Advanced Grid Current Compensator For Distributed Generation Under Nonlinear Loads And Voltage Distortion

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***Abstract* - In this paper proposed a fuzzy logic controller based current controller is designed in the synchronous reference frame and compared with the conventional PI controller and with a combination of a proportional–integral (PI) controller and a repetitive controller (RC). It is for an application of 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. In addition, the proposed control method does not require the local load current measurement or harmonic analysis of the grid voltage. 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. 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 advanced methodologies like artificial intelligence. The operation principle of the proposed control method is analyzed in detail, and its effectiveness is validated through MATLAB/SIMULINK simulation results.**

IndexTerms - Distributed generation (DG), Fuzzy controller grid-connected inverter, harmonic compensation, nonlinear load, repetitive control.

I. INTRODUCTION

Renewable energy production has been steadily increasing, as international goals to reduce dependence on fossil fuels have been on the agenda for nations worldwide. Distribution generation units popularly 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. Grid Current Compensator for Grid-Connected Distributed Generation under linear and non-linear load condition is analyzed with PI-RC controller in [1] and the operational observations show the efficiency of bitterly. As a remark, large renewable energy sources have been integrated into power distribution systems in the form of distributed generation (DG) [2]. DG systems can offer many advantages over traditional power generation, such as small size, low cost, high efficiency, and clean electric power generation.

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 [3]–[8] and [11], 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.

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 [10], 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 [11]. To address this problem, the local load current measurement and a load current feed-forward loop are regularly adopted [12]. 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 [13]. Then, an advanced control strategy is introduced to address those issues. The proposed current controller is designed in the d–q reference frame and is composed of a PI and an RC.

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 designed in the d-q reference frame and is composed of a Fuzzy controller. 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 with fuzzy technique is significantly improved compared with that of the PI current controller. In addition, with the combination of fuzzy, the dynamic response of the proposed current controller is also greatly enhanced compared with that of the traditional PI-RC. The feasibility of the proposed control strategy is completely verified by simulation results.

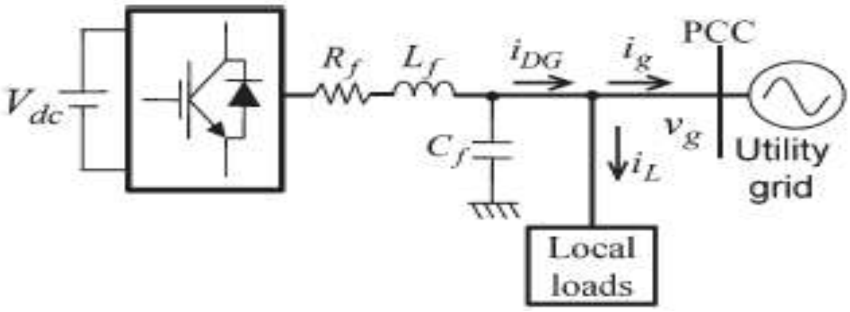

Fig.1. System configuration of a grid-connected DG system with local load

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 the 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 to the system. In Fig. 2(a), the voltage equation of the system is given as

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

$$v_i = v_{i1} + \sum_{h\neq 1} v_{ih}$$

$$v_g = v_{g1} + \sum_{h\neq 1} v_{gh} \quad (2)$$

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

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

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.

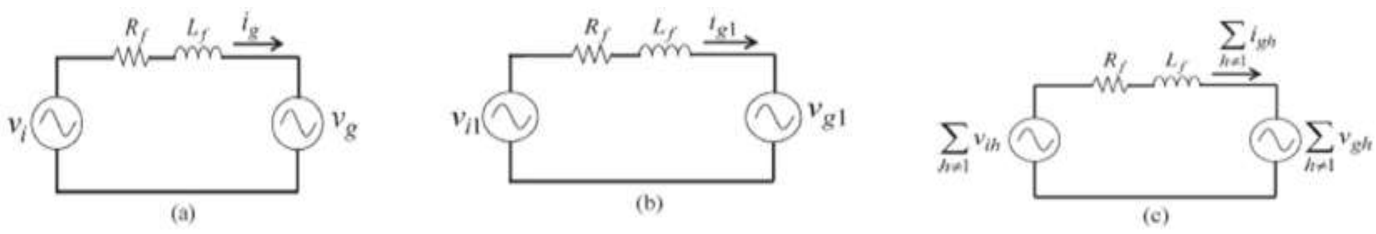

Fig. 2. Model of grid-connected DG system under distorted grid voltage condition. (a) General condition; (b) at the fundamental frequency, and (c) at harmonic frequencies.

