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Voltage Harmonic Distortion Compensation with Non-Linear Load Power Sharing in Low-Voltage Islanded Microgrid

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Abstract – Microgrids are designed to operate at a fundamental frequency (50 or 60 Hz). However, certain types of loads generate voltage and/or current harmonics that increase power system heat losses. These harmonic losses reduce system efficiency, cause apparatus overheating and increase power costs. Besides that, the Distributed Generation (DG) is expected to play an important role in future power systems, since it is able to reduce losses, improve power quality to end users. In this paper we propose new harmonic droop controller to compensate the harmonic currents produced by each DG to feed the nonlinear loads. Furthermore, the proposed controller is able to damp the total harmonic distortion of the voltage at the common connection point (PCC). Modeling and simulations incorporate to define the best control parameters for a proper operation. Experimental results are given to show the efficiency of the proposed algorithm.

Keywords – Droop Control, Interfaced Converters, Islanded Microgrid, Harmonic compensation, Nonlinear Load, Power Sharing.

NOMENCLATURE

DG	Distributed Generation.
PCC	Point of common coupling.
THD	Total Harmonic Distortion.
SPWM	Sinusoidal Pulse Width Modulation.
ω_i, V_i	Angular frequency and voltage magnitude of DG_i .
ω_n, V_n	Nominal angular frequency and voltage magnitude.
m_i, n_i	Proportional gain of the $Q-\omega$ and $P-V$ respectively.
P_{i_rated}, Q_{i_rated}	Rated active and reactive power capacity of DG_i .
P_i, Q_i	Active and Reactive powers generated by Distributed Generation (DG_i).
V_{ref}	Voltage magnitude reference.
R_i, L_i	DG_i feeder resistance and inductance.
$V_{DG_i}^{fund}, V_{DG_i}^h$	DG_i fundamental and h -harmonic rms-Voltage.
$V_{PCC}^{fund}, V_{PCC}^h$	Fundamental and h -harmonic rms-Voltage at point of common coupling (PCC).
I^h	h -harmonic current of a nonlinear load.
Z_{load}^h	h -harmonic passive impedance load.
$I_{DG_i}^h$	h -harmonic current at the output of DG_i .
$Z_{DG_i}^h$	Harmonic feeder impedance of DG_i .

Q_i^h	h -harmonic power generated by DG_i .
G_i^h	h -harmonic positive gain.
HD_h	Selective h -harmonic voltage distortion.
K_h	Proportional h -harmonic distortion gain.
b_i	Proportional gain of the harmonic droop.
ξ, ω_f	Damping factor and cutoff frequency of lowpass filter.
Subscripts	
dq	Synchronous frame components.
ver	Virtual component.
eq	Equivalent component.
ref	Reference component.
n	Nominal value.
Superscripts	
h	h^{th} harmonic component.
<i>fund</i>	Fundamental component.

1. Introduction

In an islanded microgrid, Distributed Generation (DG) units use the droop method as a decentralized control to share the active and reactive power in proportion to their rated power [1]–[5]. The droop method has been proved to be an interesting strategy that enables the DG units to share fundamental real and reactive power without inter-unit communication, i.e. in autonomous way. However, system stability and proper load sharing are not always maintained when using the conventional droop. This is due to the mismatch in line impedances and the slow dynamic response of the droop. Therefore, several improvements were considered in literature to enhance the performance of the droop control [6]–[11].

Another issue in the islanded microgrid deals with harmonic power sharing when nonlinear loads are connected. In fact, the conventional droop control is designed to share the fundamental positive-sequence power components. **The traditional way to mitigate harmonics is by using passive or active filters which increase system complexity and cost. As a consequence, new research studies apply different control proposals to reduce the harmonic distortion and manage the harmonic currents between DG units. For example, a virtual output impedance loop is introduced to autonomously share the harmonic currents [6], [12]–[14]. It was seen that, in order to attenuate the effect of different feeder line impedances, a large virtual impedance value is designed. Therefore, the more voltage distortions exist.** Another approach, uses a virtual capacitive loop to improve the voltage distortion and to share accurately the harmonic current [15], [16]. The idea behind using a capacitive impedance value is to compensate the inductive line impedance by introducing a virtual capacitive element which is equal in magnitude but with opposite phase shift. However, these approaches are based on knowing the line impedance to tune the appropriate virtual impedance value. In [17], [18], the authors propose a harmonic droop controller to damp the harmonic distortion at PCC and to share the harmonic current between converters. However, additional computation and system complexity restrict the use of such controllers. It is to be noted that, in a weak low-voltage (LV) microgrid, the damping of total harmonic distortion (THD) is highly affected by the microgrid line impedances. In [19], a voltage controller method for each DG in a microgrid is proposed to compensate the voltage distortion by adjusting the DG equivalent harmonic impedance. It was seen that the harmonic sharing is sensitive to the grid impedance variation or disturbance in the main grid. To increase the reliability and efficiency of the system, new proposals based on consensus algorithm are presented recently in [20], [21]. The consensus method is a control technique that requires a minimal communication

infrastructure to significantly enhance the performance of conventional droop and harmonic power sharing as well.

In this paper, the main objective is to damp the voltage distortion at the PCC when non-linear loads are connected. Furthermore, the distribution of harmonic currents between different DGs is managed according to the harmonic power rating settings. The overall controller is applied in one loop design. The operation principles of the proposed controller are listed as:

- Design a droop function for the harmonic power. This enables the DG units to proportionally share the harmonic power between each other according to their rating powers.
- Mitigate the voltage harmonic distortion generated by non-linear loads.
- Apply a control loop that is immune from grid disturbance and line impedance mismatch.
- Simplify the control design as possible. There is no need to know the feeder impedances in advance.

2. Power Sharing in Islanded Microgrid

As shown in Fig. 1, a microgrid formed by n -Distributed Generators (DGs) with linear and non-linear loads linked together by means of feeder line impedances. The harmonic (dq) extraction block is there in order to measure the voltage distortion at the PCC and share the data to all DGs by using a communication link infrastructure. It is to be noted that, the communication link is used only to improve the performance of the harmonic power sharing and to compensate the PCC voltage distortion. The only data needed by the proposed harmonic droop is the voltage distortion at the PCC. These data are dc-components (in synchronous dq -frame). This will simplify the type of communication by using low-bandwidth communication.

Each DG is represented by a Distributed Interfaced Converter (DIC) with an output filter and a local control block. The local control can be decomposed of a primary control loop which is defined here by the droop controller and an inner control loop in order to regulate the output voltage waveform as regard to the reference voltage.

