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Performance Analysis of a Grid Current Compensator using Fuzzy Logic Controller

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***Abstract*: This paper introduces an advanced current control strategy for distributed generation into the utility grid despite the distorted grid voltage and RC loads. The proposed current controller is designed in synchronous reference frame and composed of a fuzzy logic controller. The fuzzy logic controller greatly simplifies the control strategy. It does not require the local load current measurement and harmonic analysis of the grid voltage. Therefore, the proposed control method can be easily adopted into the traditional DG control system without installation of external hardware. The operation principle of the proposed control method is analyzed in detail, and its effectiveness is validated through simulated results.**

Index Terms: ***Distributed Generation (DG), RC load, Fuzzy Logic Controller (FLC), PI Controller, PI-RC Controller***

I. INTRODUCTION

Renewable energy sources such as wind energy, solar energy, photovoltaic and fuel cells usage have been greatly increased in recent decades to attain the global energy crisis. As a result, a large number of renewable energy sources have been integrated in power distribution systems in the form of distributed generation (DG). DG systems 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 agrid connected mode where the maximum available power is extracted from energy sources and transferred to the utility grid. In addition, to exploit full advantages of a DG system, the DG can also be equipped and operated with local loads, where the supplies power to the local load and transfers surplus power to the grid. 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'[12]. To produce a high-quality grid current, various current control strategies have been introduced, such as hysteresis, predictive, proportional–integral (PI), proportional-resonant (PR) and Proportional Integral – Repetitive controller (PI-RC)[1]. 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. 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. 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[4]. the grid voltage at the point of common coupling (PCC) is typically not pure sinusoidal, but instead can be unbalanced or distorted[8].These abnormal grid voltage conditions can strongly deteriorate the performance of the regulating grid current.

A PI-RC controller includes a PI controller and Repetitive controller which comprises of a bank of resonant controllers that are used to eliminate the higher order harmonics in the system. A PI-RC controller implemented in a d-q reference frame gives a better control performance by reducing the THD to below 5% even under distorted grid voltage and RC local loads connected to the grid[4]. An advanced control strategy is introduced which gives a better performance than a PI-RC controller.

A fuzzy logic controller is introduced in the control scheme to reduce the THD of the grid current. This controller reduces the control scheme complexity and calculations for the design of the RC controller. Therefore, the proposed control method can be easily adopted into the traditional DG control system without the installation of extra hardware[7]. 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 and PI-RC controller[12]. The feasibility of the proposed control strategy is completely verified by simulation results.

II. SYSTEM CONFIGURATION AND ANALYSIS OF RC LOCAL LOADS

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.

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To guarantee high-quality power, the current that the DG transfers to grid (i_g) should be balanced, sinusoidal, and have a low THD value[5]. However, because of the RC local loads that typically exist in the power system, it is not easy to satisfy these requirements.

A. Effect of Grid Voltage Distortions

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(v_i)[1]. The inverter transfers a grid current (i_g) to the utilitygrid (v_g)[6]. For simplification purpose, it is assumed that the local load is not connected into the system.

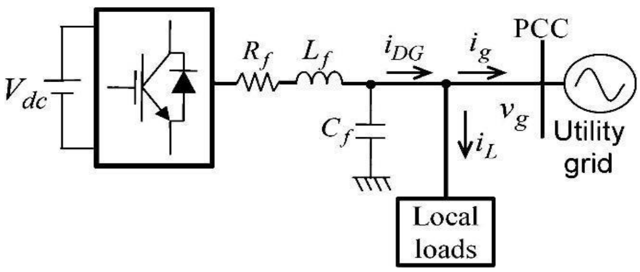

Fig. 1. System configuration of a grid-connected DG system with local load.

