Harmonic Droop Controller to Reduce the Voltage Harmonics of Inverters

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***Abstract*—In this paper, the load and/or grid connected to an inverter is modeled as the combination of voltage sources and current sources at harmonic frequencies. As a result, the system can be analyzed at each individual frequency, which avoids the difficulty in defining the reactive power for a system with different frequencies because it is now defined at each individual frequency. Moreover, a droop control strategy is developed for systems delivering power to a constant current source, instead of a constant voltage source. This is then applied to develop a harmonic droop controller so that the right amount of harmonic voltage is added to the inverter reference voltage to compensate the harmonic voltage dropped on the output impedance due to the harmonic current. This forces the output voltage at the individual harmonic frequency to be close to zero and improves the total harmonic distortion (THD) of the output voltage considerably. Both simulation and experimental results are provided to demonstrate that the proposed strategy can significantly improve the voltage THD.**

***Index Terms*—Droop control, harmonic droop controller, parallel operation of inverters, power quality, proportional load sharing, total harmonic distortion (THD).**

I. Introduction

NOWADAYS, more and more distributed generation and renewable energy sources, e.g., wind, solar, and tidal power, are developed. They often form microgrids via power inverters [1]–[5], which may or may not be connected to the grid. One of the major problems in these applications is the harmonics in the voltage provided by the inverters. There are two sources of harmonics: one is from the inverters (e.g., because of the pulsewidth modulation (PWM) and the switching), and the other is from loads or the grid. The majority of loads today are nonlinear and generate harmonic currents when a purely sinusoidal voltage supply is provided. These harmonic currents then cause harmonic components in the voltage because of the impedances in the distribution network and, also, inside the voltage source. Of course, harmonic voltages then cause harmonic currents as well. The odd multiples of the 3rd harmonic (3rd, 9th, 15th, 21st, $\ldots$), i.e., the $6n-3$ harmonics, are called triplen harmonics. These currents on a three-phase system are zero-sequence harmonics, which are additive in the neutral line and cause particular concern. The $6n-1$ harmonics are negative-sequence harmonics and can cause problems to electrical machines because these harmonics create a negative torque and attempt to drive machines in reverse. Harmonics are not desirable because they cause overheating, increased losses, decreased voltampere capacity, neutral-line overloading, distorted voltage and current waveforms, etc. It has become a very serious issue in modern power systems. Hence, stringent regulations have been put into place [6], [7]. The total harmonic distortion (THD) of voltages and currents needs to be maintained low, often below 5%. This paper focuses on the cancellation of harmonics in voltage. For the cancellation of current harmonics, active power filters can be adopted. See, for example, [8]–[10].

Several feedback control schemes have been proposed to reduce the voltage THD of inverters. Deadbeat or hysteresis controllers [11] are some examples. Repetitive control theory [12], which is regarded as a simple learning control method, provides an alternative to eliminate periodic errors in dynamic systems, using the internal model principle [13]. Such a closed-loop system can deal with a very large number of harmonics simultaneously, as it has high gains at the fundamental and all harmonic frequencies of interest. It has been successfully applied to constant-voltage constant-frequency PWM inverters [14]–[19], grid-connected inverters [5], [6], [20], [21], and active filters [22], [23] to obtain very low THD. Strategies have been developed to maintain low THD in the current exchanged with the grid [6], in the microgrid voltage [5], [20], and in both the current exchanged with the grid and the microgrid voltage at the same time [24]. A cooperative harmonic filtering strategy was proposed in [25] to share the harmonic var [26] among distributed inverters, which has the capability of improving the voltage THD. The drawback is that extensive experiments are needed to determine the reference value for the harmonic var.

It is well understood [27] that the output impedance of an inverter plays an important role in power sharing, and a droop controller for inverters with resistive output impedances was proposed for sharing linear and nonlinear loads [28]. The output impedance of an inverter also plays a critical role in reducing the THD of the output voltage. The voltage THD could be improved via reducing the output impedance [29] or changing the output impedance to be capacitive [30]. In this paper, another approach is proposed to reduce the voltage THD. Its development involves three steps. First, the load or grid connected to an inverter is modeled as the combination of voltage and current sources at harmonic frequencies. Based on

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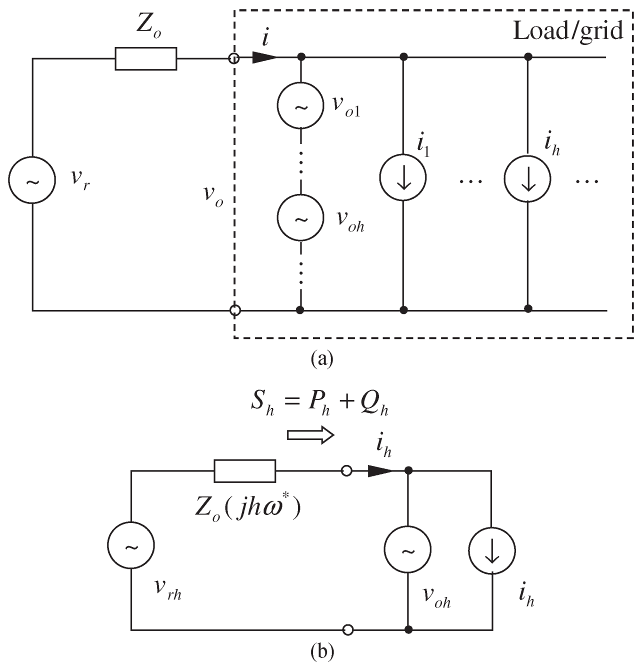

Fig. 1. Model of an inverter connected to a load/grid. (a) One circuit including all harmonics. (b) Circuit at the hth-harmonic frequency.

this, the voltage harmonics can be treated individually at each harmonic frequency. If the right amount of harmonic voltage is added to the reference voltage for the inverter, then the harmonic component in the output voltage can be made zero. Second, a droop control strategy is developed to deliver power to a constant current source/sink.[1] Finally, a harmonic droop control strategy is proposed to reduce individual harmonics. Effectively, it means that the power sharing or droop control should be done at each individual harmonic frequency, which avoids the difficulty in defining/calculating the reactive power at different frequencies together [26], [31]. Simulation and experimental results are provided to show that the proposed strategy could considerably improve voltage THD.

