (1)$$

Where Rf and Lf are the equivalent resistance and inductance of the inductor Lf , respectively.

If both the inverter voltage and the grid voltage are composed of the fundamental and harmonic components as (2), the voltage equation of (1) can be decomposed into (3) and (4), and the system model shown in Fig. 2(a) can be expressed as Fig. 2(b) and (c), respectively. That is

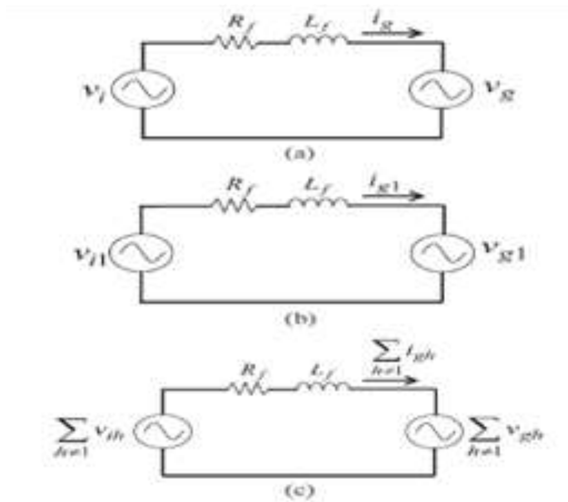


Fig. 2. Model of grid-connected DG system under distorted grid voltage condition. (a) General condition; (b) at the fundamental frequency; and (c) at harmonic frequencies.

$$v_i = v_{i1} + \sum_{h\neq 1} v_{ih}$$
$$v_g = v_{g1} + \sum_{h\neq 1} v_{gh} \qquad (2)$$

$$v_{i1} - v_{g1} - L_f \frac{di_{g1}}{dt} - R_f i_{g1} = 0 \qquad (3)$$

$$\sum_{h\neq 1} v_{ih} - \sum_{h\neq 1} v_{gh} - L_f \frac{d\left(\sum_{h\neq 1} i_{gh}\right)}{dt} - R_f \sum_{h\neq 1} i_{gh} = 0. \qquad (4)$$

From (4), due to the existence of the harmonic components vgh in the grid voltage, the harmonic currents igh are induced into the grid current if the DG cannot generate harmonic voltages. vih that are exactly the same as vgh. As a result, the distorted grid voltage at the PCC causes nonsinusoidal grid current ig if the current controller cannot handle harmonic grid voltage vgh.

B. Effect of Nonlinear Local Load

Fig. 3 shows the model of a grid-connected DG system with a local load, whereby the local load is represented as a current source iL, and the DG is represented as a controlled current source iDG. According to Fig. 3, the relationship of DG current iDG, load current iL, and grid current ig is described as

$$i_{DG} = i_L + i_g. \quad (5)$$

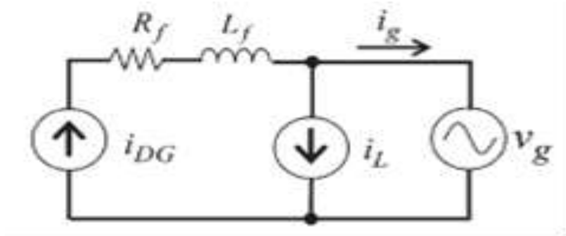


Fig. 3. Model of grid-connected DG system with nonlinear local load

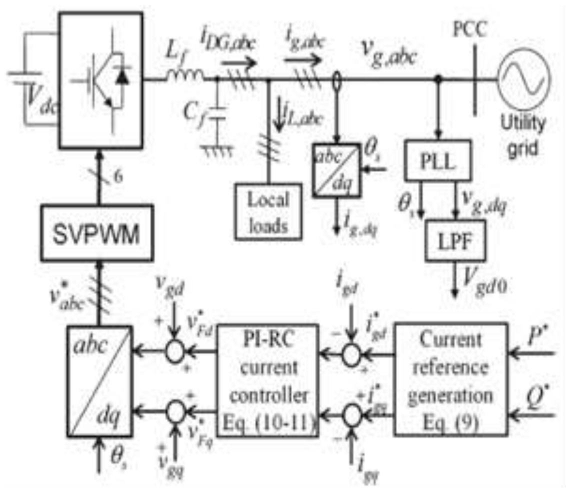


Fig. 4. Overall block diagram of the proposed control Strategy

Assuming that the local load is nonlinear, e.g., a three-phase diode rectifier, the load current is composed of the fundamental and harmonic components as

$$i_L = i_{L1} + \sum_{h\neq 1} i_{Lh} \quad (6)$$

where iL1 and iLh are the fundamental and harmonic components of the load current, respectively.