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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 *i*DG. According to Fig. 3, the relationship of DG current *i*DG, load current *iL*, and grid current *ig* is described as

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

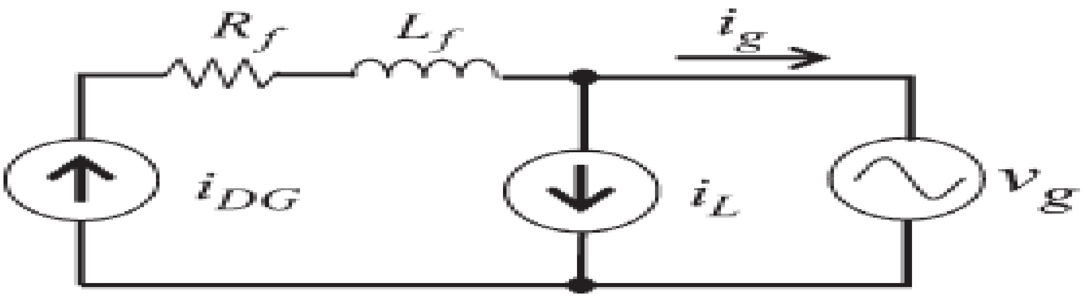


Fig. 3. Model of grid-connected DG system with the nonlinear local load.

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

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

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

Substituting (6) into (5), we have From (7), it is obvious that, in order to transfer sinusoidal grid current *ig* into the grid, DG current *i*DG should include the harmonic components that can compensate the load current harmonics $\sum_{h \neq 1} i_{Lh}$ 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.

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

III. PROPOSED 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) [14], 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.

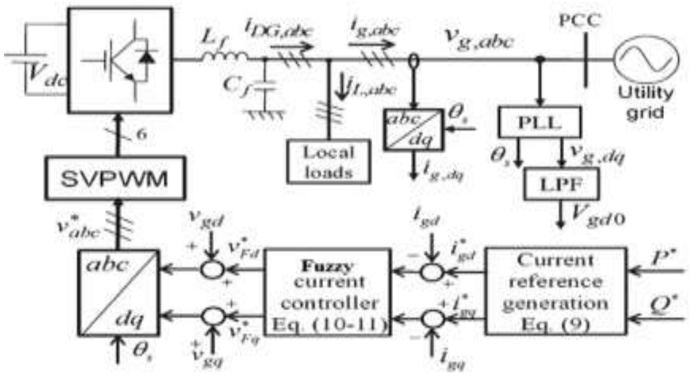


Fig. 4. An overall block diagram of the proposed control strategy.

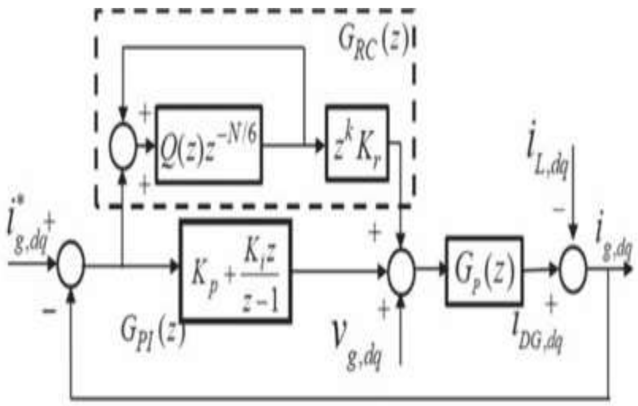


Fig. 5. Block diagram of the current controller.

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 [16]; therefore, it will not be addressed in this paper. As shown in Fig. 4, the control Fig. 6. Bode diagram of the proposed PI- RC current controller. 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.

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 [15]:

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

where P ∗ and Q∗ are the references active and reactive power, respectively; vgd represents the instantaneous grid

Voltage in the d-q frame; and igd and igq 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 igd and igq 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, whereVgd0 is the average value of vgd, which is obtained through the LPF in Fig. 4

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

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

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

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.

