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Improved Droop Control Strategy for Grid-Connected Inverters

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Abstract

In this project, the load and/or grid linked with an inverter is made as the combination of voltage sources and current sources at harmonic wavelengths. Moreover, a droop control technique is designed for systems providing power to a continuous current source, instead of a continuous voltage source. This is then used to create a harmonic droop operator so that the right amount of harmonic voltage is added to the inverter reference voltage to make up the harmonic voltage decreased on the outcome impedance due to the harmonic current. Simulation results are offered to show that the suggested technique can considerably improve the voltage THD.

Keywords: Droop Control Technique, Harmonic Droop Operator, Load/Grid Linked, Voltage THD

1. Introduction

Of course, harmonic voltage then causes harmonic currents as well. The odd many of the 3rd harmonic (3rd, 9th, 15th, 21st . . .), i.e., the 6n – 3 harmonics, are known as tripled harmonics. These currents on a three-phase program are zero-sequence harmonics, which are preservative in the fairly neutral line and cause particular concern. It is well recognized that the outcome impedance of an inverter performs a crucial part in power sharing and a droop operator for inverters with resistive outcome impedances was suggested for discussing linear and non linear loads. If the right quantity of harmonic voltage is included to the reference voltage for the inverter, then the harmonic element in the output voltage can be made to zero. Second, a drop control strategy is designed to provide energy to a continuous current source/sink. Lastly, a harmonic drop management technique is suggested to reduce individual harmonics. Successfully, it means that the energy sharing or drop management should be done at each individual harmonic frequency, which prevents the problems in defining/calculating the reactive power at different wavelengths together. Simulation results are offered to show that the suggested technique could significantly improve voltage THD.

2. Model of An Inverter System

It is commonly known that a (linear) circuit having supplies/sinks with different wavelengths can be examined independently at each regularity according to the superposition theorem. Here, this will be used to inverter techniques. For an inverter, whether it is connected with load or grid, or both, the statistical design of the program can be proven as proven in Figure 1 (a), where the inverter is made as a voltage reference V_r with output impedance $Z_o(s)$ and the load is made as the combination of voltage and current sources. The terminal or output voltage is

$$V_0 = V_{01} + \sum_{h=2}^{\infty} V_{0h}$$

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

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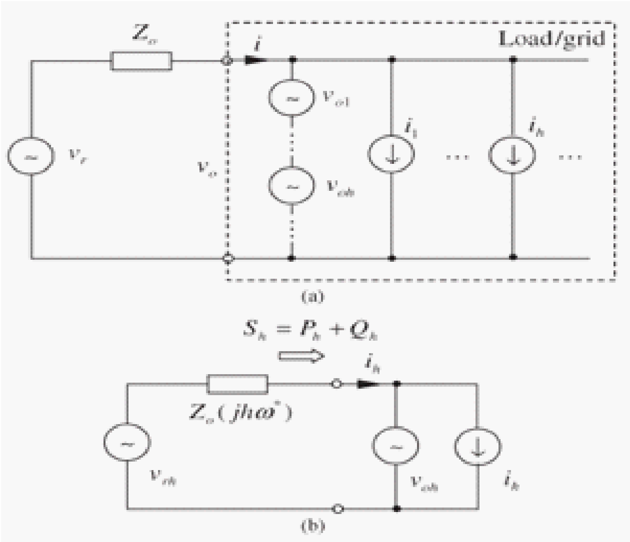


Figure 1. Model of an inverter connected to a load/grid. **(a)** One circuit including all harmonics. **(b)** Circuit at the hth-harmonic frequency.