Substituting (6) into (5), we have

$$i_g = i_{DG} - \left(i_{L1} + \sum_{h\neq 1} i_{Lh}\right). \quad (7)$$

From (7), it is obvious that, in order to transfer sinusoidal grid current ig into the grid, DG current iDG should include the harmonic components that can compensate the load current harmonics iLh. Therefore, it is important to design an effective and low-cost current controller that can generate the specific harmonic components to compensate the load current harmonics. Generally, traditional current controllers, such as the PI or PR controllers, cannot realize this demand because they lack the capability to regulate harmonic components.

III. PI +RC BASED CONTROL SCHEME

To enhance grid current quality, an advanced current control strategy, as shown in Fig. 4, is introduced. Although there are several approaches to avoid the grid voltage sensors and a phase-locked loop (PLL) [19], Fig. 4 contains the grid voltage sensor and a PLL for simple and effective implementing of the proposed algorithm, which is developed in the d–q reference frame.

The proposed control scheme is composed of three main parts: the PLL, the current reference generation scheme, and the current controller. The operation of the PLL under distorted grid voltage has been investigated, in detail, in [20]; therefore, it will not be addressed in this paper. As shown in Fig. 4, the control strategy operates without the local load current measurement and harmonic voltage analysis on the grid voltage. Therefore, it can be developed without requiring additional hardware. Moreover, it can simultaneously address the effect of nonlinear local load and distorted grid voltage on the grid current quality.

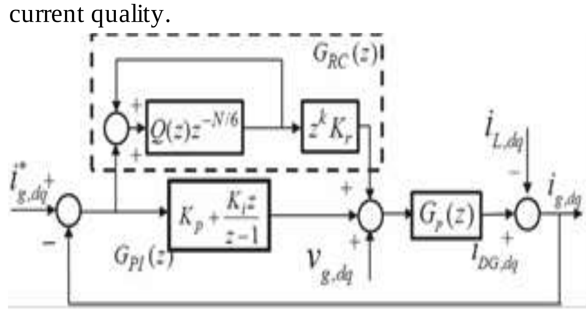


Fig.5. Block diagram of the current controller

A. Current Reference Generation

As shown in Fig. 4, the current references for the current controller can be generated in the d–q reference frame based on the desired power and grid voltage as follows [14]:

$$i^*_{gd} = \frac{2}{3}\frac{P^*}{v_{gd}}$$
$$i^*_{gq} = -\frac{2}{3}\frac{Q^*}{v_{gd}} \quad (8)$$

where P∗ and Q∗ are the reference active and reactive power, respectively; vgd represents the instantaneous grid voltage in the d–q frame; and i∗ gd and i∗ gq denote the direct and quadrature components of the grid current, respectively.

Under ideal conditions, the magnitude of vgd has a constant value in the d–q reference frame because the grid voltage is pure sinusoidal. However, if the grid voltage is distorted, the magnitude of vgd no longer can be a constant value. As a consequence, reference current i∗ gd and i∗ gq cannot be constant in (8). To overcome this problem, a low-pass filter (LPF) is used to obtain the average value of vgd, and the d–q reference currents are modified as follows:

$$i^*_{gd} = \frac{2}{3}\frac{P^*}{V_{gd0}}$$
$$i^*_{gq} = -\frac{2}{3}\frac{Q^*}{V_{gd0}} \quad (9)$$

where Vgd0 is the average value of vgd, which is obtained through the LPF in Fig. 4.