The rest of this paper is organized as follows. In Section II, a method to model inverter systems is proposed. In Section III, after reviewing how the power is delivered to a constant voltage source through an impedance, how the power is delivered to a constant current source through an impedance is developed. This is then applied to develop a harmonic droop control strategy in Section IV to reduce voltage harmonics. Simulation and experimental results are given in Sections V and VI, respectively, followed by conclusions made in Section VII.

II. Model of an Inverter System

It is widely known that a (linear) circuit having supplies/sinks with different frequencies can be analyzed separately at each frequency according to the superposition theorem. Here, this will be applied to inverter systems.

For an inverter, whether it is connected to a load, a grid, or both, the mathematical model of the system can be illustrated as shown in Fig. 1(a), where the inverter is modeled as a voltage reference v_r with an output impedance $Z_o(s)$, and the load is modeled as the combination of voltage and current sources. The terminal or output voltage is

$$v_o = v_{o1} + \Sigma_{h=2}^{\infty} v_{oh}$$

with $v_{o1} = \sqrt{2}V_{o1}\sin(\omega^* t)$ and $v_{oh} = \sqrt{2}V_{oh}\sin(h\omega^* t + \psi_h)$, where ω^* is the rated fundamental angular frequency of the system, V_{o1} is the rms voltage of the fundamental component, and V_{oh} is the rms voltage of the hth-harmonic component. The output or load current is described as

$$i = \Sigma_{h=1}^{\infty} i_h$$

with $i_h = \sqrt{2}I_h\sin(h\omega^* t + \phi_h)$. This represents the effect of nonlinear loads or harmonic currents and forces the current flowing through the series of voltage sources to be zero. The voltage reference v_r in the general case is described as

$$v_r = v_{r1} + \Sigma_{h=2}^{\infty} v_{rh}$$

with $v_{r1} = \sqrt{2}E\sin(\omega^* t + \delta)$ and $v_{rh} = \sqrt{2}E_h\sin(h\omega^* t + \delta_h)$. In many cases, in particular, when a droop controller is used in the inverter, E_h is often set to be zero. In this paper, E_h will be designed to be nonzero to make v_{oh} close to zero.

This circuit can be analyzed after decomposing it into multiple circuits at each harmonic frequency, according to the superposition theorem. The hth-harmonic circuit of the system is shown in Fig. 1(b). The load of the circuit $(V_{o1}/I_1)\angle-\phi_1$ at the fundamental frequency[2] is expressed as the combination of the voltage source $V_{o1}\angle 0^\circ$ and the current source $I_1\angle\phi_1$. If v_{oh} $(h \neq 1)$ is close to zero, then what is left in the right-hand side of Fig. 1(b) is a current source i_h.

The main function of an inverter (or a generator) is to supply the load with real and reactive powers at the right voltage level and at the right frequency, which are regulated by industrial standards and/or law. To be more precise, this should be done *at the fundamental frequency*, without harmonics. When multiple inverters are connected in parallel, they should also share the real and reactive powers in proportion to their capacity, again *at the fundamental frequency*. Then, what happens with harmonics? Ideally, the harmonics in the output voltage are expected to be zero, i.e., $v_{oh} = 0$ $(h = 2, 3, \ldots)$, even when there are harmonics in the current i. This can be achieved when the voltage drop of the hth-harmonic current $\sqrt{2}I_h\sin(h\omega^* t + \phi_h)$ on the output impedance $Z_o(j\omega)$ is the same as the hth-harmonic component of the voltage reference $\sqrt{2}E_h\sin(h\omega^* t + \delta_h)$, i.e., when

$$E_h = I_h\left|Z_o(jh\omega^*)\right|, \quad \delta_h = \phi_h + \angle Z_o(jh\omega^*). \tag{1}$$

In this paper, this idea will be exploited to design a controller for the inverter so that the harmonics in the output voltage are considerably reduced, after filling a gap in the theory of power delivery through an impedance.

[1] In this paper, a source is used to represent a source or a sink.

[2] Note that the phasors in this paper may be at different frequencies, which should be clear from the context.

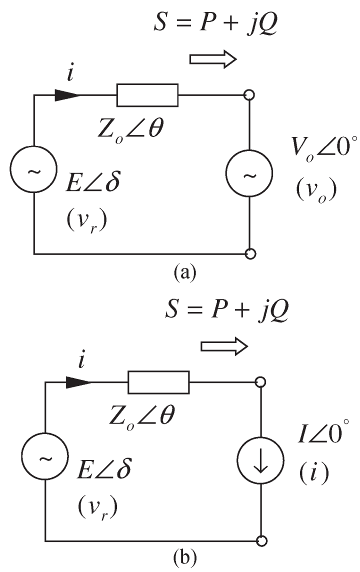

Fig. 2. Real and reactive powers delivered by a voltage source through an impedance. (a) To a voltage source. (b) To a current source.