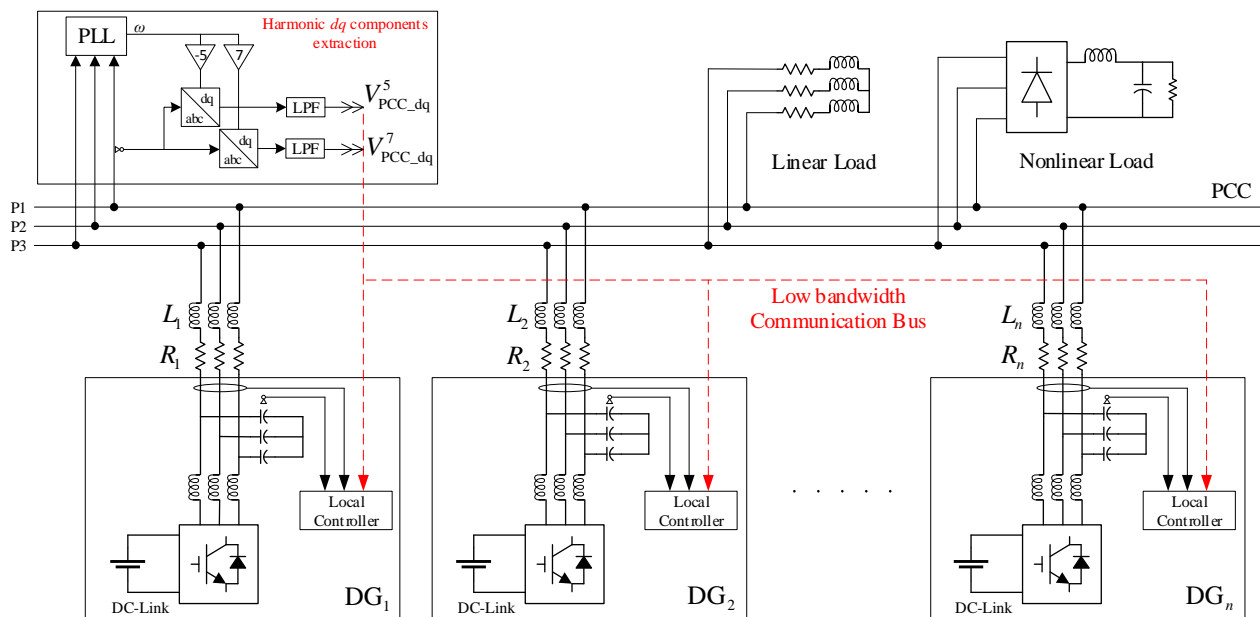


Fig. 1. Three-phase microgrid with parallel DGs, Linear and nonlinear loads.

A) Droop Control for fundamental power sharing

The droop control for voltage source converters (VSC) is commonly used to achieve the power balance in islanded microgrid. It consists of a simple proportional control and the selection of its gains are commonly based on power sharing criteria. To demonstrate the droop control, two DG-sources with general output impedances are connected to common linear and nonlinear loads as in Fig. 2. The real and reactive power delivered through the output impedance can be written as:

$$\begin{aligned} P_i &= \frac{3}{2} \left(\frac{V_i V_{PCC}}{Z_i} \cos \delta_i - \frac{V_{PCC}^2}{Z_i} \right) \cos \theta_i + \frac{3}{2} \frac{V_i V_{PCC}}{Z_i} \sin \delta_i \sin \theta_i \\ Q_i &= \frac{3}{2} \left(\frac{V_i V_{PCC}}{Z_i} \cos \delta_i - \frac{V_{PCC}^2}{Z_i} \right) \sin \theta_i - \frac{3}{2} \frac{V_i V_{PCC}}{Z_i} \sin \delta_i \cos \theta_i \end{aligned} \quad (1.1)$$

where V_i is the output voltage amplitude of DG_i ($i \in \{1, 2\}$), V_{PCC} is the common bus voltage, δ_i is the power angle between V_i and V_{PCC} . Z_i and θ_i are, respectively, the corresponding magnitude and phase of the equivalent impedance between DG_i and the common AC bus.

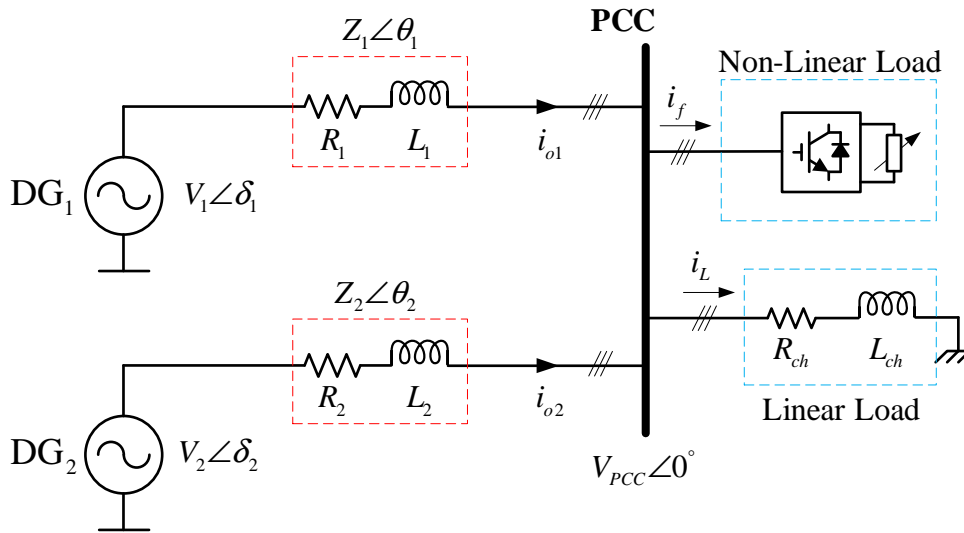


Fig. 2. Microgrid system with two DGs.

i. Case 1: Inductive Impedance ($\theta_i = 90^\circ$)

Let us consider first, the feeder line is mainly inductive (i.e. $X_i \gg R_i$). Assuming that the phase difference δ_i between V_i and V_{PCC} is very small ($\cos \delta_i \approx 1$ and $\sin \delta_i \approx \delta_i$), (1.1) can be simplified as follows:

$$\begin{aligned} P_i &= \frac{3}{2} \frac{V_i V_{PCC}}{X_i} \delta_i \\ Q_i &= \frac{3}{2} \frac{V_{PCC}}{X_i} (V_i - V_{PCC}) \end{aligned} \quad (1.2)$$