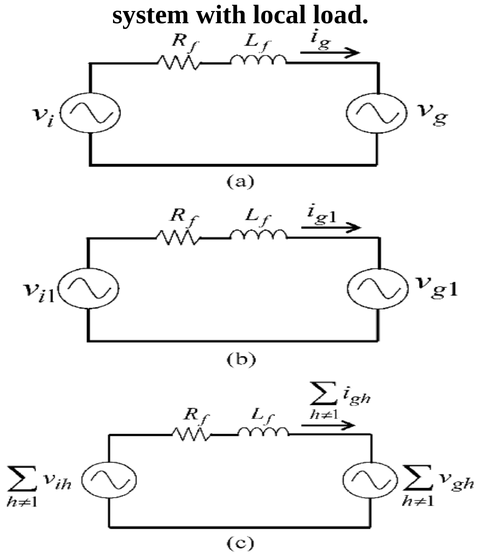

Fig. 2. Model of grid-connected DG system (a) General condition (b) at the fundamental frequency and (c) at harmonic frequencies

In Fig. 2, the voltage equation of the system is given as

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

Where R_f and L_f are the equivalent resistance and inductance of the inductor L_f respectively.

If both the inverter voltage [6] and the grid voltage are composed of the fundamental and harmonic components as(2) the voltage equation can be composed in to(3) and (4) and the system model shown in fig.2(a) can be expressed as Fig.2(b) and (c),respectively. That is

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

$$v_g = v_{g1} + \sum_{h=1} v_{gh} \tag{2}$$

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

$$\sum_{h=1} v_{ih} - \sum_{h=1} v_{gh} - L_f \frac{d(\sum_{h=1} i_{gh})}{dt} - R_f \sum_{h=1} i_{gh} = 0 \tag{4}$$

From(4) due to the existence of the harmonic components in the grid voltage, the harmonic currents are induced into the grid current if the DG cannot generate the harmonic voltages which are exactly same as a result the distorted grid voltage at the PCC causes non-sinusoidal grid currents i_g. If the current controller cannot handle harmonic grid voltage.

B. Effect of RC local loads:

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 i_L, and the DG is represented as a controlled current source i_{DG}.

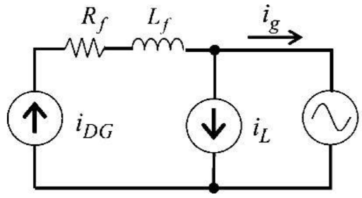

Fig. 3. Model of grid connected DG system with power RC local load

According to Fig. 3, the relationship of DG current i_{DG}, load current i_L, and grid current i_g is described as

$$i_{DG} = i_L + i_g \tag{5}$$

Assuming that the local load is a three-phase diode rectifier feeding an RC load, the load current is composed of the fundamental and harmonic components as

$$i_L = i_{L1} + \sum_{h=1} i_{Lh} \tag{6}$$

where i_{L1} and i_{Lh} are the fundamental and harmonic components of the load current, respectively. Substituting

(3) into (2), we have

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

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$\sum_{h=1} i_{Lh}$. 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 [1], cannot realize this demand because they lack the capability to regulate harmonic components.

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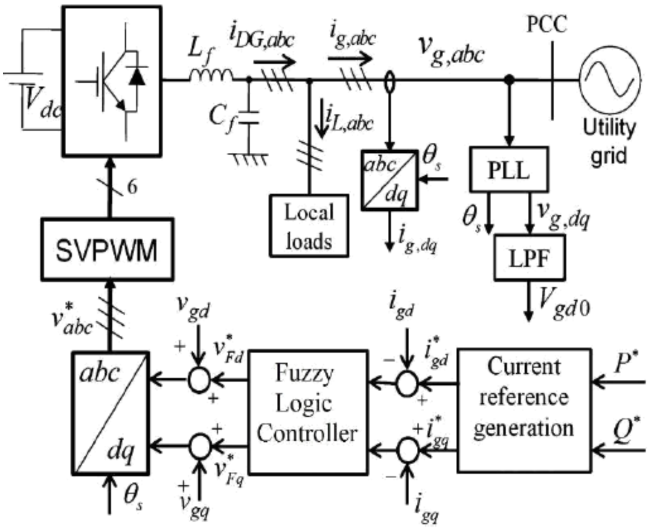

Fig. 4. Overall block diagram of the proposed control strategy.

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), Fig. 4 contains the grid voltage sensor and a PLL for simple and effective implementation of the proposed control scheme, which is developed in the d–q reference frame [12].