hth-harmonic component. The output or load current is described as

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

with $i_h = \sqrt{2} I_h \sin(h\omega_* t + \varphi_h)$. This symbolizes the impact of nonlinear loads or harmonic voltages and causes the current flowing through the sequence of voltage sources to be zero. The voltage reference V_r in the general case is described as

$$V_r = V_{r1} + \sum_{h=2}^{\infty} V_{rh}$$

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 project, 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 Figure 1(b). 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, . . .), even when there are harmonics in the current i. This can be achieved when the voltage drop of the hth-harmonic current $2I_h \sin(h\omega_* t + \varphi_h)$ on the output impedance $Z_o(j\omega)$ is the same as the hth-harmonic component of the voltage reference $2E_h \sin(h\omega_* t + \delta_h)$, i.e., when

$$E_h = I_h \,|Z_0\left(jhw^*\right)|\, \delta_h = \varphi_h + \angle Z_0\left(jhw^*\right)$$

In this project, this concept will be utilized to design an operator for the inverter so that the harmonics in the output voltage are significantly decreased, after stuffing a gap in the concept of power distribution through impedance.

3. Power Delivered through an Impedance

It has been well recognized how real and reactive power are provided through an impedance, whether it is inductive, resistive, capacitive or other kinds, when the terminal voltage is more or less managed continuous as a voltage source. Moreover, power-sharing techniques, e.g., different droop control strategies, have been designed for this case. However, it has not been analyzed how real and active powers are provided when the terminal is linked with a current resource with a continuous current. In this area, this is designed after examining how the power is sent to a continuous voltage source.

3.1 Power Delivered to a Voltage Source

Figure 2(a) shows a voltage source V_r delivering power to another voltage source $V_o\angle 0°$ through impedance $Z_o\angle\theta$. The current flowing through the terminal is

$$I = \frac{E\angle\delta - V_0\angle 0^0}{Z_0\angle\theta}$$

$$= \frac{E\cos\delta - V_0 + jE\sin\delta}{Z_0\angle\theta}$$

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

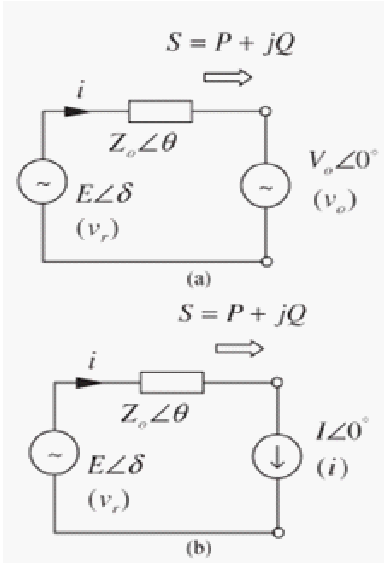


Figure 2. Real and reactive powers delivered by a voltage source through impedance. **(a)** To a voltage source. **(b)** To a current source.

$$P = \left(\frac{EV_0}{Z_0}\cos\delta - \frac{V_0^{\,2}}{Z_0}\right)\cos\theta + \frac{EV_0}{Z_0}\sin\delta\sin\theta$$

$$Q = \left(\frac{EV_0}{Z_0}\cos\delta - \frac{V_0^{\,2}}{Z_0}\right)\sin\theta - \frac{EV_0}{Z_0}\sin\delta\cos\theta$$

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

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

$$P = \frac{EV_0}{Z_0}\sin\delta \quad Q = \frac{EV_0}{Z_0}\cos\delta - \frac{V_0^2}{Z_0}$$

When δ is small

$$P \approx \frac{EV_0}{Z_0}\delta \quad Q \approx \frac{V_0}{Z_0}E - \frac{V_0^2}{Z_0}$$

and, roughly

$$P \approx \delta, Q \approx E$$

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

$$E_i = E^* + n_i Q_i$$

$$w_i = w^* + m_i p_i$$

where E^* is the rated RMS voltage of the inverter. This strategy is sketched in Figure 3(a). For a resistive impedance, $\theta = 0°$. Then

$$P = \frac{EV_0}{Z_0}\cos\delta - \frac{V_0^2}{Z_0} \quad Q = -\frac{EV_0}{Z_0}\sin\delta$$

When δ is small

$$P \approx \frac{V_0}{Z_0}E - \frac{V_0^2}{Z_0} \quad Q \approx -\frac{EV_0}{Z_0}\delta$$

and, roughly

$$P \approx E, Q \approx -\delta$$

Hence, the conventional droop control strategy takes the form

$$E_i = E^* - n_i p_i$$

$$w_i = w^* + m_i Q_i$$

This is sketched in Figure 3(b).