B. Current Controller

An advanced current controller is proposed by using a PI and an RC in the d–q reference frame. The block diagram of the current controller is shown in Fig. 5. The open-loop transfer function of the PI and RC in a discrete-time domain is given respectively in

$$G_{\text{PI}}(z) = K_p + \frac{K_i z}{z-1} \quad (10)$$
$$G_{\text{RC}}(z) = \frac{K_r z^k z^{-N/6}}{1 - Q(z) z^{-N/6}} \quad (11)$$

where Kp and Ki are the proportional and integral gains of the PI controller, z−N/6 is the time delay unit, zk is the phase lead term, Q(z) is a filter transfer function, and Kr is the RC gain. In Fig. 5, the RC is used to eliminate the harmonic components in the grid current caused by the nonlinear local load and/or distorted grid voltage. Meanwhile, the role of the PI controller is to enhance the dynamic response of the grid current and to stabilize the whole control system. The number of delay samples of the RC given in (11) is N/6, where N = fsample/fs is the number of samples in one fundamental period, which is defined as the ratio of the sampling frequency (fsample) and the fundamental frequency of system (fs). In fact, the traditional RC can be used in this case to compensate the harmonic components. However, the traditional RC suffers the severe drawback of a very slow dynamic response due to the long delay time by N samples. To remove the delay problem of the traditional RC, we consider only the (6n ± 1)th (n = 1, 2, 3 . . .) harmonics because they are dominant components in three-phase systems. The time delay of the RC in (13) is thereby reduced six times compared with the traditional one as N/6 [21].

TABLE I SYSTEM PARAMETERS

Parameters	*Values*
Grid voltage	110 V (rms)
Grid frequency (f_s)	50 Hz
Rated output power	5 kW
DC-link voltage (V_{dc})	350 V
Sampling/switching frequency (f_{sample})	9 kHz
Output filter inductance (L_f)	0.7 mH
Output filter resistance (R_f)	0.1 Ω
Output filter capacitance (C_f)	27 μF
Load of three-phase diode rectifier	R = 30 Ω, C = 2200 μF
Three-phase linear load	R = 30 Ω

IV PROPOSED FUZZY LOGIC CONTROLLER

A. STRUCTURE OF FUZZY LOGIC CONTROLLER

Fuzzy controller the word Fuzzy means vagueness. Fuzziness occurs when the boundary of piece of information is not clear-cut. Fuzzy set theory exhibits immense potential for effective solving of the uncertainty in the problem. Fuzzy set theory is an excellent mathematical tool to handle the uncertainty arising due to vagueness.

Understanding human speech and recognizing handwritten characters are some common instances where fuzziness manifests. Fuzzy set theory is an extension of classical set theory where elements have varying degrees of membership. Fuzzy logic uses the whole interval between 0 and 1 to describe human reasoning.

In FLC the input variables are mapped by sets of membership functions and these are called as "FUZZY SETS". Fuzzy set comprises from a membership function which could be defines by parameters. The value between 0 and 1 reveals a degree of membership to the fuzzy set. The process of converting the crisp input to a fuzzy value is called as "fuzzificaton." The output of the Fuzzier module is interfaced with the rules.

The basic operation of FLC is constructed from fuzzy control rules utilizing the values of fuzzy sets in general for the error and the change of error and control action. Basic fuzzy module is shown in Fig.6. The results are combined to give a crisp output controlling the output variable and this process is called as “defuzzification”

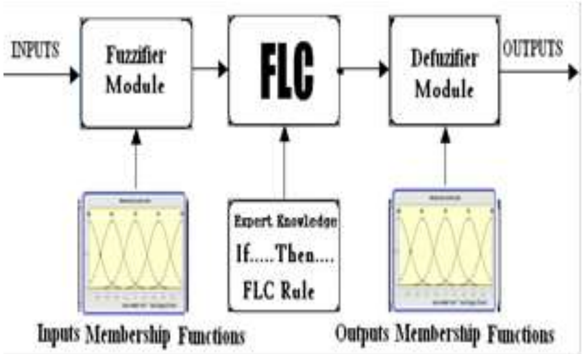


Fig.6. Fuzzy Basic Module

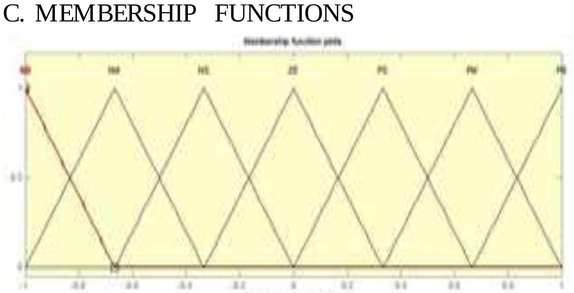
B. FUZZY RULES

TABLE II: FUZZY RULES

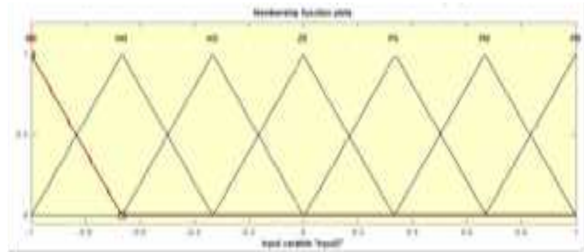
COE / E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PB	NS	ZE
PS	NM	NS	ZE	PS	PM	PM	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