III. Power Delivered Through an Impedance

It has been well understood how real and reactive powers are delivered through an impedance, whether it is inductive, resistive, capacitive, or other types, when the terminal voltage is more or less maintained constant as a voltage source. Moreover, power-sharing schemes, e.g., different droop control strategies [27]–[29], [32]–[35], have been developed for this case. However, it has not been studied how real and reactive powers are delivered when the terminal is connected to a current source with a constant current. In this section, this is developed after reviewing how the power is delivered to a constant voltage source.

A. Power Delivered to a Voltage Source

Fig. 2(a) shows a voltage source v_r delivering power to another voltage source $V_o\angle 0^\circ$ through an impedance $Z_o\angle\theta$. The current flowing through the terminal is

$$\bar{I} = \frac{E\angle\delta - V_o\angle 0^\circ}{Z_o\angle\theta} = \frac{E\cos\delta - V_o + jE\sin\delta}{Z_o\angle\theta}.$$

The real and reactive powers delivered to the terminal via the impedance are then obtained as

$$P = \left(\frac{EV_o}{Z_o}\cos\delta - \frac{V_o^2}{Z_o}\right)\cos\theta + \frac{EV_o}{Z_o}\sin\delta\sin\theta$$

$$Q = \left(\frac{EV_o}{Z_o}\cos\delta - \frac{V_o^2}{Z_o}\right)\sin\theta - \frac{EV_o}{Z_o}\sin\delta\cos\theta$$

where δ is the phase difference between the supply and the terminal, often called the power angle.

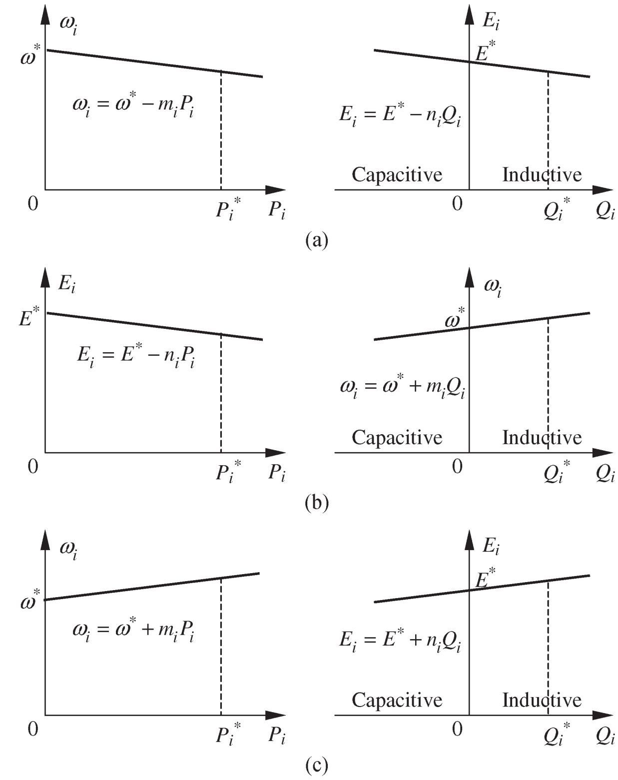

Fig. 3. Droop control for inverters maintaining a constant output voltage. (a) For an inductive Z_o. (b) For a resistive Z_o. (c) For a capacitive Z_o.

For an inductive impedance, $\theta = 90^\circ$. Then

$$P = \frac{EV_o}{Z_o}\sin\delta, \quad Q = \frac{EV_o}{Z_o}\cos\delta - \frac{V_o^2}{Z_o}.$$

When δ is small

$$P \approx \frac{EV_o}{Z_o}\delta, \quad Q \approx \frac{V_o}{Z_o}E - \frac{V_o^2}{Z_o}$$

and, roughly

$$P \sim \delta, \quad Q \sim E$$

where $\sim$ means in proportion to. As a result, the conventional droop control strategy for an inductive Z_o takes the form

$$E_i = E^* - n_i Q_i,$$
$$\omega_i = \omega^* - m_i P_i$$

where E^* is the rated rms voltage of the inverter. This strategy is sketched in Fig. 3(a).

For a resistive impedance, $\theta = 0^\circ$. Then

$$P = \frac{EV_o}{Z_o}\cos\delta - \frac{V_o^2}{Z_o} \quad Q = -\frac{EV_o}{Z_o}\sin\delta.$$

When δ is small

$$P \approx \frac{V_o}{Z_o}E - \frac{V_o^2}{Z_o} \quad Q \approx -\frac{EV_o}{Z_o}\delta$$

and, roughly

$$P \sim E \quad Q \sim -\delta.$$

Hence, the conventional droop control strategy takes the form

$$E_i = E^* - n_i P_i$$
$$\omega_i = \omega^* + m_i Q_i.$$

This is sketched in Fig. 3(b).

If the impedance is capacitive, then $\theta = -90^\circ$ and

$$P = -\frac{EV_o}{Z_o}\sin\delta, \quad Q = -\frac{EV_o}{Z_o}\cos\delta + \frac{V_o^2}{Z_o}.$$

When δ is small

$$P \approx -\frac{EV_o}{Z_o}\delta, \quad Q \approx -\frac{V_o}{Z_o}E + \frac{V_o^2}{Z_o}$$

and, roughly

$$P \sim -\delta, \quad Q \sim -E.$$

Hence, the strategy following the conventional droop control strategy for inverters with capacitive output impedances takes the form

$$E_i = E^* + n_i Q_i$$
$$\omega_i = \omega^* + m_i P_i.$$

This is sketched in Fig. 3(c).