The proposed control scheme is composed of three main parts: the PLL, the current reference generation scheme, and the current controller. 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.

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:

$$i_{gd}^{*} = \frac{2}{3}\frac{P^{*}}{V_{gd}}$$
$$i_{gq}^{*} = -\frac{2}{3}\frac{Q^{*}}{V_{gq}} \quad (8)$$

where P^* and Q^* are the reference active and reactive power, respectively. v_{gd}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 v_{gd}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 v_{gd} 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 v_{gd}, and the d–q reference currents are modified as follows:

$$i_{gd}^{*} = \frac{2}{3}\frac{P^{*}}{V_{gd0}}$$
$$i_{gd}^{*} = -\frac{2}{3}\frac{P^{*}}{V_{gq0}} \quad (9)$$

where V_{gd0} is the average value of v_{gd}, which is obtained through the LPF in Fig. 4.

B. Current Controller

An advanced current controller is proposed by using a fuzzy logic controller. A fuzzy logic controller by the use of rule base and membership function eliminates the harmonic components of the grid current caused by the RC local load and/or distorted grid voltage. Fig (5) shows the basic block diagram of a fuzzy logic controller.

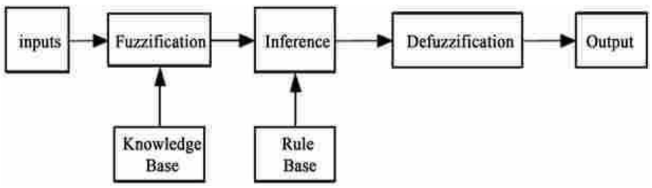

Fig. (5). Basic block diagram of a fuzzy logic controller

The fuzzy controller has four main components (i) the "rule-base" holds the knowledge, in the form of a set of rules, of how best to control the system (ii) the inference mechanism evaluates which control rules are relevant at the current time and then decides what the input should be (iii) the fuzzification interface simply modifies the inputs so that they can be interpreted and compared to the rules in the rule-base and (iv) the defuzzification interface converts the conclusions reached by the inference mechanism into the output. The logic involved can deal with concepts that cannot be expressed as "true" or "false" but rather as "partially true". Although genetic algorithms and neural networks can perform just as well as fuzzy logic in many cases, fuzzy logic has the advantage that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller[10]. This makes it easier to mechanize tasks that are already successfully performed by humans. A fuzzy control system is a control system based on logical mathematical system that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic, which operates on discrete values of either 1 or 0.

TABLE I. SYSTEM PARAMETERS

Parameters	Values
Grid Voltage	110 V(rms)
Grid frequency	50 Hz
Rated output power	5kw
DC-link voltage	350V
Output filter inductance (L_f)	0.7 mH
Output filter resistance (R_f)	0.1Ω
Output filter capacitance (C_f)	27μF
Load of 3 phase diode rectifier	R=30Ω, C=2200 μF
Three phase resistive load	R=30Ω

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IV. SIMULATION RESULTS

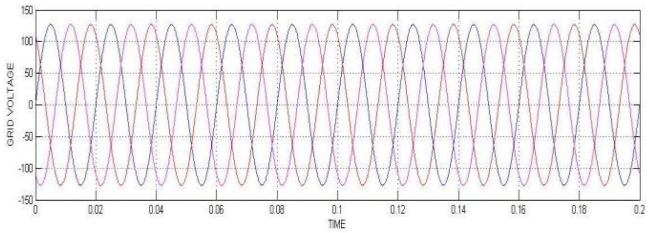
A simulation model of the DG system is built by PSIM simulation software to verify the effectiveness of the proposed control method. The system parameters are given in Table I. In the simulation, three cases are taken into account. (1) Case I: The grid voltage is sinusoidal and the RC load is used (2) Case II: The grid voltage is distorted and the RC load is used In Case I the grid voltage is assumed as a pure sinusoidal waveform. InCaseII, 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%.

In all test cases, the reference grid current is set at i^*_{gd}=10A and i^*_{gq}=0, and the conventional PI current controller, PI-RC controller and the proposed current controller are investigated to compare their control performances.