In the fuzzy control, input and output variables are the size of the form to describe in words, so to select special vocabulary to describe these variables, generally used in "big, medium and small" Three words to express the controller input and output variables state, plus the positive and negative directions, and zero, a total of seven words : { negative big, negative medium, negative small, zero, positive small, middle, CT } , the general terms used in the English abbreviation prefix : {NB , NM, NS , ZE, PS , PM, PB}.

C. MEMBERSHIP FUNCTIONS



(a)



(b)

Fig.7.Member Ship Function of (A) Error (B) Change in Error

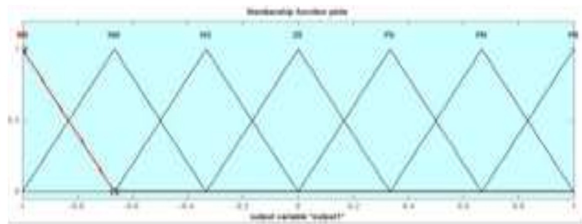


Fig.8.Member Ship Function of Output

V. SIMULATION RESULTS

A simulation model of the DG system is built by PSIM simulation software to verify the effectiveness of the proposed control method. The system parameters are given in Table I. In the simulation, three cases are taken into account.

1) Case I: The grid voltage is sinusoidal and the linear local load is used.

2) Case II: The grid voltage is sinusoidal and the nonlinear local load is used.

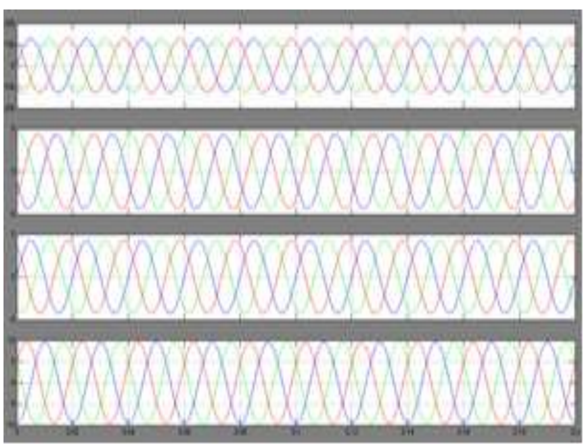
3) Case III: The grid voltage is distorted and the nonlinear local load is used.

In all test cases, the reference grid current is set at i∗ gd = 10 A and i∗ gq = 0, and the conventional PI current controller and the proposed current controller are investigated to compare their control performances. Fig. 9 depicts the steady-state performance of the grid connected DG by using the conventional PI current controller, in which the waveforms of grid voltage (vg,abc), grid current (ig,abc), local load current (iL,abc), and DG current (iDG,abc) are plotted. As shown in Fig. 9, the PI current controller is able to offer a good performance only in Case I, when the grid voltage is ideal sinusoidal and the local load is linear. In the other circumstances, due to the effect of distorted grid voltage and the nonlinear local load, the PI current controller is unable to transfer a sinusoidal grid current to the utility grid. In fact, because of the popular use of nonlinear loads in the DG local load and distribution system, the ideal sinusoidal condition of the grid voltage is very rare.