Thus, the real power is strongly dependent on the power angle δ_i , while the reactive power is mainly subjected to the voltage amplitude V_i . Then, the conventional droop controller can be expressed as:

$$\begin{aligned}\omega_i &= \omega_0 - m_i P_i \\ V_i &= V_0 - n_i Q_i\end{aligned}\quad (1.3)$$

where ω_0 and V_0 are the output frequency and voltage at no load, m_i and n_i are the frequency and amplitude droop coefficients of DG_i , respectively. However, the conventional droop controller is not always true since in Low-voltage (LV) microgrid, the feeder lines are mainly resistive. In this case, the droop control in its previous configuration may cause stability problem due to the coupling between the real and reactive power.

ii. Case 2: Resistive Impedance ($\theta_i = 0^\circ$)

In the case of a LV microgrid, R_i is much larger than X_i ($R_i \gg X_i$). Thus, after performing some assumptions in equation (1.1), it will be rewritten as follow

$$\begin{aligned}P_i &= \frac{3}{2} \frac{V_{PCC}}{R_i} (V_i - V_{PCC}) \\ Q_i &= -\frac{3}{2} \frac{V_i V_{PCC}}{R_i} \delta_i\end{aligned}\quad (1.4)$$

So here, the real power is controlled by controlling the voltage amplitude V_i and the reactive power is controlled by the power angle δ_i . Hence the droop control strategy takes the form

$$\begin{aligned}\omega_i &= \omega_0 + m_i Q_i \\ V_i &= V_0 - n_i P_i\end{aligned}\quad (1.5)$$

B) Harmonic Power Sharing

When significant non-linear loads are connected to a microgrid, harmonic power sharing errors present due to different DG ratings and grid parameters. Inaccurate sharing of harmonic power can lead to a DG overcapacity, overheating, losses and distortion in current and voltage waveforms. Therefore, a control strategy is investigated to accurately share harmonic power and compensate the THD of the PCC voltage. It was shown that, DG units location can have significant impact on power quality. In fact, the location of DG plays a vital role in improving the voltage profile and reducing losses. The way to share harmonic power between different DG units is achieved by changing the effective line impedances. If the equivalent harmonic impedance is reduced properly, the PCC voltage quality can be improved [19]. Fig. 3 shows a simplified circuit of two DG units connected to a non-linear load represented by a passive impedance Z_{Load}^h and a harmonic current source I^h . In ideal case, when harmonic current passed, the DG unit is equivalent to a zero impedance. In Fig. 3 the DG unit harmonic impedance is considered based on the existence of internal output impedance.

To effectively change the physical line impedance, two ways were reported in literature. The first method is done by adding a virtual conductance [29]. In this way, harmonic sharing error may exist if the difference between the feeder line impedances, Z_{Line1}^h, Z_{Line2}^h is important. The second method was proposed in [6], [12]–[14], which is based on adding a virtual impedance in series to the harmonic line impedance. This virtual part is designed to be larger than the line impedance. This will insure equal impedances for the DG units to share equally the harmonic power. However, this method will increase the voltage distortion at the PCC.

3. Proposed Harmonic Droop Controller

It is clear that sharing the harmonic power and compensating the PCC voltage distortion cannot be done unless using several virtual impedance loops. The proposed harmonic droop is able to make the two tasks in one control loop. Furthermore, the proposed method is less sensitive to physical line impedance mismatch. Therefore, accurate harmonic sharing can be carried out with a simpler controller.

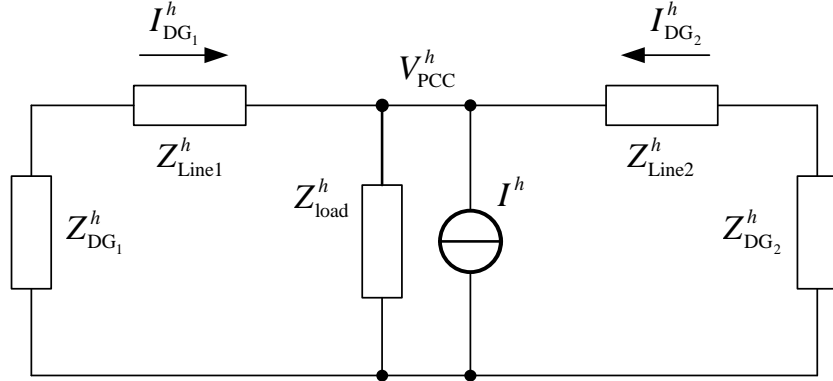


Fig. 3. Equivalent circuit of two DGs at harmonic frequency range

A) The essence of the proposed harmonic droop

Figure 4 shows a simplified microgrid with two DG units supplying a common non-linear load. The load is modeled as a harmonic source current I^h and a passive impedance Z_{Load}^h . Each DG unit is represented by a voltage source $V_{DG_i}^h$ connected to the load via feeder impedance Z_{DG_i} ($i=1, 2$).

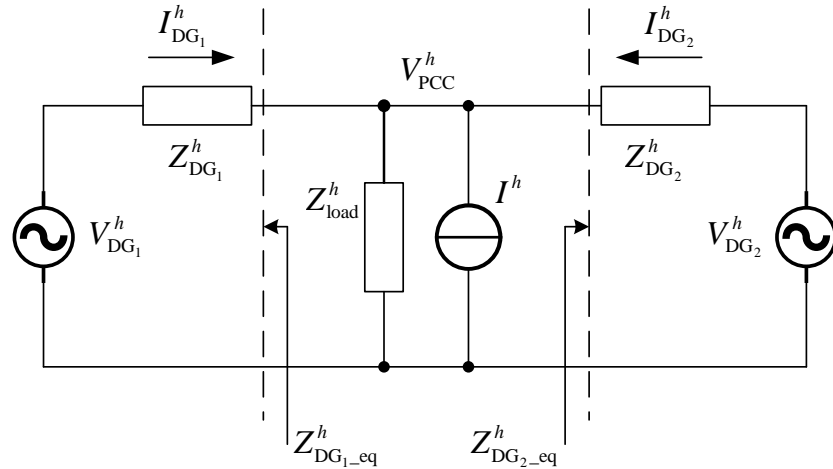


Fig. 4. Simplified Microgrid with two DGs connected to a non-linear load.

The idea behind the proposed harmonic droop is to set a reference voltage ($V_{DG_i}^h$) with the employment of the PCC harmonic voltage (V_{PCC}^h) and a positive gain, G_i^h . The DG_i reference voltage is expressed as:

$$V_{DG_i}^h = -G_i^h \cdot V_{PCC}^h \quad (1.6)$$

Therefore, the equivalent harmonic impedance of DG_i seen from the PCC point can be obtained as follow:

$$\begin{aligned}
I_{DG_i}^h &= (V_{DG_i}^h - V_{PCC}^h) / Z_{DG_i}^h \\
&= -(1 + G_i^h) V_{PCC}^h / Z_{DG_i}^h \\
Z_{DG_i_eq}^h &= \frac{-V_{PCC}^h}{I_{DG_i}^h} = \frac{Z_{DG_i}^h}{(1 + G_i^h)}
\end{aligned} \tag{1.7}$$

where, $I_{DG_i}^h$ and $Z_{DG_i}^h$ are the output harmonic current and the harmonic impedance of DG_i respectively.

