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Modeling and Simulation of Grid Current Controller for Grid Connected Distributed System under Nonlinear loads

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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 current controller is designed in the synchronous reference frame and composed of a proportional–integral (PI) controller and a repetitive controller (RC). 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 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. 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. 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. 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.

***Keywords:* Distributed generation, grid connected inverter, harmonic compensation, nonlinear load, repetitive control**

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 form of 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]. The proposed current controller is 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.

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

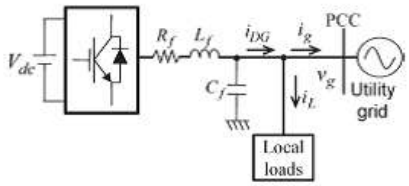

Fig 1. System configuration of a grid-connected DG system with local load

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

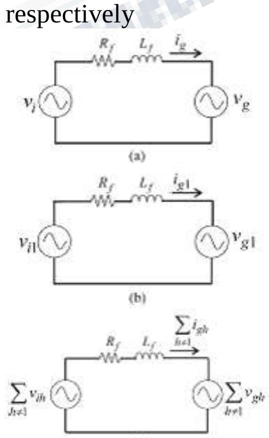

Fig 2. Model of grid-connected DG system under distorted grid voltage condition. (a) General condition; (b) at the fundamental frequency; and (c) at harmonic frequencies.

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

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

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

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

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 , and the DG is represented as a controlled current Source . According to Fig.3, the relationship of DG current, load current, and grid current igis described as

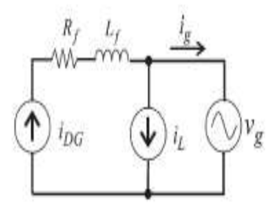

Fig. 3. Model of grid-connected DG system with nonlinear local load.

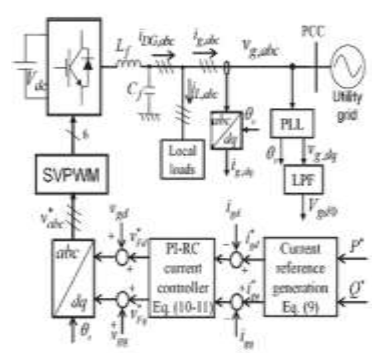

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Fig. 4. Overall block diagram of the proposed control strategy.

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 and 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 should include the harmonic components that can compensate the load current harmonics. 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. is near to battery voltage at the pins, separated from the latter by only a resistance, called R_0in figure. The energy that enters the e.m.f. force *Ep* abandons the state of electric power, and is converted into other forms of energy. For instance, for lead–acid batteries, the parasitic branch models the water electrolysis that occurs at the end of the charge process and the energy entering E_p is absorbed by the reaction of water dissociation. The power dissipated in the real parts of impedances and is converted into heat that contributes to the heating of the battery itself.

C.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 implementing of the proposed algorithm, which is developed in the d–q reference frame.

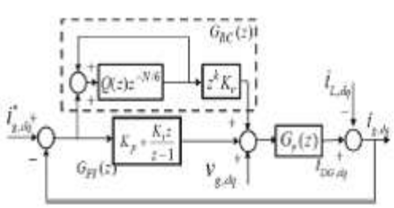


Fig. 5. Block diagram of the current controller.

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 [20]; therefore, it will not be addressed in this paper. As shown in Fig.4.4, 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.

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

III. 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 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% [25]. 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.