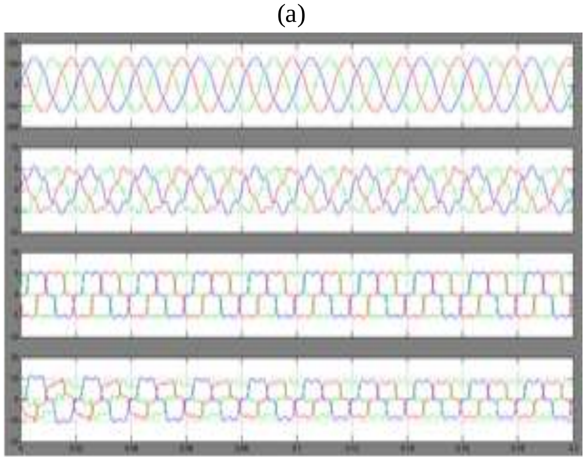
On the other hand, the conditions, as given in Cases II and III, frequently occur in practice. As a result, the conventional PI controller is insufficient to offer a good quality of the grid current. To demonstrate the superiority of the proposed current controller over the traditional PI controller, the DG system with the proposed current controller is also simulated, and the results are shown in Fig. 9.

As shown in the results, the proposed control strategy can provide a good quality grid current, i.e., sinusoidal grid currents, despite the distorted grid voltage and nonlinear local load conditions. Therefore, with the aid of the RC in the proposed current controller, the distorted grid voltage and nonlinear load current no longer affect the grid current quality.

A.SIMULATION RESULT WITH PI CONTROLLER



(a)



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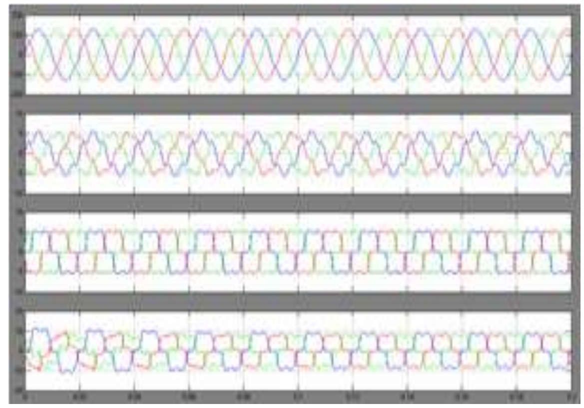
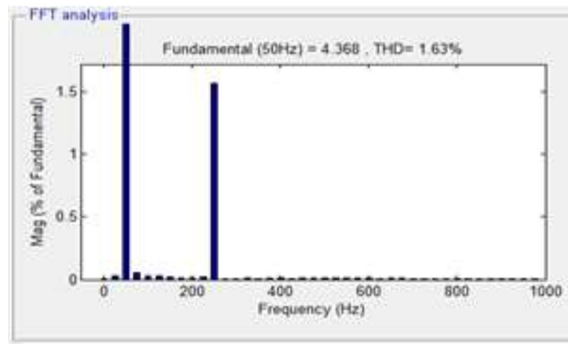
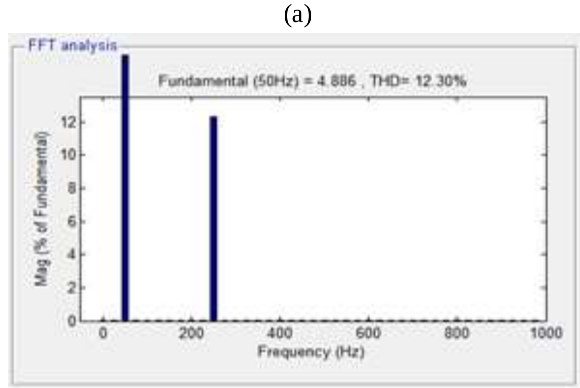


(c)

Fig.9. Simulation results with the PI current controller: (a) Case I;(b) Case II; and (c) Case III.



(a)