Based on equation (1.7), it is obvious to interpret that a proper control of the positive gain G_i^h leads to a reduction in DG_i line impedance by a factor of $(1 + G_i^h)$. In this way, it is clear that the PCC harmonic voltage is minimized. To accurately share the harmonic current between different DGs, the proposed harmonic droop is designed to control the positive gain G_i^h as regard to the harmonic sharing criteria given for the different DG units in a microgrid.

B) Proposed Harmonic Droop characteristics

The overall block diagram representing the DG_i connected to a microgrid across a feeder line impedance with the proposed harmonic droop controller is shown in Fig. 5. It is seen that a minimal communication link is used to send the harmonic voltages at the PCC to the harmonic droop controller. The harmonic droop uses that information to generate the appropriate reference voltage ($V_{DG_i_ref}^h$). The proposed harmonic droop works in collaboration with the fundamental droop control to generate the total reference voltage of DG_i unit. The inner controller is there to insure the measure voltage follows perfectly the reference.

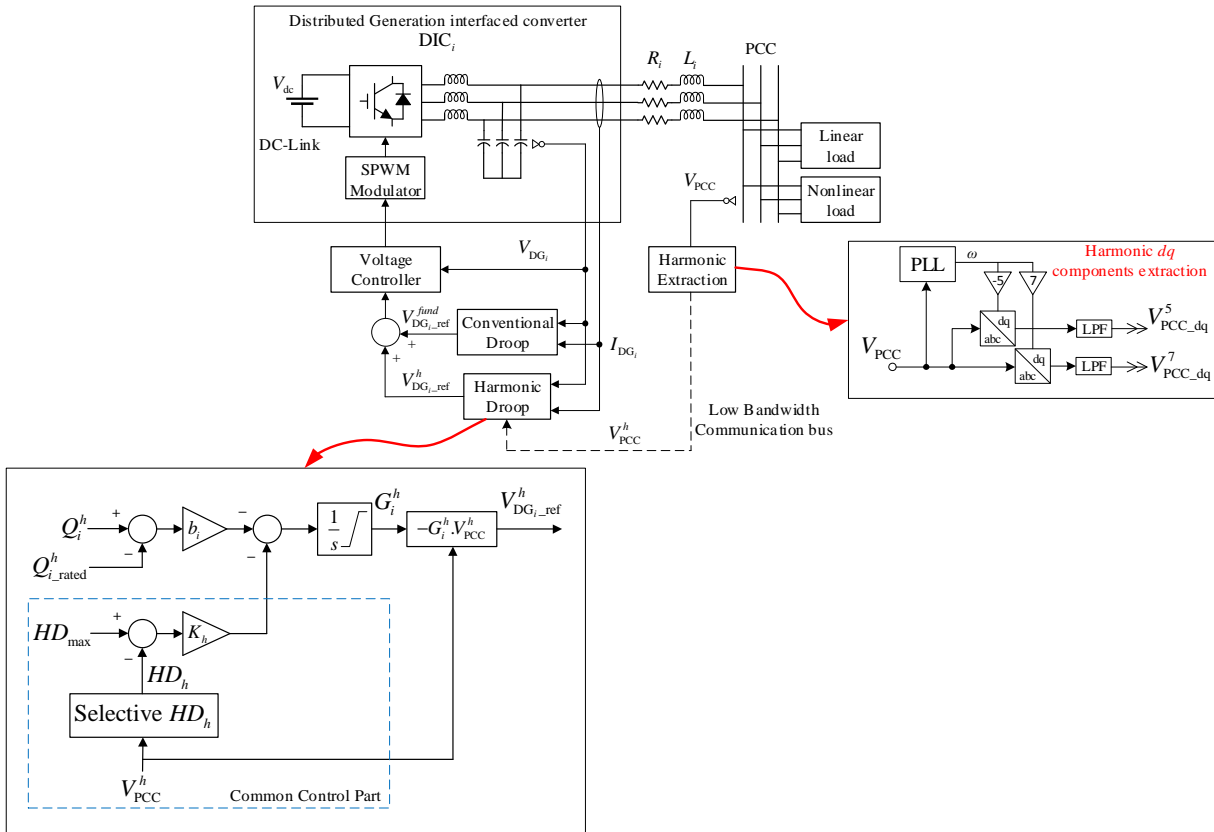


Fig. 5. The overall proposed control strategy with the harmonic droop controller for DG interfaced converter.

Based on the proposed harmonic technique ($Q_i^h - G_i^h$) presented in Fig. 5, the positive gain (G_i^h) is defined as function of the harmonic power rating ($Q_{i_rated}^h$) and the measured harmonic power (Q_i^h). The characteristics of the harmonic droop controller is identical to the conventional droop where the respective parameters are designed in similar way. The harmonic droop coefficient (b_i) for all DG units is defined as:

$$b_1 Q_{1_rated}^h = b_2 Q_{2_rated}^h = \dots = b_n Q_{n_rated}^h \quad (1.8)$$

where $Q_{i_rated}^h$ ($i = 1 \dots n$), is the rated harmonic capacity of each DG unit.

To maintain a proportional share of harmonic power between DG units without being affected by the mismatch in line impedances, a common control part is added in the proposed harmonic droop ($Q_i^h - G_i^h$). As seen in Fig. 5, a selective harmonic distortion (HD_h) is compared with an input setting value, HD_{max} , the maximum allowed harmonic distortion. At steady state condition, the integrator input value will reach zero. Since the common control part is designed to be the same for all DG units, then we obtain the following:

$$b_1 (Q_1^h - Q_{1_rated}^h) = b_2 (Q_2^h - Q_{2_rated}^h) = \dots = b_n (Q_n^h - Q_{n_rated}^h) \quad (1.9)$$

And according to equation (1.8), a proportional share of harmonic power is satisfied. The following equation will be considered as:

$$b_1 Q_1^h = b_2 Q_2^h = \dots = b_n Q_n^h \quad (1.10)$$

The harmonic power drawn by each DG unit to the non-linear load is defined as:

$$Q_i^h = 3 \cdot V_{DG_i}^{fund} \cdot I_{DG_i}^h \quad (1.11)$$

where, $V_{DG_i}^{fund}$ and $I_{DG_i}^h$ represent the fundamental rms-voltage at the output of DG_i and the h -harmonic current traversing the DG_i line impedance.