B. Power Delivered to a Current Source

Fig. 2(b) shows a voltage source v_r delivering power to a current source $I\angle 0^\circ$ through an impedance $Z_o\angle\theta$. Then, the terminal voltage is

$$\begin{aligned}\bar{V}_o &= E\angle\delta - Z_o I\angle\theta \\ &= E\cos\delta - Z_o I\cos\theta + j(E\sin\delta - Z_o I\sin\theta)\end{aligned}$$

and the real and reactive powers delivered to the terminal are, respectively

$$P = EI\cos\delta - Z_o I^2\cos\theta \tag{2}$$
$$Q = EI\sin\delta - Z_o I^2\sin\theta. \tag{3}$$

Again, δ is the phase difference between the supply (voltage) and the terminal (current). When δ is small

$$P \approx EI - Z_o I^2\cos\theta$$
$$Q \approx EI\delta - Z_o I^2\sin\theta.$$

Hence, roughly

$$P \sim E \quad Q \sim \delta$$

for any type of impedance $Z_o\angle\theta$. This is quite different from the case with a voltage source, where these relationships change with the type of the impedance. The conventional droop control strategy should then take the form

$$E_i = E^* - n_i P_i \tag{4}$$
$$\omega_i = \omega^* - m_i Q_i. \tag{5}$$

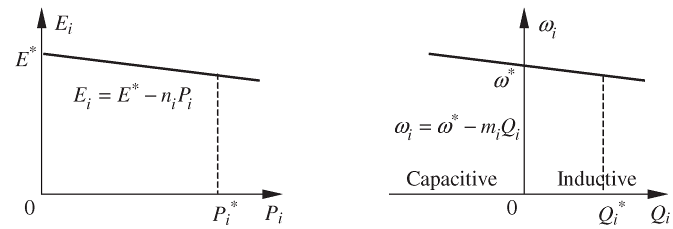

Fig. 4. Droop control for inverters maintaining a constant output current (for any type of impedances).

This strategy, as sketched in Fig. 4, is different from any of the droop control strategies when the power is delivered to a voltage source. Note that, in order to make sure that the $P - E$ loop and the $Q - \omega$ loop are of a negative feedback, respectively, so that the droop controller is able to regulate the frequency and the voltage, the signs before $n_i P_i$ and $m_i Q_i$ are all negative, which makes them droop terms. The main advantage of this scheme is that it does not depend on the type of the impedance, and hence, it can be used for any type of impedances. This facilitates the controller design, without the need of checking the impedance type at the corresponding harmonics. The purpose of this paper is to develop a strategy to improve the voltage THD based on this, instead of developing a control strategy for parallel operation of power sources. This is being investigated and will be reported separately.

Note that $P = 0$ and $Q = 0$ when

$$E = Z_o I, \quad \delta = \theta$$

according to (2) and (3). This is another way to express (1) and can be used to reduce or even eliminate harmonics in the output voltage.

IV. Reduction of Harmonics in the Output Voltage

In this section, a strategy will be proposed to reduce voltage harmonics via injecting harmonics into the voltage reference.

As discussed previously, in order to force the hth harmonics in the output voltage of an inverter to be (nearly) zero, the voltage source v_{oh} in Fig. 1(b) needs to be zero. In other words, the real and reactive powers delivered to the current source i_h in Fig. 1(b) should be zero. As a result, the voltage set-point E^* for the droop controller obtained in (4) should be zero for the hth harmonics $(h \neq 1)$. The frequency set-point should simply be set as the hth-harmonic frequency. This leads to the following hth-harmonic droop controller:

$$E_h = -n_h P_h, \tag{6}$$
$$\omega_h = h\omega^* - m_h Q_h \tag{7}$$

where P_h and Q_h are the real and reactive powers at the terminal for the hth-harmonic frequency, respectively, and n_h and m_h are the corresponding droop coefficients. Here, the subscripts of the relevant variables are changed to reflect the hth harmonics. The reference voltage v_{rh} at the hth-harmonic frequency can then be formed with the rms value E_h and the phase angle generated from the integration of ω_h. In practice, instead of generating a harmonic frequency ω_h from (7), it can be obtained from $h\omega t$ with the addition of δ_h, which is integrated from $-m_h Q_h$. Here, ωt is the phase of the voltage reference

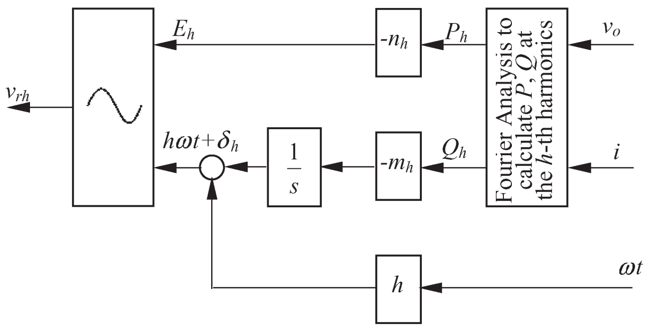

Fig. 5. Proposed hth-harmonic droop controller ($h \neq 1$).

at the fundamental frequency. This leads to the proposed hth-harmonic droop controller shown in Fig. 5. As explained earlier, it does not depend on the type of the output impedance at the hth-harmonic frequency, which could be resistive, inductive, capacitive, or even complex.