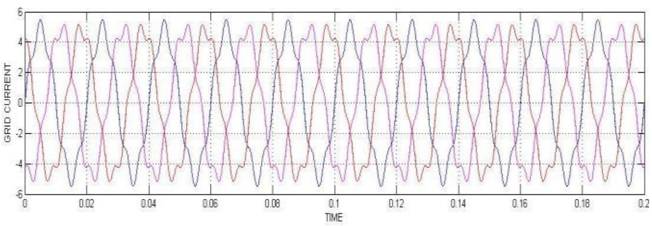
The grid voltage is sinusoidal and the local load used is a three phase diode rectifier with RC load. In all test cases, the reference grid current is set at i^*_{gd} = 10 A and i^*_{gq} = 0, and the conventional PI current controller, PI-RC controller and the proposed current controller are investigated to compare their control performances.

Fig. 6 depicts the steady-state performance of the grid-connected DG by using the conventional PI current controller, in which the waveforms of grid voltage (v_g), grid current (i_g) and the FFT analysis of grid current are plotted. As shown in Fig. 6, the PI current controller is able to offer a good performance when the grid voltage is ideal sinusoidal and the local load is purely resistive. In the other circumstances, due to the effect of RC local loads, the PI current controller is unable to transfer a sinusoidal grid current to the utility grid. In fact, because of the popular use of RC loads in the DG local load and distribution system, the ideal sinusoidal condition of the grid voltage is very rare. As a result, the conventional PI controller is insufficient to offer a good quality of the grid current. The DG system with the PI-RC controller is simulated, and the results are shown in Fig. 7.

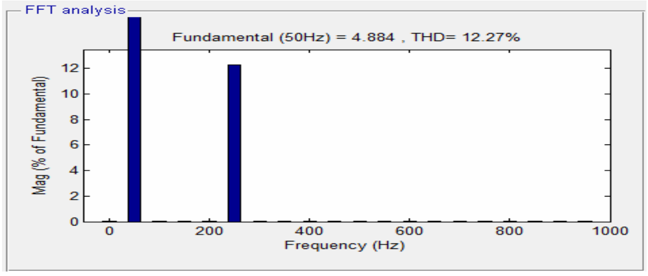
Case I: Grid voltage sinusoidal and RC Load with PI



Grid Voltage

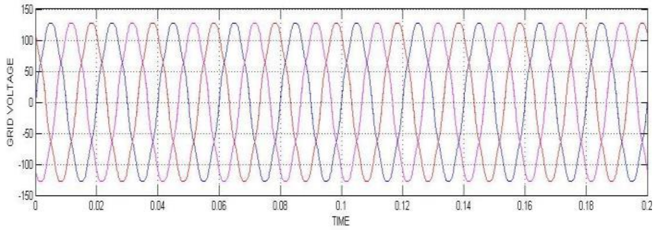


Grid Current

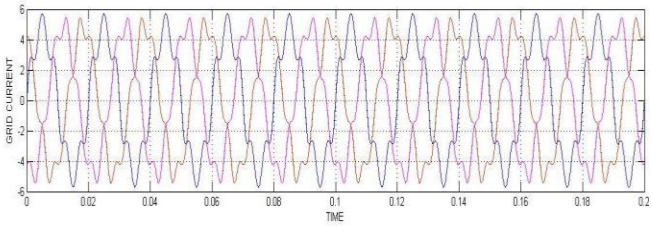


THD of i_g

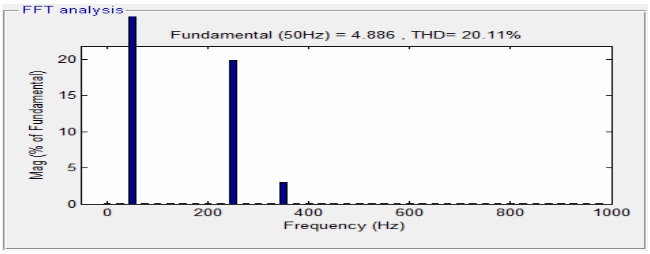
Case II: Distorted grid voltage and RC Load with PI