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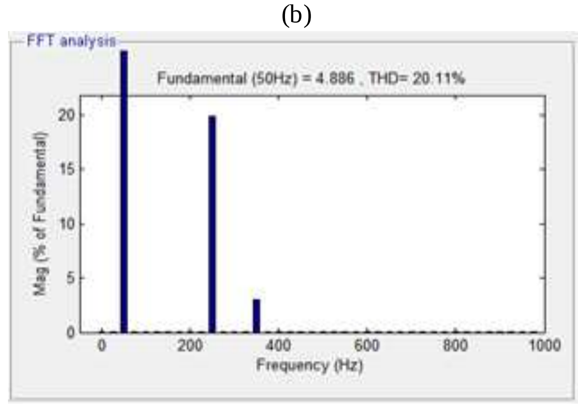
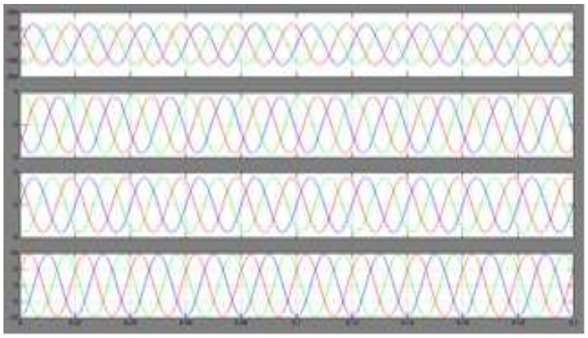
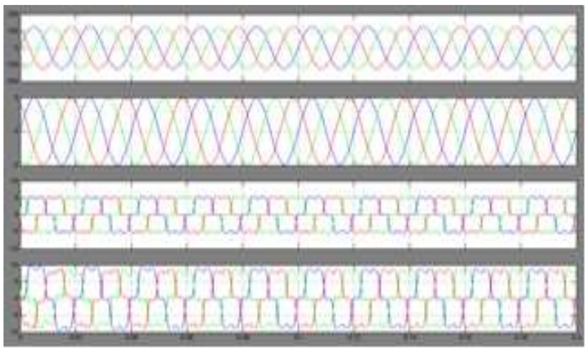


Fig.10. % THD at (a) case I as 1.63 (b) case II as 12.3(c) case III as 20.11

B.SIMULATION RESULT WITH PI-RC CONTROLLER:



(a)



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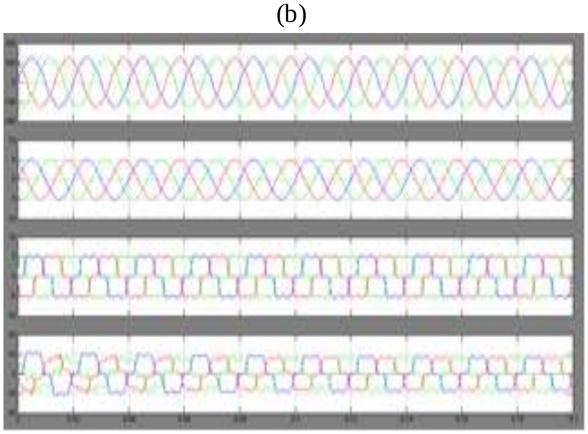
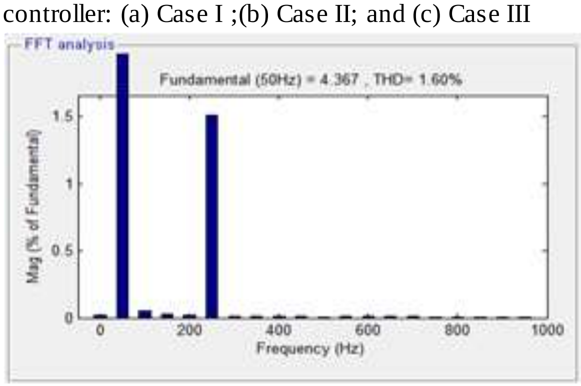
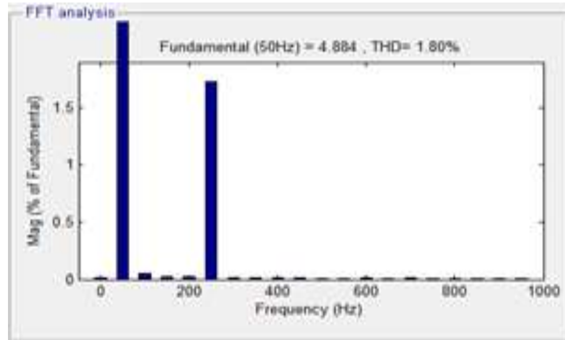


(c)

Fig.11. Simulation results with the PI-RC current controller: (a) Case I ;(b) Case II; and (c) Case III



(a)