Since the controller (6) in the voltage channel is a proportional controller, there will be a static error and V_{oh} will not be exactly zero (but close to zero). The V_{oh} can be calculated approximately via

$$V_{oh} \approx E_h - |Z_o(jh\omega^*)| \, I_h \approx -n_h V_{oh} I_h - |Z_o(jh\omega^*)| \, I_h.$$

That is

$$V_{oh} \approx -\frac{|Z_o(jh\omega^*)| \, I_h}{n_h I_h + 1}.$$

Its contribution to the voltage THD is approximately $(|Z_o(jh\omega^*)| I_h/(n_h I_h + 1)E^*)$. The smaller the output impedance at the harmonic frequency $h\omega^*$, the smaller the THD. Hence, strategies like the one proposed in [29] can be adopted to reduce $|Z_o(jh\omega^*)|$ and the voltage THD. The parameter n_h can be chosen big to make V_{oh} small as long as the system remains stable. As a rule of thumb, the tuning can be started with

$$n_h = \frac{|Z_o(jh\omega^*)|}{\gamma E^*}$$

with which the contribution of the h-harmonic component to the THD is about γ. If this causes instability, then it can be reduced. The parameter m_h can be determined in the same way as m_1 because $(m_h Q_h^*)/h\omega^*$ is the frequency drop ratio at the hth harmonics, which should be the same as that at the fundamental frequency, i.e., $(m_1 Q^*)/\omega^*$. Hence

$$m_h = m_1 \frac{hQ^*}{Q_h^*}.$$

As a result, m_h is often much larger than m_1 because Q_h^* is often much smaller than hQ^*.

In order to reduce multiple harmonics in the output voltage, several harmonic droop controllers corresponding to the harmonic orders can be included in the controller to generate the required $\Sigma_h v_{rh}$. The voltage reference v_r can then be obtained via adding $\Sigma_h v_{rh}$ to v_{r1}, which is generated by the droop controller at the fundamental frequency, e.g., the robust droop controller proposed in [35]. The resulting complete droop controller is shown in Fig. 6. It is worth noting that the fundamental droop controller depends on the type of the output impedance and that the fundamental droop controller adopted in Fig. 6 is for inverters with resistive output impedances at the fundamental frequency. If the output impedance of the inverter at the fundamental frequency is not predominantly resistive, then the fundamental droop controller should be changed accordingly. It is worth stressing that the difficulty in defining the reactive power [26], [31] for the conventional droop controller has been avoided because the reactive power in the proposed strategy is defined at the corresponding frequency.

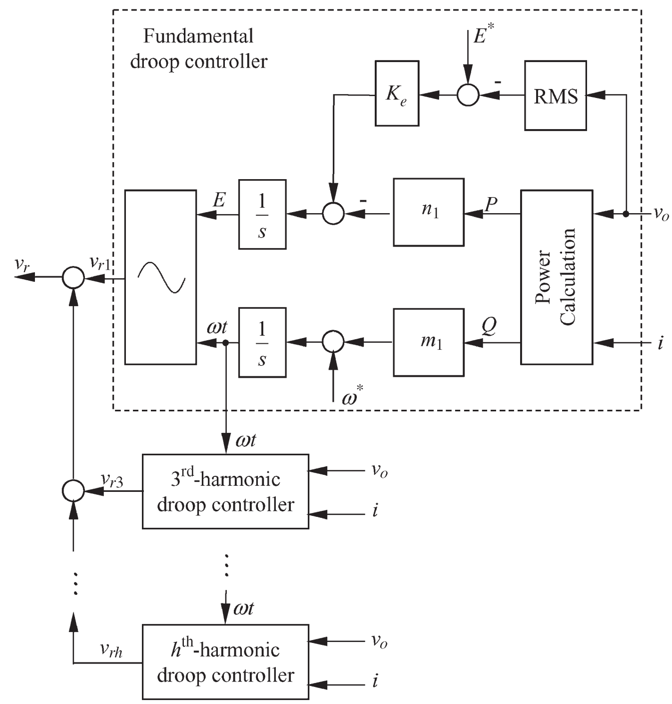

Fig. 6. Proposed droop controller consisting of a robust droop controller at the fundamental frequency and several harmonic droop controllers at individual harmonic frequencies.

V. Simulation Results

Simulations were carried out with two inverters connected in parallel to verify the proposed strategy. The values of the inductors and capacitors are 2.35 mH and 22 μF, respectively. The fundamental frequency of the system was 50 Hz, and the rated output voltage was 12 V rms. The inverter load was a rectifier bridge connected to a 9-Ω resistor after an LC filter with a 0.15-mH inductor and a 1000-μF capacitor. The inverters were designed, according to Zhong [35], to have resistive output impedances with an inner current loop shown in Fig. 7. It is worth mentioning that the inner loop controller can be designed with other methods or even removed, i.e., with $K_i = 0$. The proposed droop controller shown in Fig. 6 provides the voltage reference v_r to the inner current loop shown in Fig. 7. The droop controllers at the fundamental frequency were also designed according to Zhong [35] with the droop coefficients $n_1 = 2.2$ and $m_1 = 0.14$ for Inverter 1 and $n_1 = 1.1$ and $m_1 = 0.07$ for Inverter 2. The current feedback gains were chosen as $K_{i1} = 4$ and $K_{i2} = 2$, and the parameter K_e was chosen as $K_e = 20$. The third- and fifth-harmonic droop controllers were adopted with coefficients chosen as $n_h = 5$ and $m_h = 50$.