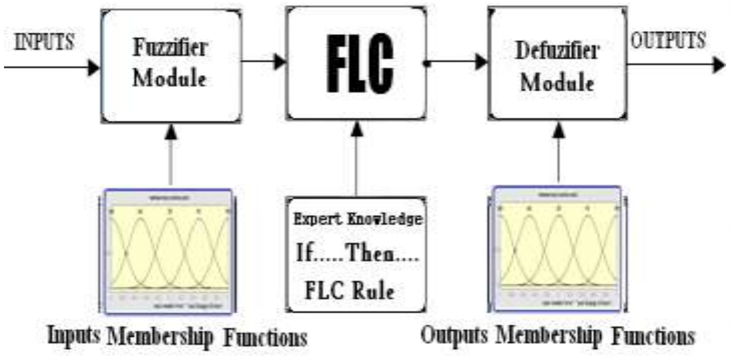
IV. FUZZY LOGIC CONTROLLER

A. Structure of fuzzy logic controller

Fuzzy controller the word Fuzzy means vagueness. Fuzziness occurs when the boundary of a piece of information is not clear-cut. Fuzzy set theory exhibits immense potential for effective solving of the uncertainty in the problem. The 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. The 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. The fuzzy set comprises from a membership function which could be defined 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 fuzzification. 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. The 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.

B. Fuzzy rules

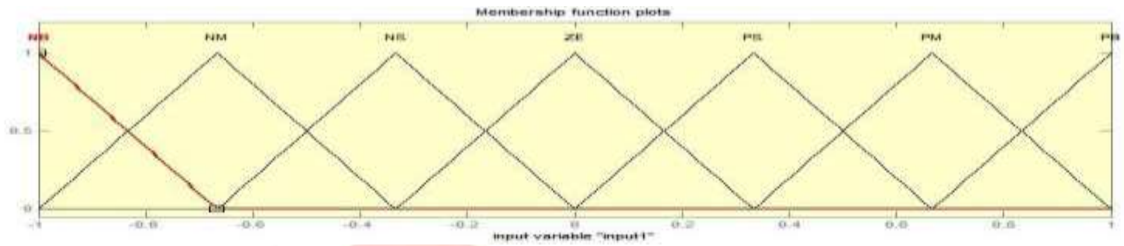
In the fuzzy control, input and output variables are the size of the form to describe in words, so to select special vocabulary to describe these variables, generally used in "big, medium and small" Three words to express the controller input and output variables state, plus the positive and negative 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}.



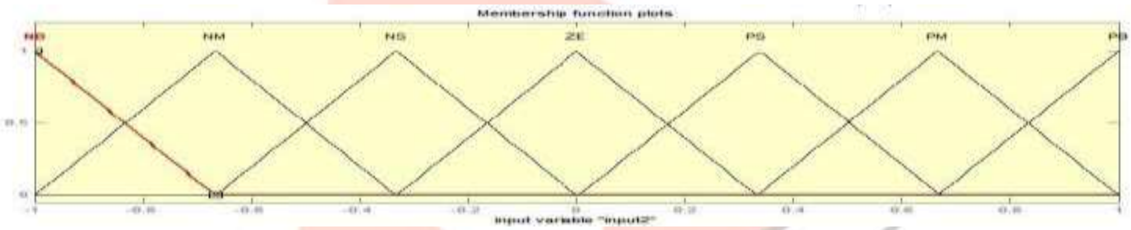
COE \ E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PB	NS	ZE
PS	NM	NS	ZE	PS	PM	PM	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

Fig.6. Fuzzy Basic Module and Fuzzy Rules

B. MEMBERSHIP FUNCTIONS



(a)



(b)

Fig.7. Member Ship Function of (a) Error (b) Change In Error

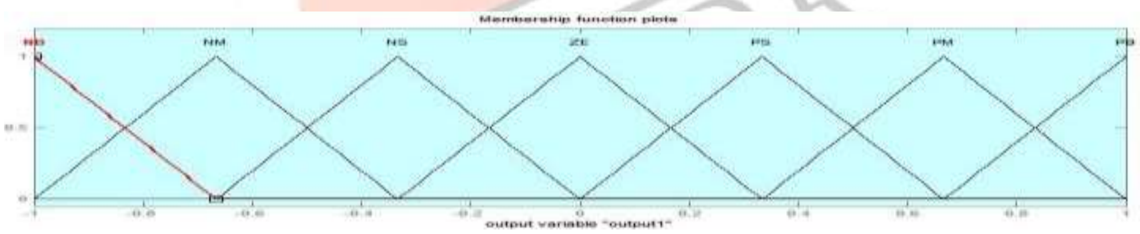


Fig.8. Member Ship Function of Output

V. SIMULATION RESULTS

A simulation model of the DG system is built by MATLAB simulation software to verify the effectiveness of the proposed control method. 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.