To set the harmonic droop coefficients, the following equation is used:

$$b_i = b_0 / Q_{i_rated}^h \quad (1.12)$$

The gain b_0 is tuned to be high enough with a compromised strategy in order to adopt a proper harmonic sharing and ensure a stable system at the same time. The gain K_h is selected to be the same for all DG units and defined as

$$K_h = b_0 / HD_{max} \quad (1.13)$$

Consequently, by adjusting the gain b_0 and the maximum harmonic distortion HD_{max} , the proposed harmonic droop controller become easy to tune and flexible to work with. The proposed controller will dynamically change the gain G_i^h for each specific harmonic frequency in order to set the reference harmonic voltage for the DG unit to generate at the output.

The h -harmonic distortion of the PCC voltage can be evaluated using the following equation:

$$HD_h = V_{PCC}^h / V_{PCC}^{fund} \quad (1.14)$$

where, V_{PCC}^{fund} and V_{PCC}^h represent the fundamental and the h -harmonic component of the voltage at PCC. The harmonic component is extracted using real time dq -synchronous individual harmonic frame method as shown in Fig. 5.

After adding a harmonic reference voltage to the input of the DG inner controller, a saturation process should be avoided. For this reason, the integrator of the proposed harmonic droop should be limited to the inverter saturation boundaries when using a specific Modulation. In the case of sinusoidal PWM, the saturation limit is given as:

$$V_{DG_i\text{-ref}} \leq \sqrt{3/2}(V_{dc}/2) \quad (1.15)$$

After adding the harmonic reference voltage to the DG_i inner controller, the reference rms-voltage, $V_{DG_i\text{-ref}}$, can be expressed as:

$$V_{DG_i\text{-ref}} = \sqrt{(V_{DG_i\text{-ref}}^{fund})^2 + (V_{DG_i\text{-ref}}^h)^2} \quad (1.16)$$

The h -harmonic reference voltage is written as:

$$\begin{aligned} V_{DG_i\text{-ref}}^h &= -G_i^h \cdot V_{PCC}^h \\ V_{DG_i\text{-ref}}^h &= -G_i^h \cdot HD_{\max} \cdot V_{PCC}^{fund} \end{aligned} \quad (1.17)$$

Therefore, substituting equations (1.16) and (1.17) in the inequality (1.15), the following limiting values of the gain G_i^h is obtained:

$$0 \leq G_i^h \leq \frac{\sqrt{\frac{3}{2}(V_{dc}/2)^2 - (V_{DG_i}^{fund})^2}}{HD_{\max} V_{DG_i}^{fund}} \quad (1.18)$$

TABLE I. SIMULATION PARAMETERS FOR THREE DGs CONFIGURATION

System Parameters			
Fundamental Line voltage (V)/frequency (Hz)	110V/60Hz		
Feeder impedance $Z_{DG_1} (R_1, L_1)$	(0.58 Ω , 0.05 mH)		
Feeder impedance $Z_{DG_2} (R_2, L_2)$	(0.2 Ω , 0.02 mH)		
Feeder impedance $Z_{DG_3} (R_3, L_3)$	(0.1 Ω , 0.01 mH)		
5 th harmonic current source $I_{dq}^5 = I_d^5 + jI_q^5$	6 - j2 (A)		
7 th harmonic current source $I_{dq}^7 = I_d^7 + jI_q^7$	-5 (A)		
Max. Harmonic distortion HD_{\max} (%)	0.1%		
DG Droop Characteristics			
Control Parameters	DG ₁	DG ₂	DG ₃
m_i (rad/Var)	1.33×10^{-4}	1.33×10^{-4}	1.33×10^{-4}
n_i (V/W)	2.5×10^{-3}	2.5×10^{-3}	2.5×10^{-3}
	Case A/Case B	Case A/Case B	Case A/Case B
$Q_{i\text{-rated}}^h$ (Var)	500/500	500/500	500/1000
b_i (1/Var)	0.06/0.06	0.06/0.06	0.06/0.03

4. Simulation Results

The proposed harmonic droop controller is tested in MATLAB simulator for a microgrid with three DGs connected to a linear and non-linear load. The linear load is represented by a classical R-L impedance and the nonlinear is modeled by current sources that inject harmonics to the grid. The performance of the proposed harmonic droop is checked for 5th and 7th harmonic orders. The dynamic behavior of the harmonic current is limited to the bandwidth of the voltage controller of the DG unit.

The system parameters of the LV-microgrid considered in this test are given in Table I. The three DG units are provided with the proposed harmonic droop in addition to the fundamental droop controller. In the following, the proposed harmonic droop is tested in two different cases.

A) *Equal harmonic power ratings of DG units*

The three sources are designed to have equal power ratings for both fundamental and harmonics with different line impedances. In this case, we will analyze the difference before and after activating the proposed harmonic droop to illustrate its performance in balancing the draw of current between the three DG units. In Fig. 6, the fundamental power sharing is presented when P - V and Q - ω droop is adopted for LV microgrid. The results show an equal fundamental power sharing after using an improved droop controller as proposed in [3].

The 5th and 7th harmonic power sharing are shown in Fig. 7. In the first stage, when the proposed harmonic droop is turned OFF, the harmonic power sharing between DG units is not satisfied. After turning ON the harmonic droop controller in three DG units, the harmonic power is balanced between the units regardless of the mismatched in line impedances. It is to be noted that in [22], the harmonic droop control is tested on a microgrid with inductive line impedances. In this case P - ω and Q - V are adopted to share the fundamental power and according to Fig. 8, the harmonic power is shared equally between two DG units by applying the proposed harmonic droop.