Grid Voltage



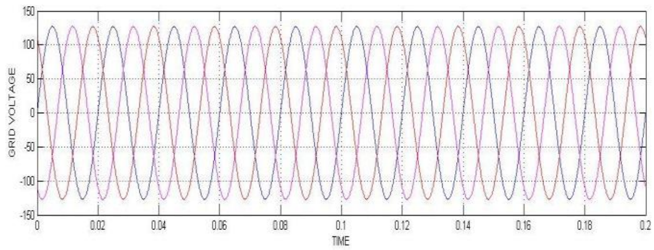
Grid Current



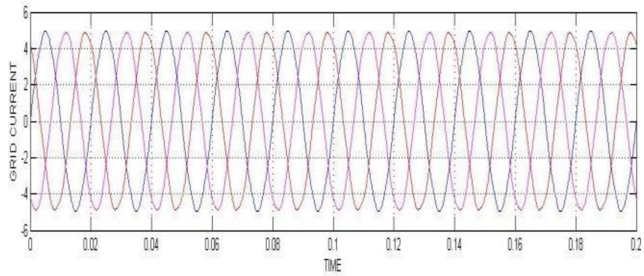
THD of i_g

Fig. 6. Simulation results with PI current controller

Case I: Grid voltage sinusoidal and RC Load with PI-RC



Grid Voltage



Grid Current

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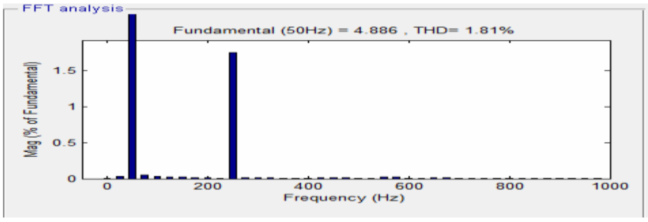
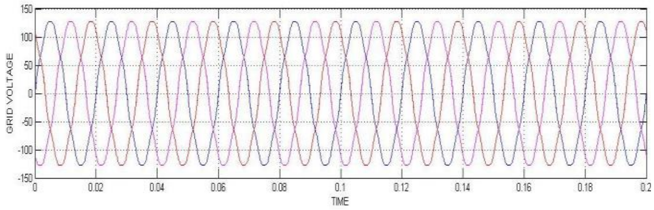
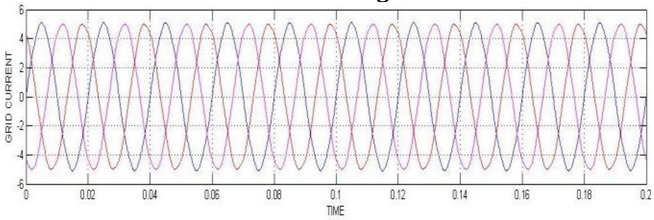


THD of i_g

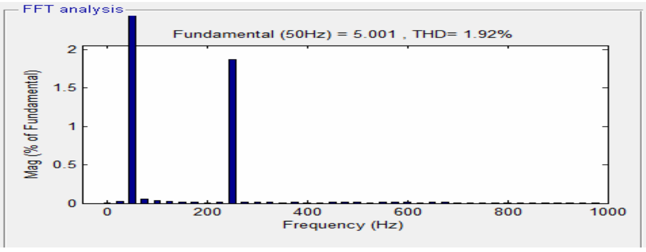
Case II: Distorted grid voltage and RC Load with PI-RC