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

$$P = -\frac{EV_0}{Z_0}\sin\delta \quad Q = \frac{EV_0}{Z_0}\cos\delta + \frac{V_0^2}{Z_0}$$

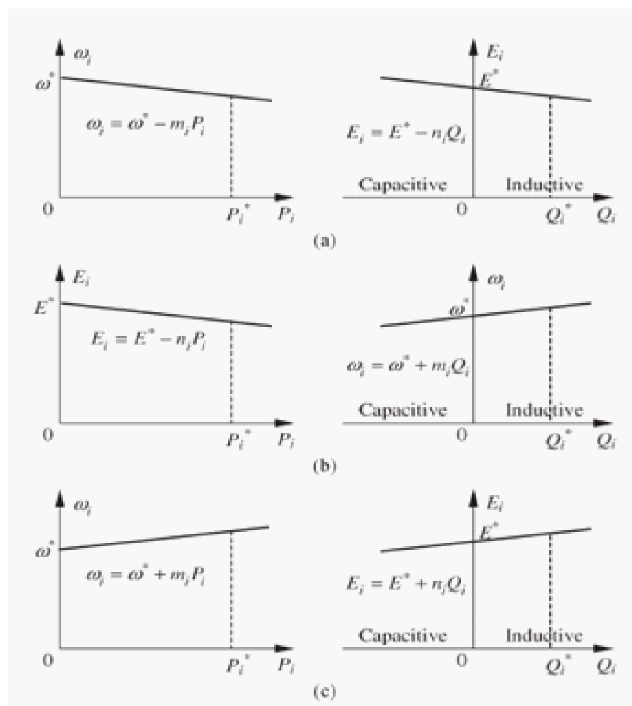


Figure 3. Droop control for inverters maintaining a constant output voltage. **(a)** For an inductive Z_o. **(b)** For a resistive Z_o. **(c)** For a capacitive Z_o.

When δ is small

$$P \approx -\frac{EV_0}{Z_0}\delta \quad Q \approx -\frac{V_0}{Z_0}E + \frac{V_0^2}{Z_0}$$

and, roughly

$$P \approx -\delta, Q \approx -E$$

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

$$E_i = E^* - n_i p_i$$

$$w_i = w^* + m_i Q_i$$

This is sketched in Figure 3(c).

3.2 Power Delivered to a Current Source

Figure 2(b) shows a voltage source vr delivering power to a current source I∠0° through impedance $Z_o\angle\theta$. Then, the terminal voltage is

$$V_0 = E\angle\delta - Z_0 I\angle\theta$$
$$= E\cos\delta - Z_0 I\cos\theta + j\left(E\sin\delta - Z_0 I\sin\theta\right)$$

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

$$P = EI\cos\delta - Z_0 I^2\cos\theta$$

$$Q = EI\sin\delta - Z_0 I^2\sin\theta$$

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

$$P \approx EI - Z_0 I^2\cos\theta$$

$$Q \approx EI\sin\delta - Z_0 I^2\sin\theta$$

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

$$E_i = E^* - n_i p_i$$

$$w_i = w^* + m_i Q_i$$

This technique, as shown in Figure 4, is different from any of the droop management techniques when the

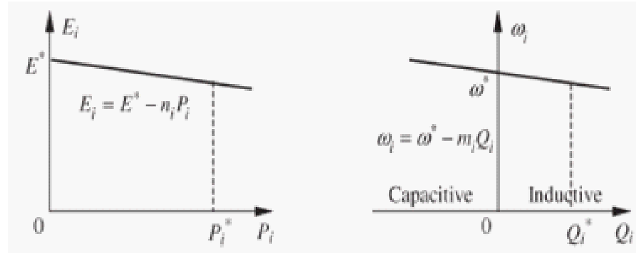


Figure 4. Droop control for inverters maintaining a constant output current (for any type of impedances).