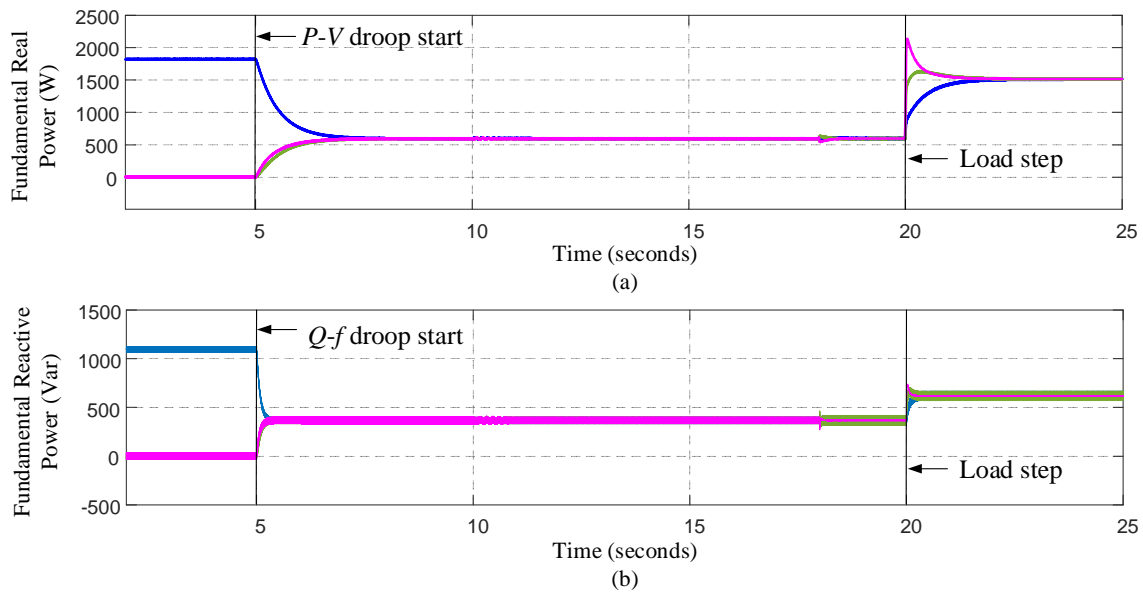


Fig. 6. Simulation Results of Case A: (a) Fundamental Real Power for three DG units: P_1 , P_2 and P_3 ; (b) Fundamental Reactive power for three DG units: Q_1 , Q_2 and Q_3 .

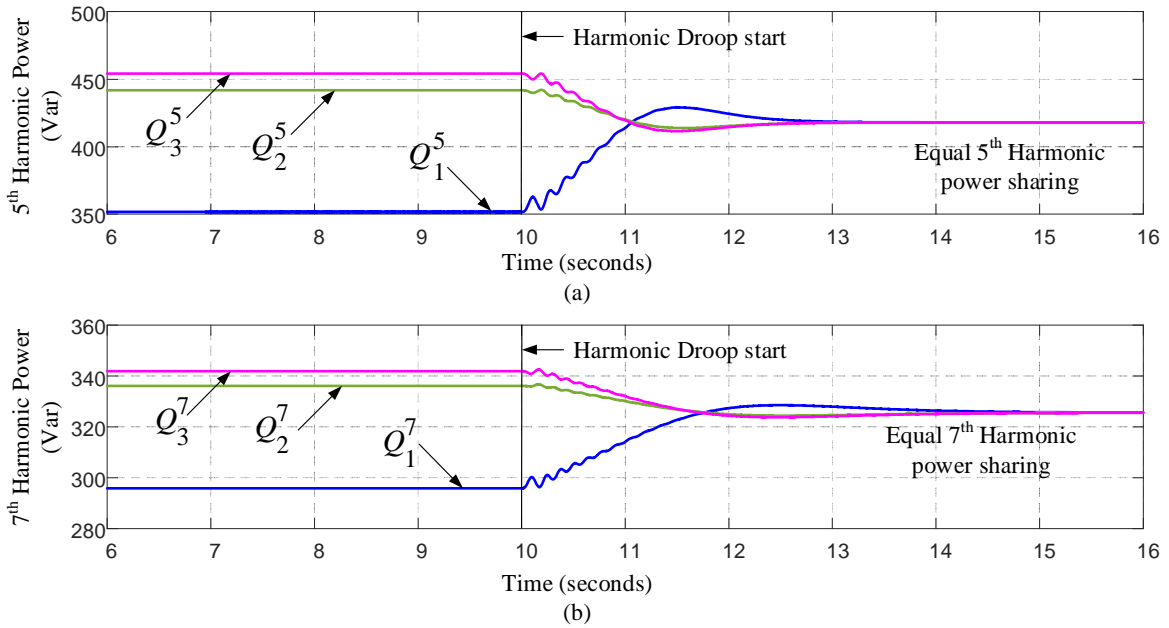


Fig. 7. Simulation Results of Case A: (a) 5th Harmonic power for three DG units: Q_1^5 , Q_2^5 and Q_3^5 ; (b) 7th Harmonic power for three DG units: Q_1^7 , Q_2^7 and Q_3^7 .

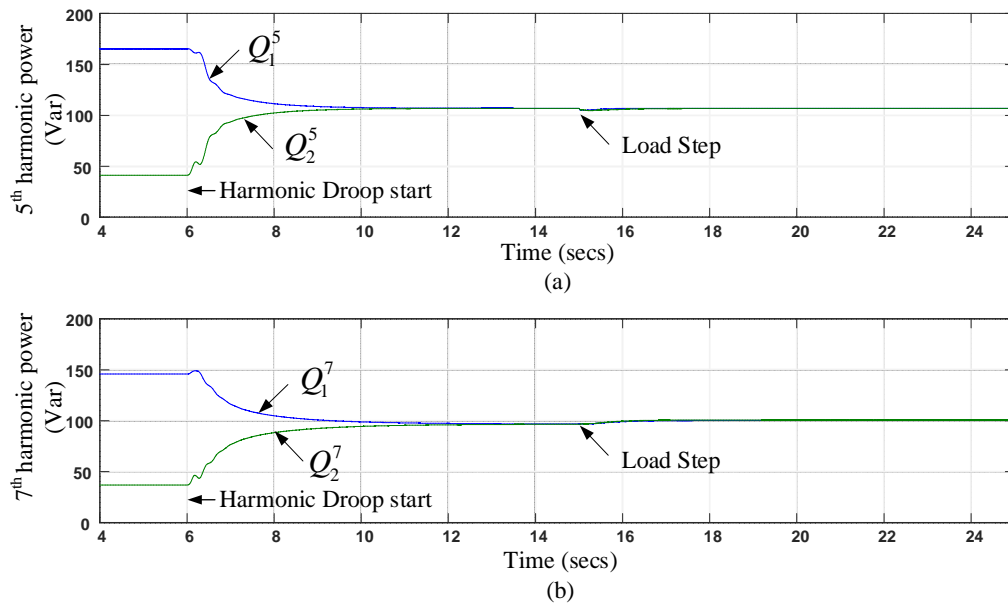


Fig. 8. Simulation results in [22]: (a) 5th Harmonic power for two DGs: Q_1^5 , Q_2^5 ; (b) 7th Harmonic power for two DGs: Q_1^7 , Q_2^7 .