For the control reference grid current is set at i*gd =10A and i*gq=0 and the conventional PI& RC current controller and the proposed current controller are investigated to compare their control performances. Moreover, the proposed control method can bring the THD of the grid current to less than 2% in all cases, as given in Table these results obviously validate the effectiveness of the proposed control approach. Fig. 9, 10, 11, depicts the steady-state performance of the grid connected DG by using the conventional PI current controller, in which the waveforms of grid voltage, grid current, local load current, and DG current are plotted.

A. Simulation Results Using PI Current Controller

Case I: Grid Voltage Sinusoidal and The Linear Local Load is Used

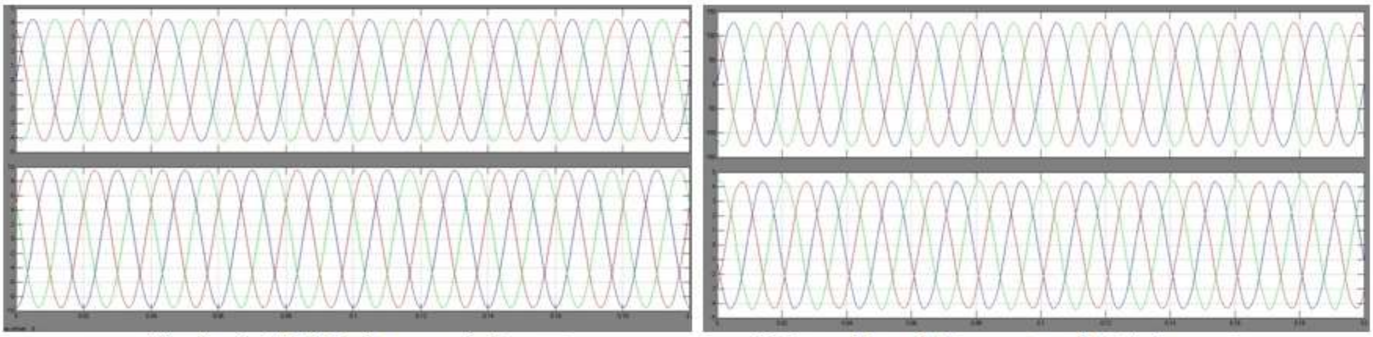


Fig.9. a) Grid Voltage and Current b) Local Load Current and DG Current

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.

Case II: The Grid Voltage Sinusoidal and The Non- Linear Local Load is Used

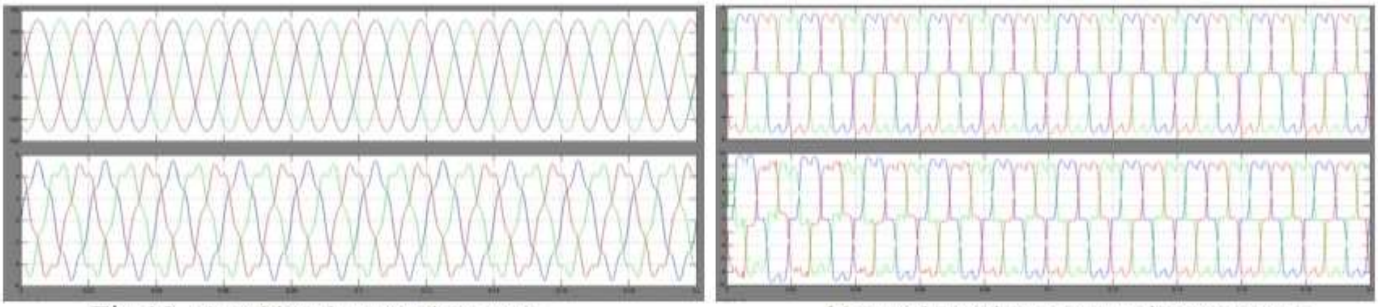


Fig.10. a) Grid Voltage and Current b) Local Load Current and DG Current

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. 9,10,11.