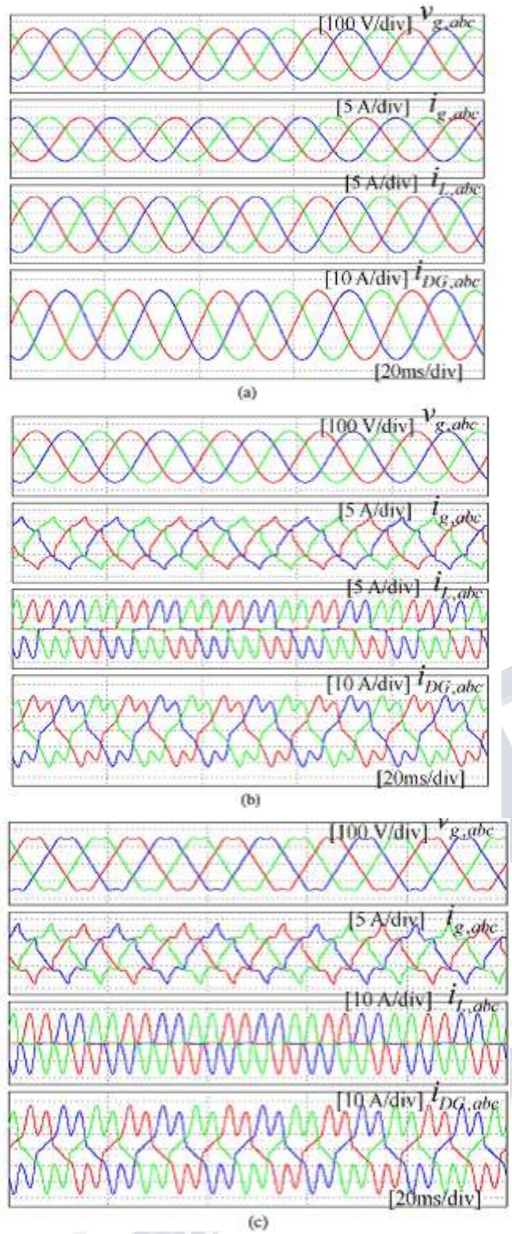
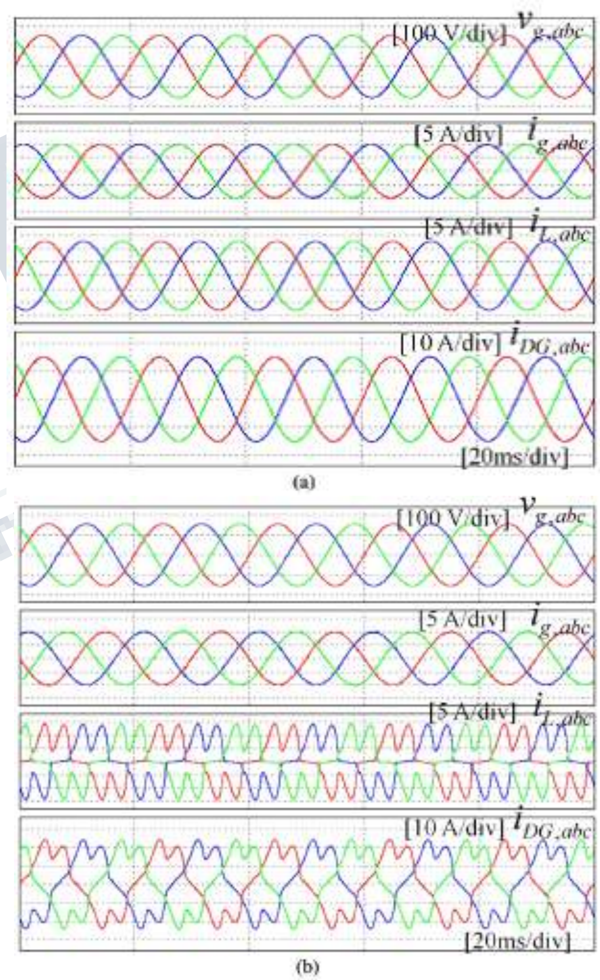


Fig. 6. Simulation results with the PI current controller: (a) Case I; (b) Case II; and (c) Case III.

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 (*vg,abc*), grid current (*ig,abc*), local load current (*iL,abc*), and DG current (*i*DG,*abc*) are plotted. As shown in Fig. 6, 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. 7. 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.



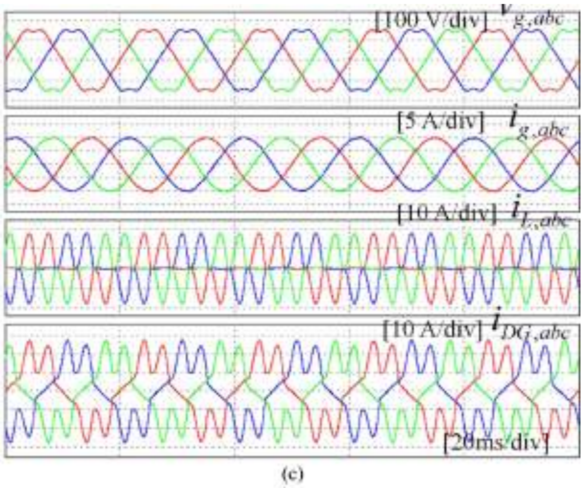


Fig.7. Simulation results with the proposed PI-RC current controller:
Case I; (b) Case II; and (c) Case III.

IV. 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 and experimental 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 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 RC, due to the PI and RC combination and the reduced RC delay time.

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