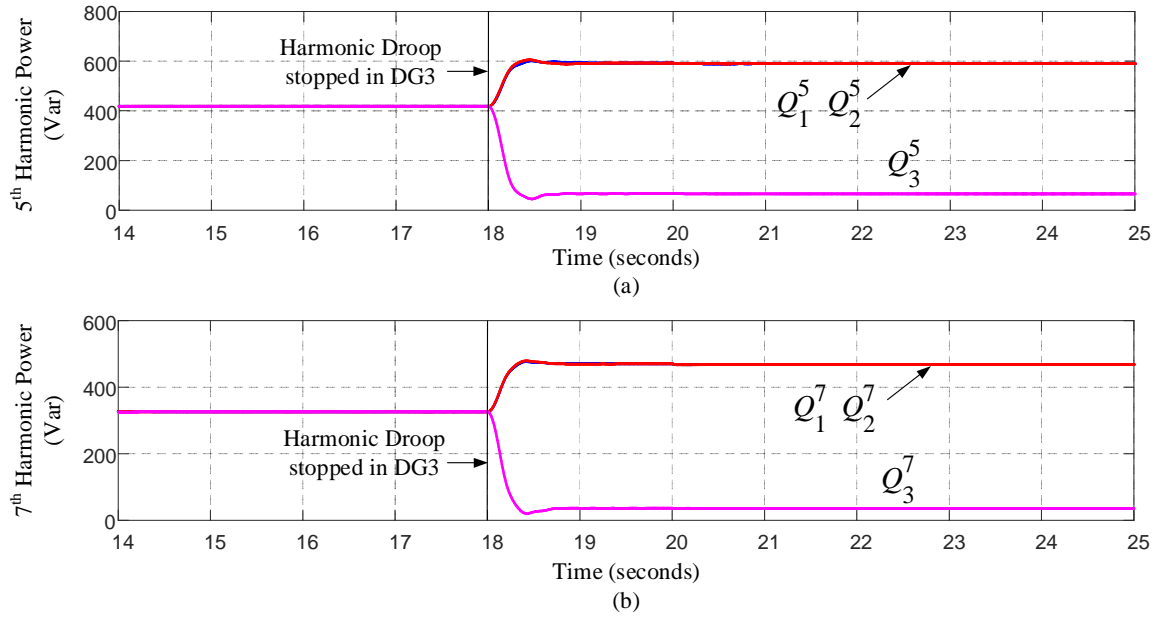


Fig. 9. Simulation Results of Case A, after stopping Harmonic Droop in DG₃: (a) 5th Harmonic power for three DG units: Q_1^5 , Q_2^5 and Q_3^5 ; (b) 7th Harmonic power for three DG units: Q_1^7 , Q_2^7 and Q_3^7 .

In Fig. 9 the harmonic droop is stopped in DG₃, the unit that is near the load, where the other DG units still participate in sharing the harmonic droop. The idea behind this test is to examine the performance of the proposed droop when communication is lost in any DG unit. The DG unit that lose communication with the PCC is allowed to share only the fundamental power whereas the harmonic droop is turned OFF. It is shown in Fig. 9 that the harmonic power is perfectly distributed between DG₁ and DG₂ with no harmonic power drawn from DG₃. Fig. 10 shows the output current waveforms generated by each DG in two stages. Fig. 10(a) represents the current waveforms when the proposed harmonic droop is running in the three DGs. While Fig. 10(b) represents the current waveforms when DG₃ stopped in sharing the harmonic power with other DG units. This part shows a sinusoidal waveform of current i_{DG_3} and the harmonic contents are distributed equally between i_{DG_1} , i_{DG_2} .

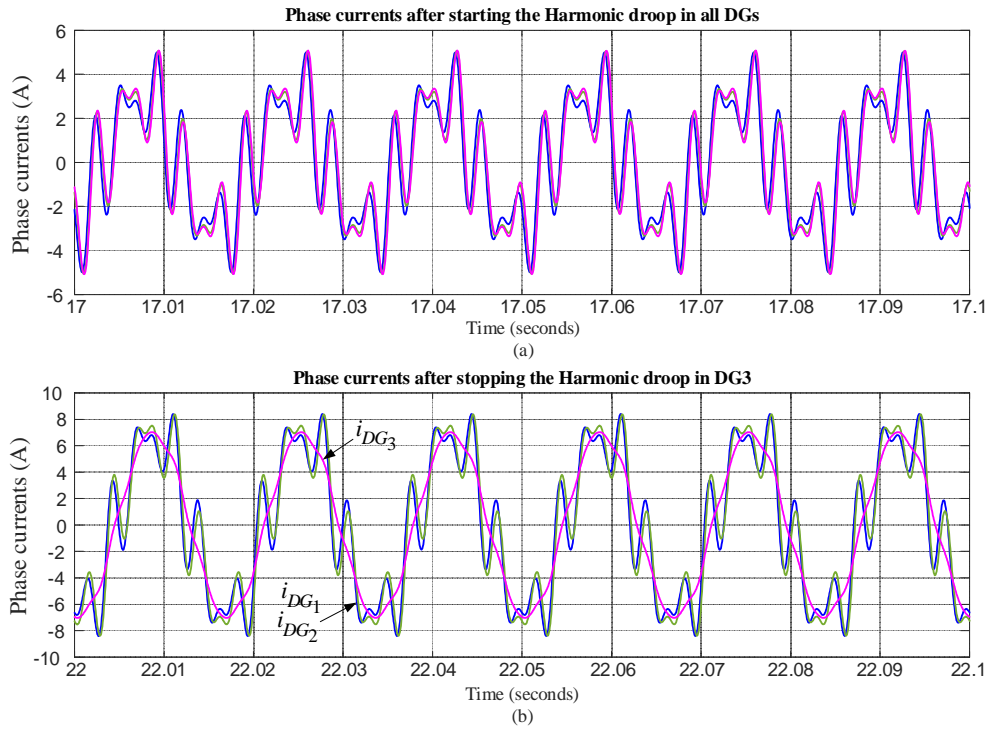


Fig. 10. Simulation Results of Case A: (a) Phase currents after harmonic compensation in all DG units; (b) Phase currents after harmonic compensation in DG₁ and DG₂.