Case III: The Grid Voltage Is Distorted and The Non- Linear Local Load is Used

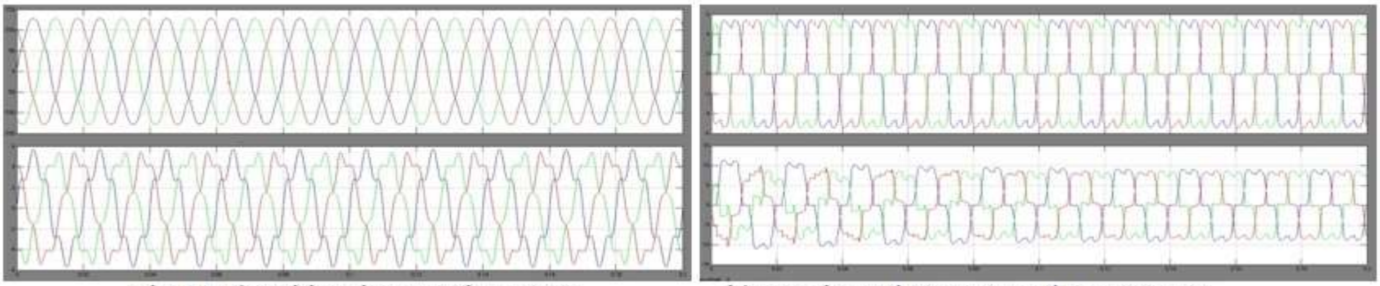


Fig.11. a) Grid Voltage and Current b) Local Load Current and DG Current

In addition, to assess the feasibility of the proposed current controller under grid frequency variations, simulation results of the proposed PI-RC current controller as shown in fig. 12, 13, 14.