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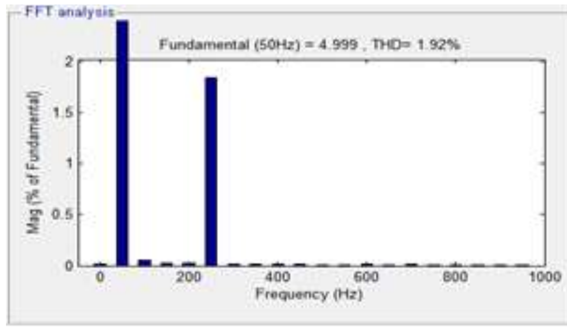
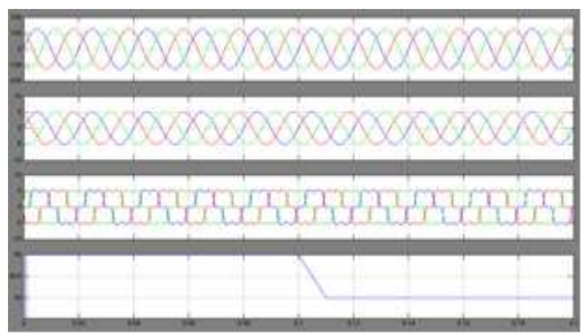


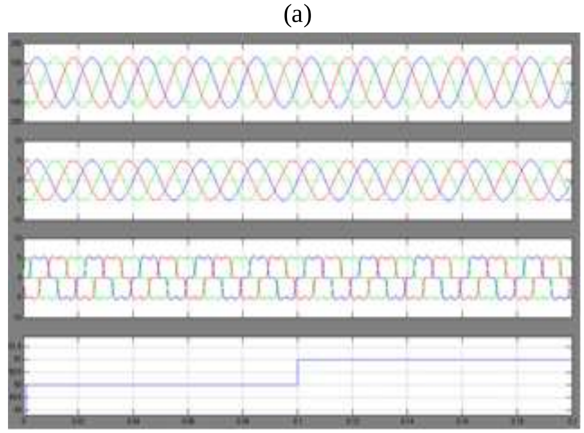
(c)

Fig.12. % THD at (a) case I as 1.60 (b) case II as 1.80(c) case III as 1.92

C.SIMULATION RESULT WITH FREQUENCY VARIATIONS



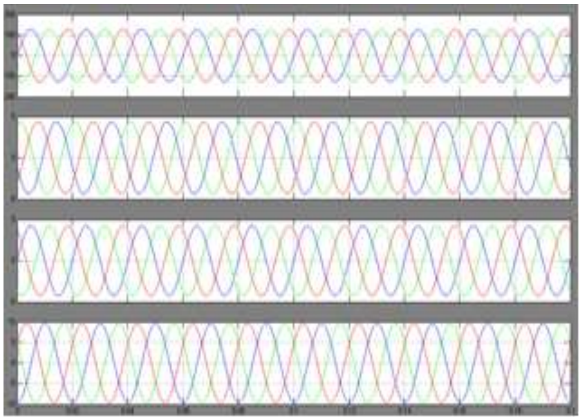
(a)



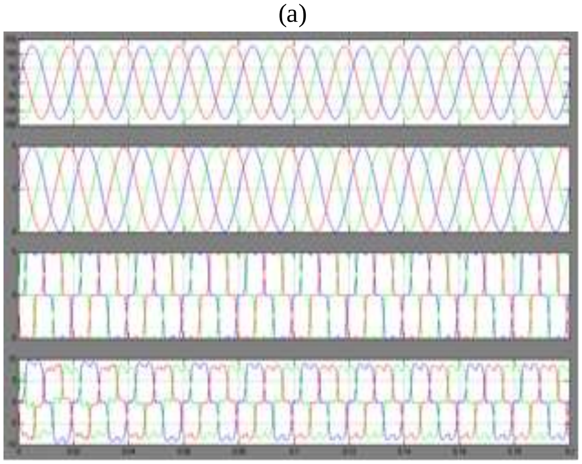
(b)

Fig. 13. Simulation results of the proposed PI-RC current controller under grid frequency variations (a) from 50 to 49 Hz and (b) from 50 to 51 Hz.