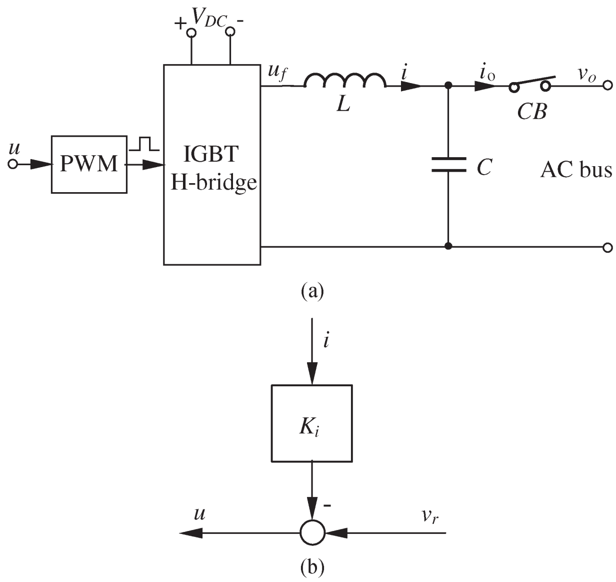

Fig. 7. Controller design to achieve a resistive output impedance. (a) Descriptive circuit. (b) Inner loop current controller.

TABLE I
VOLTAGE THD

Switching frequency	20 kHz	10 kHz	4 kHz
Voltage THD with the strategy	9.03%	9.4%	14.4%
Voltage THD without the strategy	16.53%	16.5%	20%

The switching frequency needs to be high enough in order to handle the fifth harmonic. Table I shows the voltage THD obtained for three different switching frequencies. It shows that the switching frequency of 4 kHz is not high enough, which resulted in a high THD. When the proposed strategy was not used, the results were also shown in Table I for comparison. The proposed strategy has considerably improved the voltage THD by 45%. The output voltage and the inverter currents when the switching frequency was 20 kHz are shown in Fig. 8. The third harmonic was significantly reduced from 15% to 5%, but the fifth harmonic slightly increased because of the change in the current profile caused by the reduction of the third harmonic. The two inverters shared the real and reactive powers well in the ratio of 2:1, and the voltage was maintained close to the rated voltage.

Another system consisting of two inverters rated at 230 V and 50 Hz were simulated to show the scalability of the strategy. The parameters of the LC filters and the load were not changed (but with higher current and voltage ratings). The power consumed was around 8 kVA with a power factor of 0.9. The gains of the inner loops were kept the same as well, but the fundamental droop coefficients were scaled to $n_1 = (2.2 \times 12/230) = 0.1148$ and $m_1 = 0.14 \times (12/230)^2 = 3.811 \times 10^{-4}$ for Inverter 1 and $n_1 = 0.0574$ and $m_1 = 1.9055 \times 10^{-4}$ for Inverter 2 because of the change of the rated voltage and power. The harmonic droop coefficients n_h were also scaled, correspondingly, to $n_h = (5 \times 12/230) = 0.2609$ and $m_h = 50 \times (12/230)^2 = 0.1361$. The simulation was successfully run without any difficulties. The results are shown in Fig. 9. Again, the THD of the voltage was significantly improved by 45%, from 17.7% to 9.77%. The third harmonic was reduced from 16% to 5%, but the fifth harmonic increased slightly.

VI. EXPERIMENTAL RESULTS

Experiments were carried out with a laboratory setup, which consisted of two single-phase inverters controlled by dSPACE ACE1104 kits and was powered by separate 42-V dc power supplies. The parameters of the inverters are the same as those in the simulations for the 12-V system. The switching frequency was set at 4 kHz because of the hardware limitation, partially caused by the heavy computation involved in calculating the real and reactive powers at each frequency. Due to the configuration of the hardware setup, the voltage for Inverter 2 was measured by the controller of Inverter 1 and then sent out via a digital-to-analog channel, which was then sampled by the controller of Inverter 2. This brought some latency into the system. The voltages were measured through a multiplexer, which resulted in a much lower sampling frequency for the voltage. This may have had an impact on the performance. Inverter 2 was equipped with a synchronization mechanism, which is not described in this paper because of the page limit. Inverter 2 was synchronized with Inverter 1 when its output was not connected to that of Inverter 1 and was ready to be connected at any time.

The experiments were carried out in three stages: 1) Inverter 1 was supplying the load; 2) Inverter 2 was put into parallel operation with Inverter 1; and 3) Inverter 2 was disconnected from the parallel operation. The experimental results, after being saved from dSPACE/ControlDesk and then plotted in MATLAB, are shown in the left column of Fig. 10 when the proposed harmonic droop controller was not adopted and in the right column of Fig. 10 when the proposed harmonic droop controller was added for the third and fifth harmonics. Since the dynamic process at the fundamental frequency is much lower than that at harmonic frequencies, the dynamics of the system is dominated by that of the fundamental droop controller, and the harmonic droop controller does not bring noticeable change to the response speed for the real power, the reactive power, and the output voltage rms.[3] There was no noticeable change in the steady-state performance of voltage regulation and the accuracy of power sharing, either. After the harmonic droop controller was introduced, there was significant improvement in the THD of the output voltage: from 22% to 12% for one inverter and from 15.92% to 8.57% for two inverters in parallel. This corresponds to the improvement of 46%. The third harmonic was reduced from 14% to 4.5%, but there was a slight increase in the fifth harmonic. The voltage THD is lower than that obtained from the simulation because of the filtering effect in the practical system.

It should be emphasized that the main purpose of this paper is to propose and demonstrate the harmonic droop controller for THD improvement, instead of reducing the THD to a certain level. Other strategies, e.g., repetitive control [5], [36], [37] and harmonic compensation [29], can be easily combined to

[3] On the other hand, in order to handle high-order harmonics, the sampling speed of the controller needs to be increased.