Grid Voltage



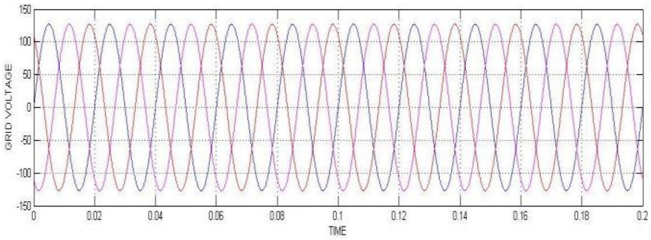
Grid Current



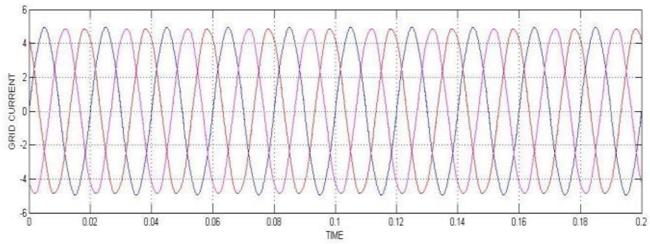
THD of i_g

Fig. 7. Simulation results with PI-RC current controller

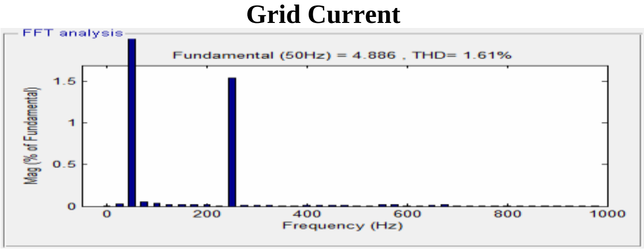
Case I: Grid voltage sinusoidal and RC Load with Fuzzy



Grid Voltage

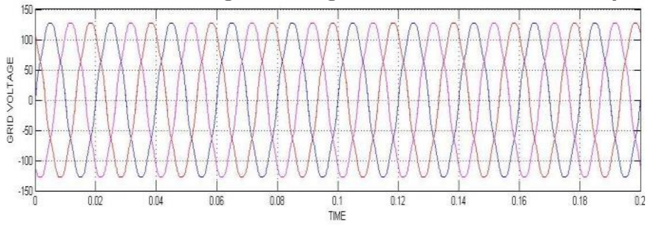


Grid Current

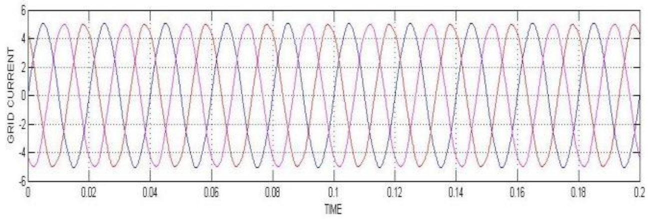


THD of i_g

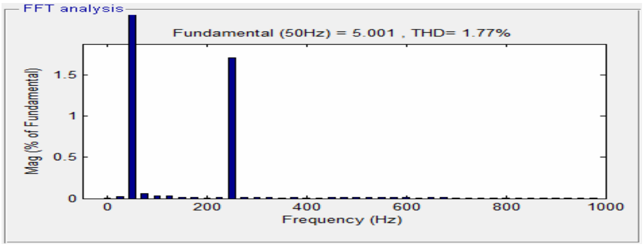
Case II: Distorted grid voltage and RC Load with Fuzzy



Grid Voltage



Grid Current



THD of i_g

Fig. 8. Simulation results with the proposed fuzzy logic current controller

TABLE II. Summary of Thd Values of Grid Current with Pi, Pi-Rc and Proposed Fuzzy Logic Current Controllers

THD of i_g	PI	PI-RC	FUZZY
Case I	12.27%	1.81%	1.61%
Case II	20.11%	1.92%	1.77%

To demonstrate the superiority of the proposed current controller over the traditional PI controller and PI-RC controller, the DG system with the proposed current controller is also simulated, and the results are shown in Fig.8. As shown in the results, the proposed control strategy can provide a good quality current than PI and PI-RC controllers and also eliminates the complexity in the design of a Repetitive controller.The results shown above in the Table II, validate the effectiveness of the proposed fuzzy logic current controller which enhances the performance of the grid current by reducing the harmonic component in the grid current even Under RC local loads.

V. CONCLUSION

This paper has proposed an advanced current control strategy for the grid-connected DG to simultaneously eliminate the effect of RC 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 local load conditions.

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The proposed 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[13]. The THD value of the grid current is decreased considerably compared with that achieved by using the conventional PI current controller and also PI-RC current controller. In addition, the proposed current controller also maintained a good quality of grid current under grid frequency variations.

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