7.4 SIMULATION RESULT WITH FUZZY LOGIC CONTROLLER:



(a)



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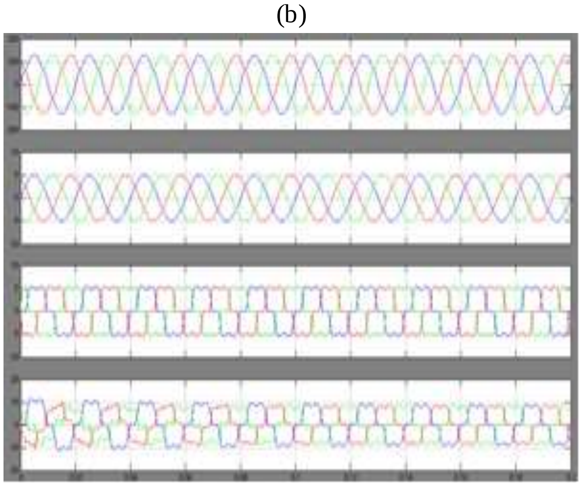
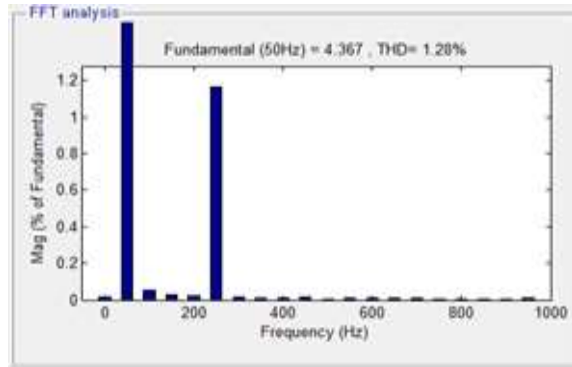
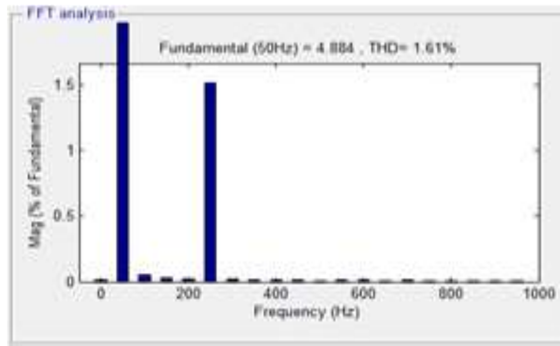


(c)

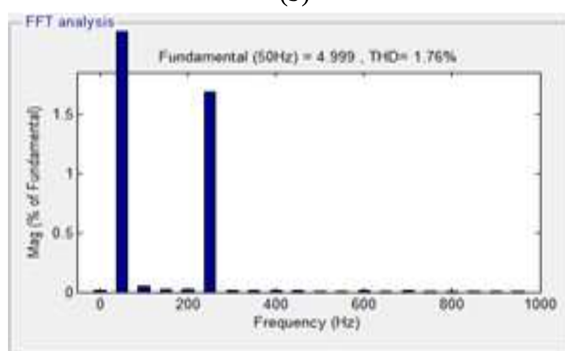
Fig.14. Simulation results with the proposed FUZZY current controller: (a) Case I; (b) Case II; and (c) Case III



(a)



(b)



(c)

Fig.15. % THD at (a) case I as 1.28 (b) case II as 1.61 (c) case III as 1.76

TABLE III SUMMARY OF THD VALUES OF GRID CURRENT WITH PI, PI-RC CONTROLLER AND PROPOSED FUZZY BASED CURRENT CONTROLLERS

% THD	PI Controller	PI-RC Controller	Fuzzy Logic Controller
Case I	1.63	1.60	1.28
Case II	12.30	1.80	1.61
Case III	20.11	1.92	1.76

VI.CONCLUSION

This paper has proposed an advanced current control strategy for the grid-connected DG to simultaneously eliminate the effect of grid voltage distortion and nonlinear local load on the grid current. The simulation results established that the DG with the proposed current controller can sufficiently transfer a sinusoidal current to the utility grid, despite the nonlinear local load and distorted grid voltage conditions. The proposed fuzzy based current control scheme can be implemented without the local load current sensor and harmonic analysis of the grid voltage; therefore, it can be easily integrated in the conventional control scheme without installation of extra hardware.

Despite the reduced number of current sensors, the quality of the grid current is significantly improved: the THD value of the grid current is decreased considerably compared with that achieved by using the conventional PI current controller. In addition, the proposed current controller also maintained a good quality of grid current under grid frequency variations. Moreover, the dynamic response of the grid current controller was also greatly enhanced compared with that of the traditional PI-RC, due to the fuzzy and the reduced RC delay time.

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