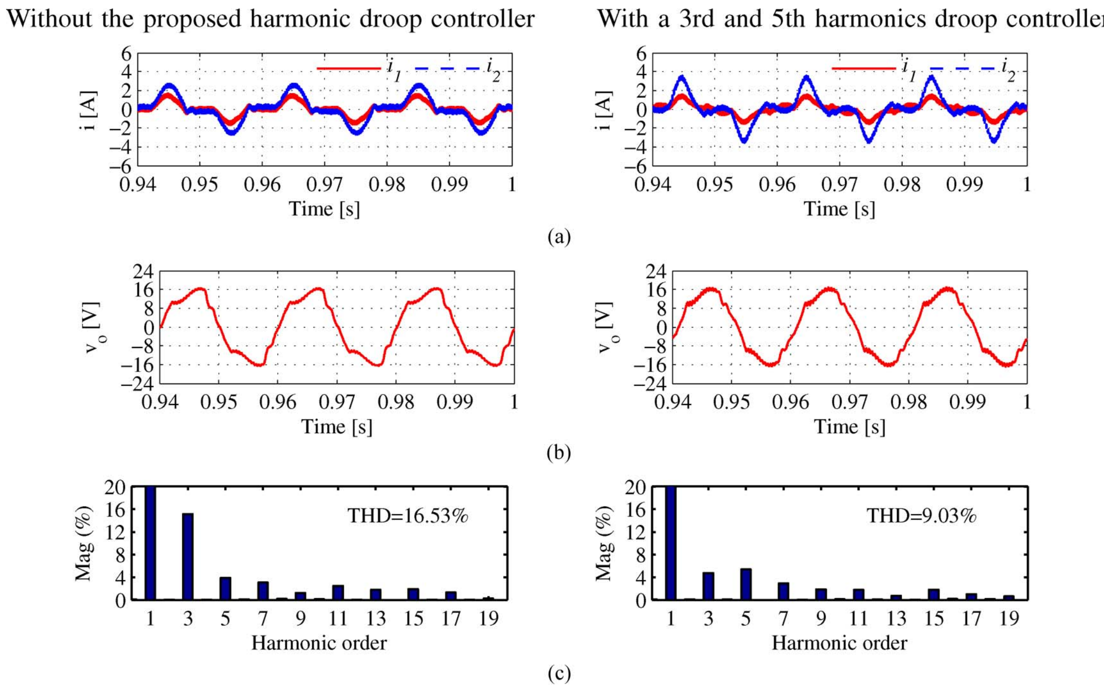

Fig. 8. Simulation results for a 12-V system: (left column) without the proposed harmonic droop controller and (right column) with a third- and fifth-harmonic droop controller. (a) Currents. (b) Output voltage. (c) Magnitude of the harmonic voltages w.r.t. the fundamental component.

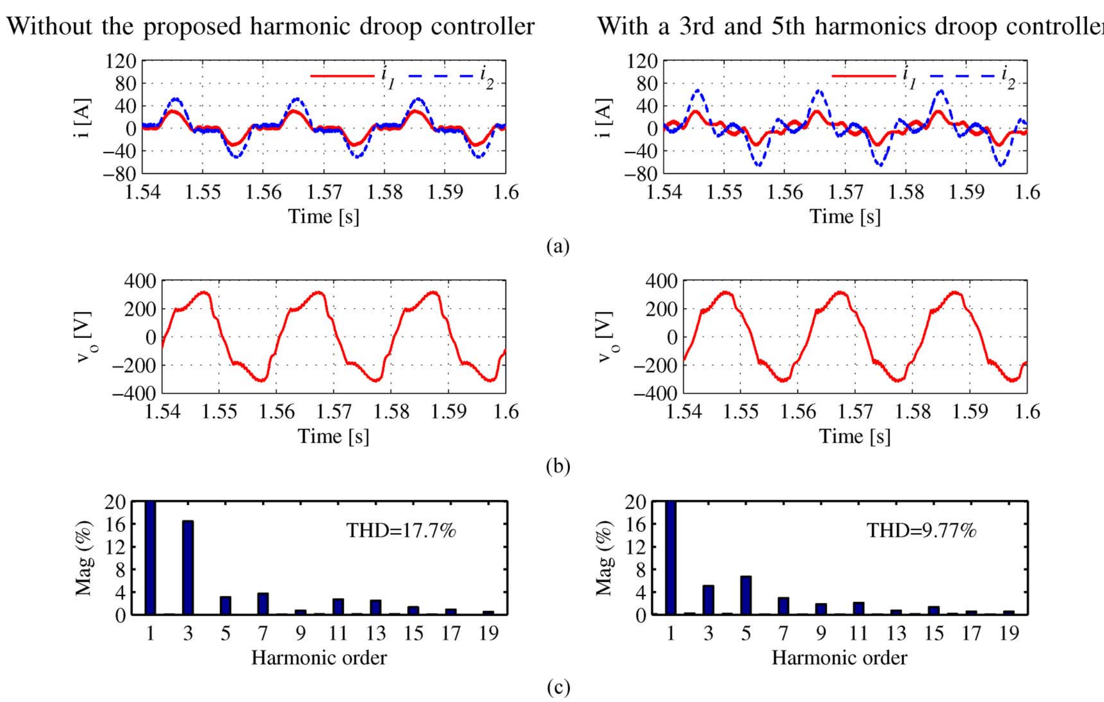

Fig. 9. Simulation results for a 230-V system: (left column) without the proposed harmonic droop controller and (right column) with a third- and fifth-harmonic droop controller. (a) Currents. (b) Output voltage. (c) Magnitude of the harmonic voltages w.r.t. the fundamental component.

further reduce the THD. The LC filter of the inverter could be optimized to reduce the THD as well because the inductance L is very high for the inverters adopted in this paper. The low voltage level of the system also adds difficulties in obtaining a low THD. Indeed, a 0.12-V harmonic component would have contributed to 1% THD. The 4-kHz switching frequency is not high enough to handle the fifth harmonic, which also has a strong impact on the performance. After taking into account the aforementioned factors, the voltage THD of an inverter could be easily made below 5%.