power is sent to a voltage source. The advantage of this plan is that it does not rely on the kind of the impedance and hence, it can be used for any kind of impedances. This helps the controller design, without the need of verifying the impedance kind at the corresponding harmonics. The objective of this project is to create a way to enhance the voltage THD based on this, instead of creating a control strategy of similar function of power sources. This is being examined and will be reported separately. Note that P = 0 and Q = 0 when

$$E = Z_0 I, \delta = \theta$$

According to[2,3]. This is another way to express[1] and can be used to reduce or even eliminate harmonics in the output voltage.

4. Reduction of Harmonics in the Output Voltage

In this section, a strategy will be recommended to reduce voltage harmonics via dealing with harmonics into the voltage recommendations. As discussed formerly, to be able to power the hth harmonics in the result voltage of an inverter to be (nearly) zero, the voltage source voh in Figure 1(b) needs to be zero. In other conditions, the real and reactive powers sent to the existing source ih in Figure 1(b) should be zero. Consequently, the voltage set-point E* for the droop controller obtained in[4] should be zero for the hth harmonics (h _= 1). The frequency set-point should generally be set as the hth-harmonic frequency. This outcomes in the following hth-harmonic fall controller:

$$E_h = -n_h p_h$$

$$w_h = hw^* - M_H Q_h$$

where Ph and Qh are the real and reactive powers at the terminal for the hth-harmonic frequency, respectively, and nh and mh are the corresponding droop coefficients. Here, the subscripts of the appropriate factors are modified to indicate the hth harmonics.

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 near to zero). The V_{oh} can be measured roughly via

$$V_{0h} \approx E_h - |Z_0(jhw^*)|\, I_h \approx -n_h V_{0h} I_h - |Z_0(jhw^*)|\, I_h$$

That is

$$V_{oh} \approx -\frac{|Z_0(jhw^*)|\, I_h}{n_h I_h + 1}$$

Its contribution to the voltage THD is approximately $(|Z_o(jh\omega_*)|I_h/(n_h|_h + 1)E_*)$. The smaller the output impedance at the harmonic frequency $h\omega_*$, the smaller the THD. Hence, strategies like the one proposed 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

$$n_h = -\frac{|Z_0(jhw^*)|}{\gamma E^*}$$

with which the participation of the h-harmonic element to the THD is about γ. If this causes uncertainty, then it can be decreased. The parameter mh can be identified in the same way as m1 because $(m_h Q_{*h})/h\omega_*$ is the frequency droop ratio at the hth harmonics, which should be the same as that at the fundamental frequency, i.e., $(m_1 Q_*)/\omega_*$. Hence

$$m_h = m_1 \frac{hQ^*}{Qh^*}$$

Consequently, mh is often much larger than m1 because Q^* h is often more smaller than hQ^*. To be able to reduce several harmonics in the output voltage, several harmonic droop controllers corresponding to the harmonic orders can be engaged in the controller to generate the required Σhvrh. The voltage recommendations vr then can be obtained via such as Σhvrh to vr1, which is created by the droop controller at the essential frequency, e.g., the efficient droop controller recommended. The resulting in complete droop controller is confirmed in Figure 6. It is worth noting that the essential droop controller depends on the kind of the result impedance and that the essential droop controller applied in Figure 6 is for inverters with resistive output impedances at the essential frequency. If the result impedance of the inverter at the essential frequency is not mainly resistive, then the essential droop controller should be customized accordingly.