B. Simulation Results Using PI and RC Current Controller

Case I: The Grid Voltage Sinusoidal and The Linear Local Load is Used

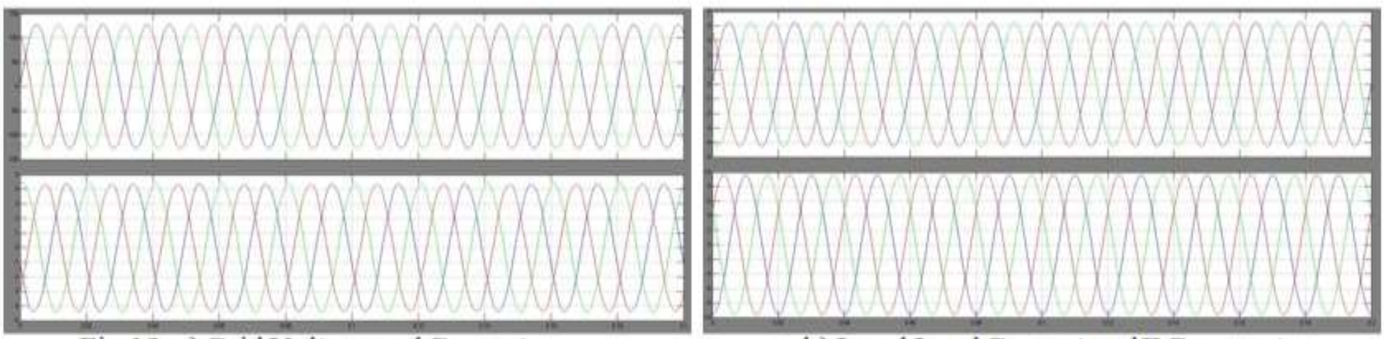


Fig.12. a) Grid Voltage and Current b) Local Load Current and DG current

Case II: The Grid Voltage Sinusoidal and The Non- Linear Local Load is Used

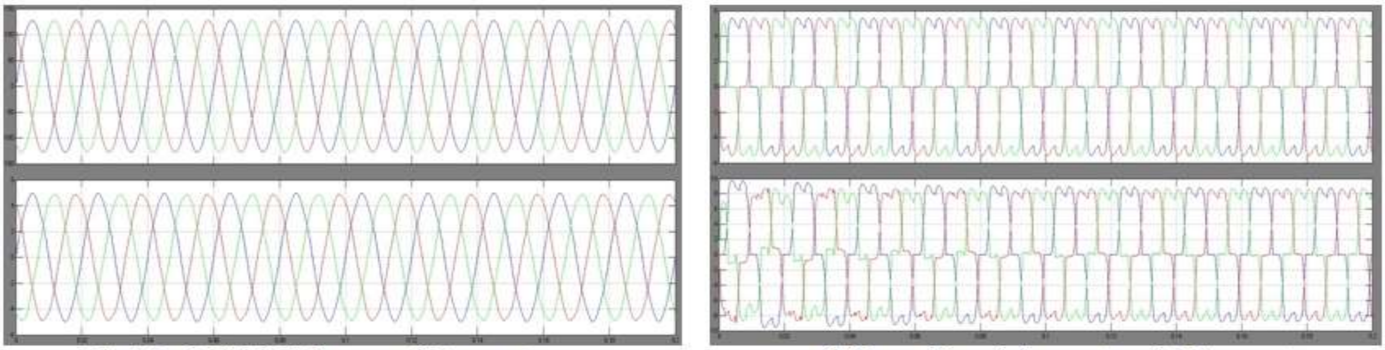


Fig.13. a) Grid Voltage and Current b) Local Load Current andDGcurrent

Case III: The Grid Voltage is Distorted and The Non- Linear Local Load is Used

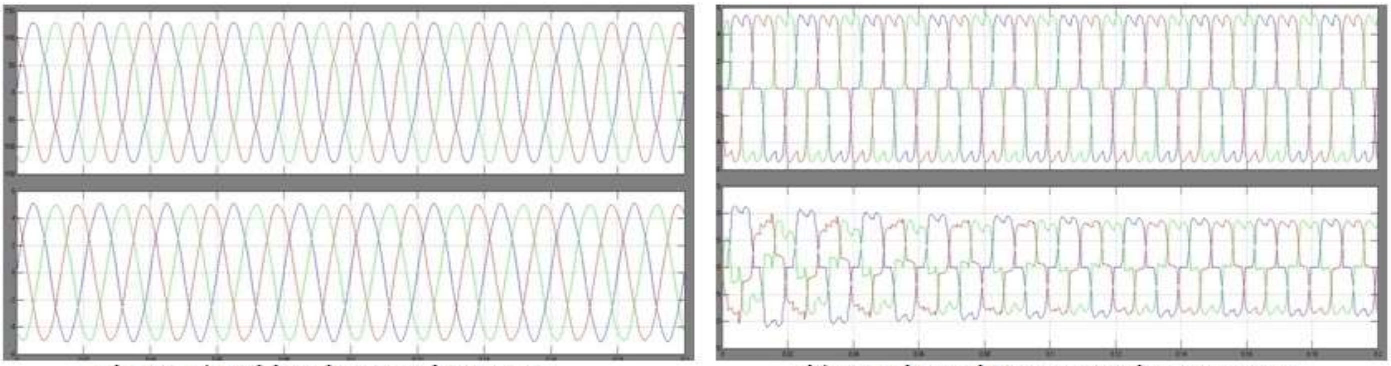


Fig.14. a) Grid Voltage and Current b) Local Load Current and DG Current

Therefore, we can say that the proposed current controller is able to maintain a high-quality grid current even under the grid frequency variations.

C. Simulation Results Using Fuzzy Current Controller
Case I: The Grid Voltage Sinusoidal and The Linear Local Load is Used

As shown in the results in fig. 15, 16, 17, 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.