VII. Conclusion

After proposing a modeling method for inverter systems, it has been found out that the harmonics in an inverter system can be treated individually. A harmonic droop control strategy

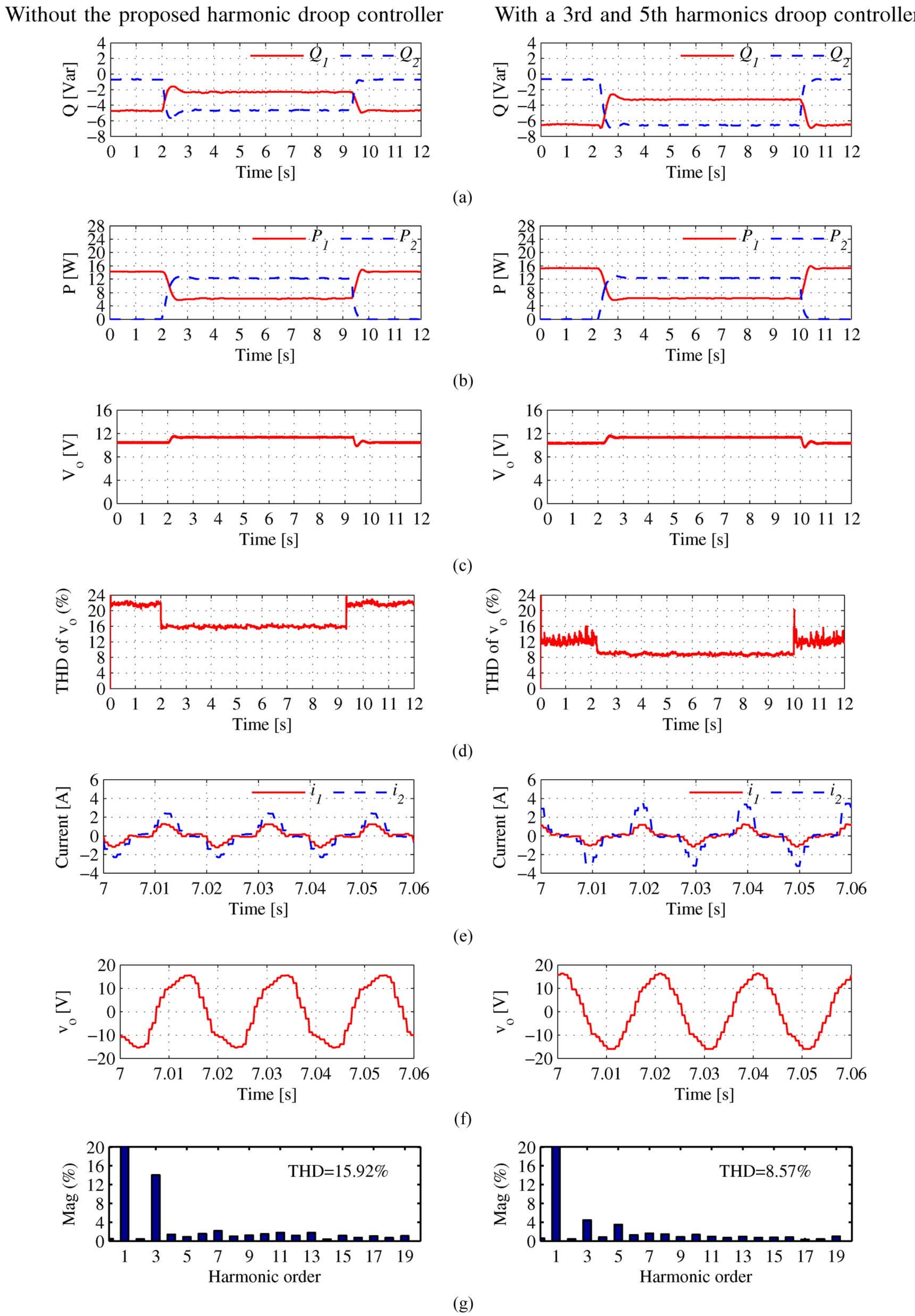

Fig. 10. Experimental results: (left column) without the proposed harmonic droop controller and (right column) with a third- and fifth-harmonic droop controller. (a) Reactive power. (b) Real power. (c) RMS value of the output voltage. (d) THD of the output voltage. (e) Currents in the steady state. (f) Output voltage. (g) Magnitude of the harmonic voltages w.r.t. the fundamental component.

has then been proposed to provide the right harmonic reference voltage to cancel the harmonic voltage dropped on the output impedance of the inverter, which reduces the harmonic components in the output voltage. The harmonic droop controller, which is developed after investigating the basic principles of delivering power to a constant current source (sink), does not depend on the type of the impedance. This avoids the need of checking the type for each harmonic frequency, which can be very difficult in practice. The proposed strategy also clarifies that the power sharing of inverters should be done at individual harmonic frequencies, which avoids the difficulty in defining the reactive power for different frequencies together. The proposed strategy is able to significantly reduce the harmonic components in the output voltage while accurately sharing the power at the fundamental frequency. Simulation and experimental results have shown that the proposed harmonic droop controller is able to considerably improve the THD of the output voltage. In some cases, there may still be a need to combine this strategy with others to further improve the THD.

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