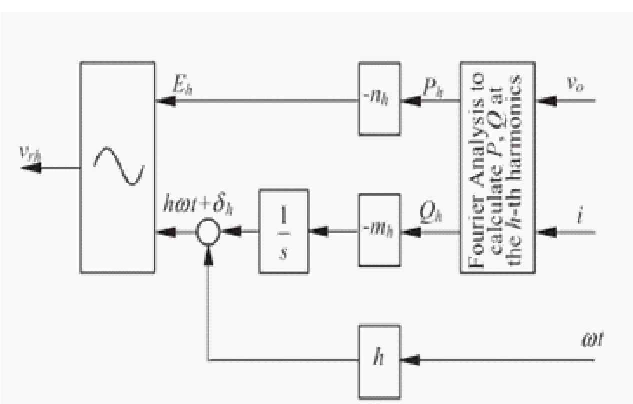


Figure 5. Proposed hth-harmonic droop controller (h_= 1).

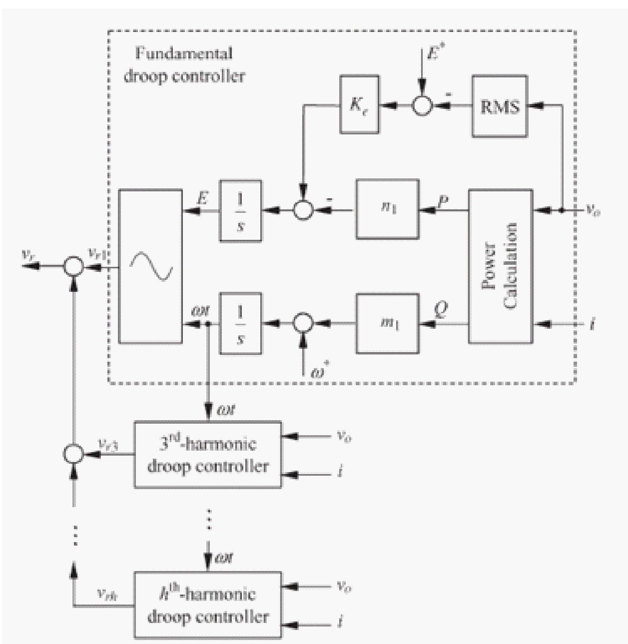
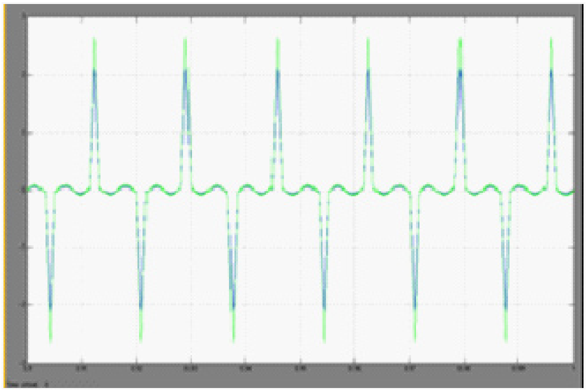
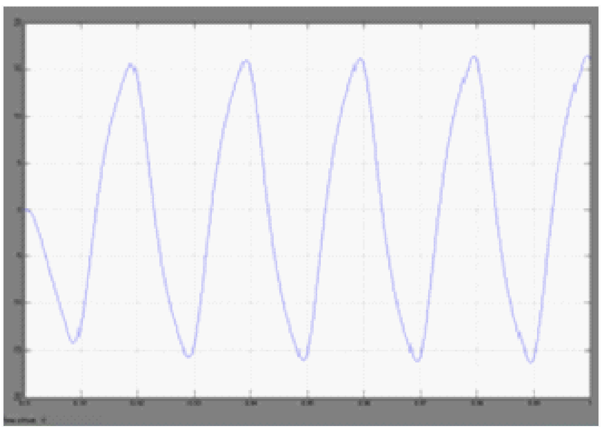


Figure 6. Proposed droop controller consisting of a robust droop controller at the fundamental frequency and several harmonic droop controllers at individual harmonic frequencies.