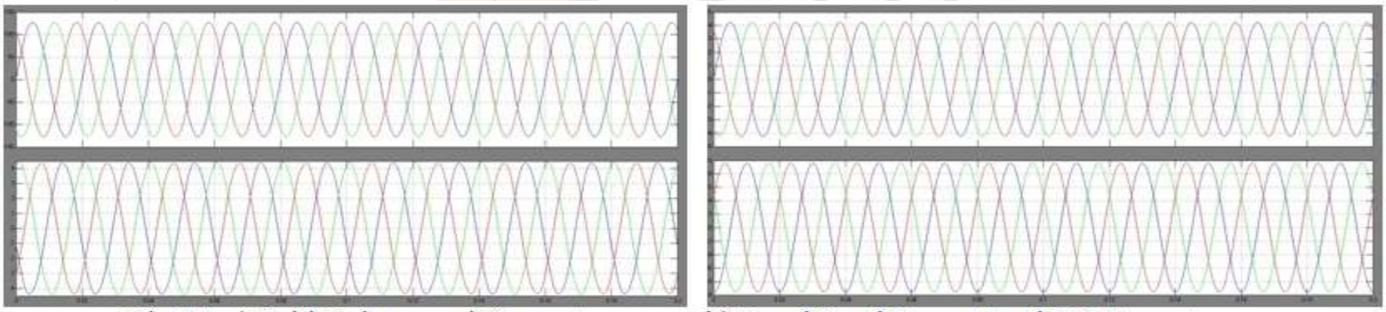


Fig.15. a) Grid Voltage and Current b) Local Load Current and DG Current

Case II: The Grid Voltage Sinusoidal and The Non- Linear Local Load is Used

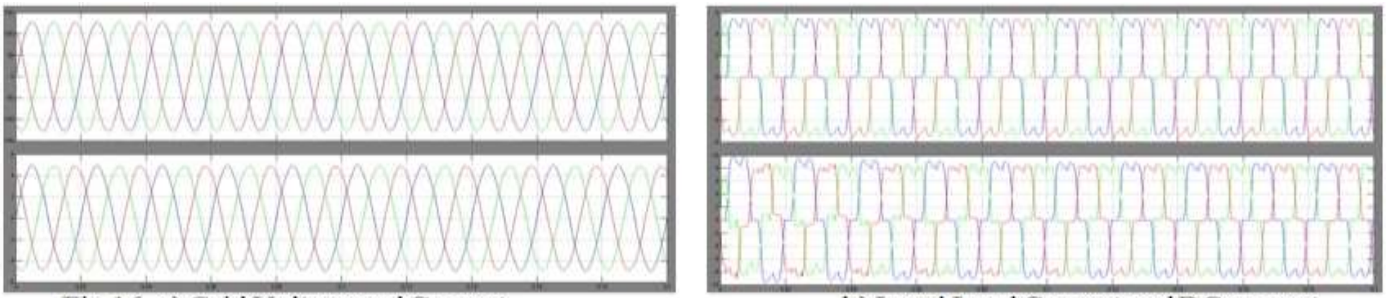


Fig.16. a) Grid Voltage and Current b) Local Load Current and DG current

Case III: The Grid Voltage Is Distorted and The Non- Linear Local Load is Used

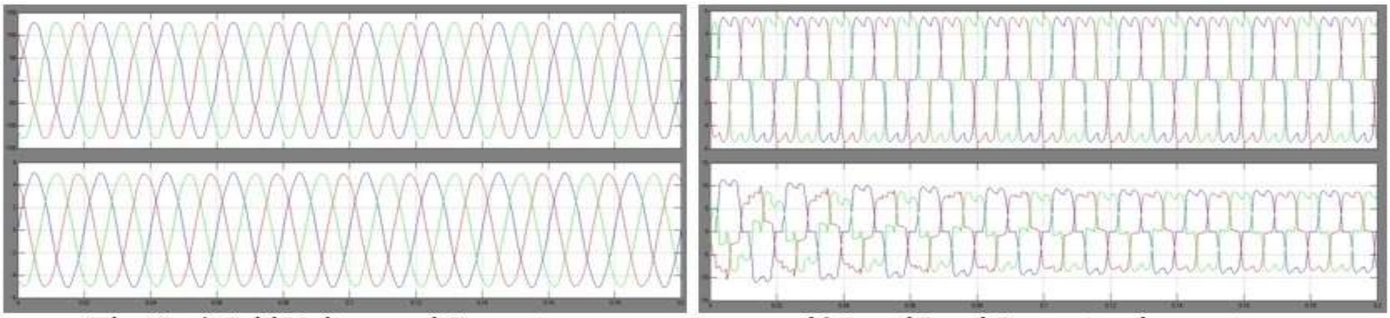


Fig.17. a) Grid Voltage and Current b) Local Load Current and current

D. THD Graphs and Values

Case I: The Grid Voltage Sinusoidal and The Linear Local Load is Used

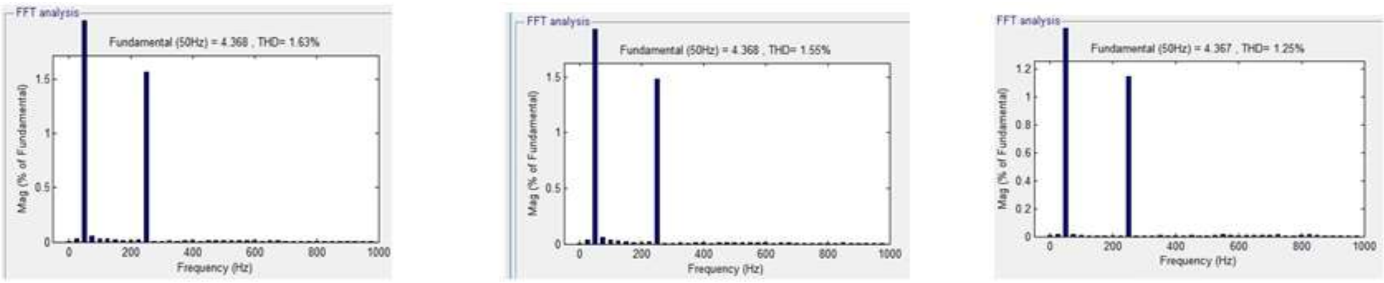


FIG. 17. A)PI CONTROLLER B)PI-RC CONTROLLER C)FUZZY CONTROLLER

Case II: The Grid Voltage Sinusoidal and The Non- Linear Local Load is Used

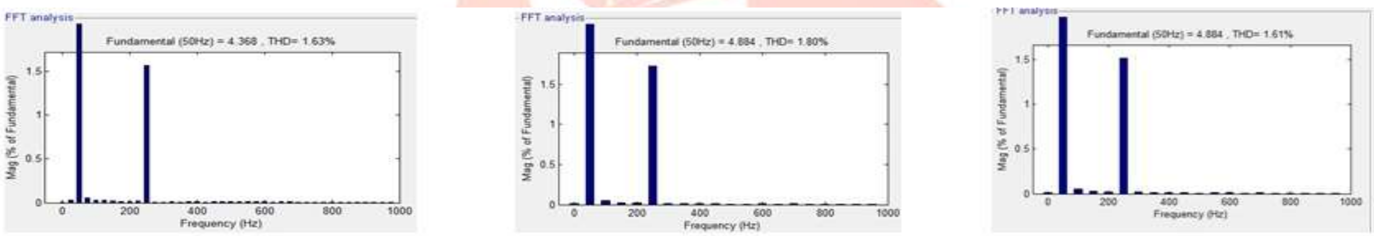


FIG.18. A) PI CONTROLLER B) PI- RC CONTROLLER C) FUZZY CONTROLLER

Case III: The Grid Voltage is Distorted and The Non- Linear Local Load is Used

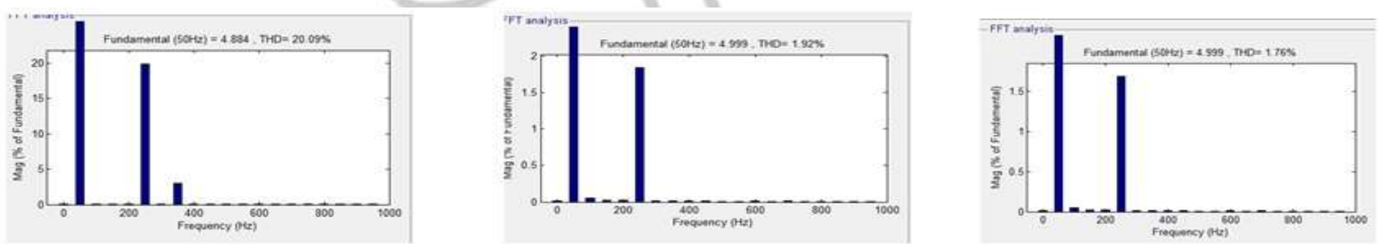


FIG.19. A) PI CONTROLLER B) PI- RC CONTROLLER C) FUZZY CONTROLLER

In Cases I and II, the grid voltage is assumed as a pure sinusoidal waveform. In Case III, the distorted grid voltage is supplied with the harmonic components: 3.5% 5th harmonic, 3%; 7th harmonic, 1% 11th harmonic, and 1% 13th harmonic. The THD of grid voltage is about 4.82%. This grid voltage condition complies with the IEEE 519-1992 harmonic restriction standards, where the THD of grid voltage is less than 5%. The proposed fuzzy control THD in case I 1.24%, case II 1.63%, case III 1.78%.

Table.1. Summary of THD Values OF Grid Current with Proposed Current Controllers

	PI current controller			**PI & RC current controller**			**FUZZY LOGIC current controller**		
	Case I	Case II	Case III	Case I	Case II	Case III	Case I	Case II	Case III
THD of i_g	1.67%	12.27%	20.69%	1.56%	1.82%	1.92%	1.24%	1.63%	1.78%

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 into 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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