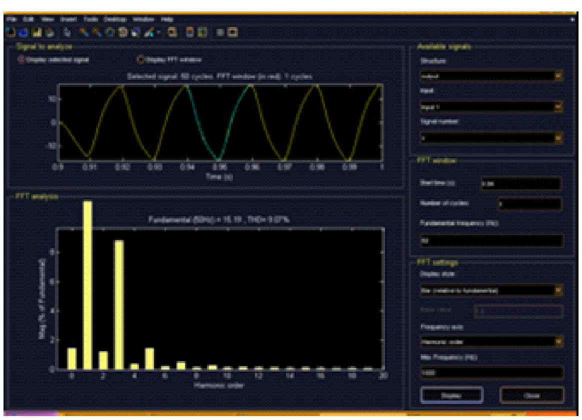
4. Simulation Results



(a)

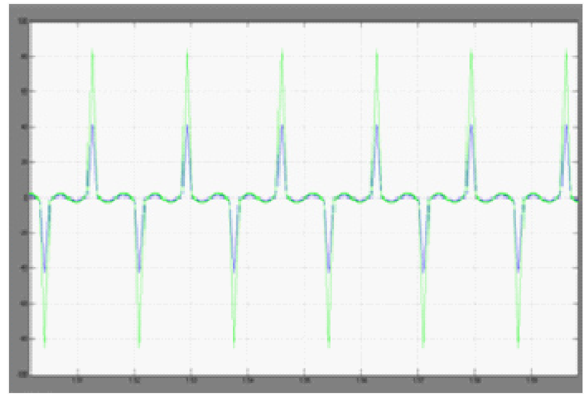


(b)

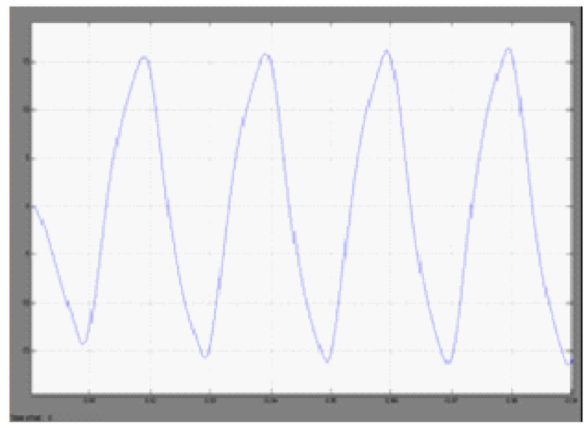


(c)

Figure 7. 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)** Input currents w.r.t the fundamental component. **(b)** Input voltage w.r.t. the fundamental component. **(c)** Magnitude of the harmonic voltages w.r.t. the fundamental component.



(a)



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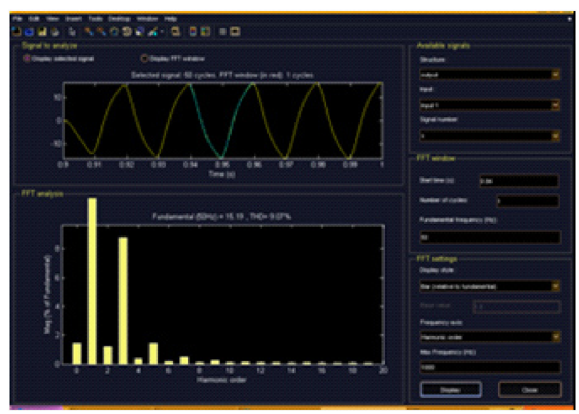

(c)

Figure 8. 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)** Output current w.r.t. the fundamental component. **(b)** Output voltage w.r.t. the fundamental component. **(c)** Magnitude of the harmonic voltages w.r.t. the fundamental component.

6. Conclusion

After suggesting a modeling means for inverter techniques, it has been discovered out that the harmonics in an inverter program can be handled independently. A harmonic droop management technique has then been suggested to offer the right harmonic reference voltage to terminate the harmonic volts decreased on the outcome impedance of the inverter, which decreases the harmonic elements in the output voltage. The suggested strategy is able to significantly decrease the harmonic elements in the output voltage while perfectly discussing the power at the essential frequency. Simulation results have proven that the suggested harmonic droop controller is able to significantly enhance the THD of the output voltage. In some situations, there may still be a need to merge this technique with others to further enhance the THD.

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