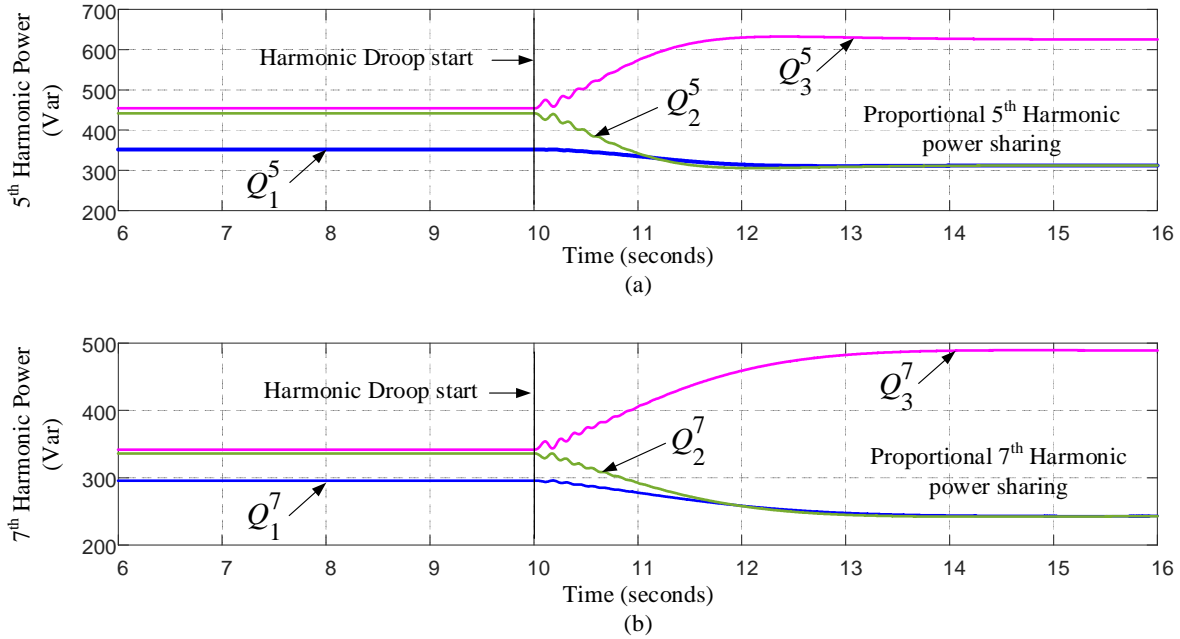


Fig. 11. Simulation Results of Case B: (a) 5th Harmonic power for three DG units: Q_1^5 , Q_2^5 and Q_3^5 ; (b) 7th Harmonic power for three DG units: Q_1^7 , Q_2^7 and Q_3^7 .

B) Different harmonic power ratings of DGs

The same microgrid configuration is adopted, but considering different harmonic power ratings for the DG units as shown in Table I. In this case, the efficiency of the proposed harmonic droop will be illustrated. All the DG units are supported by the proposed harmonic droop that will guarantee the proportional harmonic sharing between the units. The same simulation procedure is tested in this case. Fig. 11 shows the harmonic power sharing between the three sources. As represented in the figure, the two

sources DG₁ and DG₂ are able to share equally the harmonic power which is half the quantity shared by DG₃. This interprets the accuracy of the proposed harmonic droop in sharing the harmonic power. It was suggested to stop the harmonic droop in DG₃, Fig. 12 shows the repartition of harmonic power between the DG units after stopping the harmonic droop in DG₃. The 5th and 7th harmonic powers drawn by DG₃ are minimized as possible. Fig. 13 shows the output phase currents for each DG when the harmonic droop controller is applied to all DGs and after terminating the harmonic droop in DG₃. Fig. 13(b) shows how the current i_{DG_3} tends to be more sinusoidal than the others currents (i_{DG_1}, i_{DG_2}). The overall numerical results for the two case studies are summarized in table II.

TABLE II. Repartition of Harmonic power between three DG units for the cases (A) and (B)

	Equal harmonic power ratings of DG units (Case A)				Different harmonic power ratings of DG units (Case B)			
	Before Harmonic droop compensation		After Harmonic droop compensation		Before Harmonic droop compensation		After Harmonic droop compensation	
	5 th Har. (Q_i^5)	7 th Har. (Q_i^7)	5 th Har. (Q_i^5)	7 th Har. (Q_i^7)	5 th Har. (Q_i^5)	7 th Har. (Q_i^7)	5 th Har. (Q_i^5)	7 th Har. (Q_i^7)
DG1	356 Var	297 Var	419 Var	325.5 Var	356 Var	297 Var	314.25 Var	244.12 Var
DG2	443 Var	337.5 Var			443 Var	337.5 Var	314.25 Var	244.12 Var
DG3	458 Var	342 Var			458 Var	342 Var	628.5 Var	488.25 Var

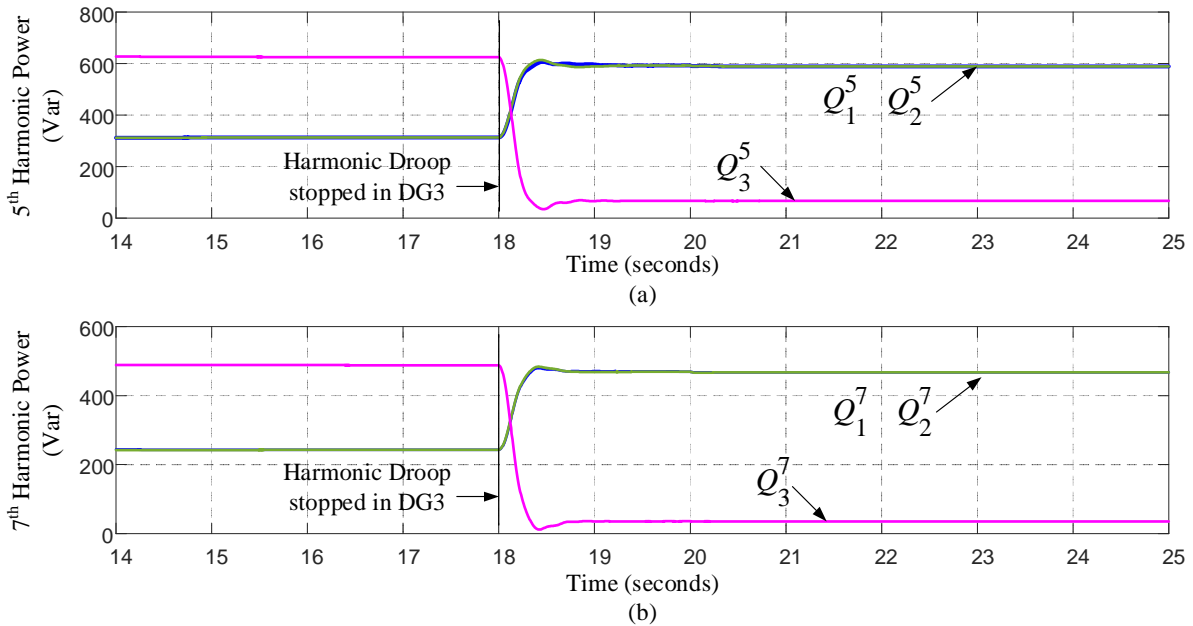


Fig. 12. Simulation Results of Case B, after stopping Harmonic Droop in DG₃: (a) 5th Harmonic power for three DG units: Q_1^5, Q_2^5 and Q_3^5 ; (b) 7th Harmonic power for three DG units: Q_1^7, Q_2^7 and Q_3^7 .

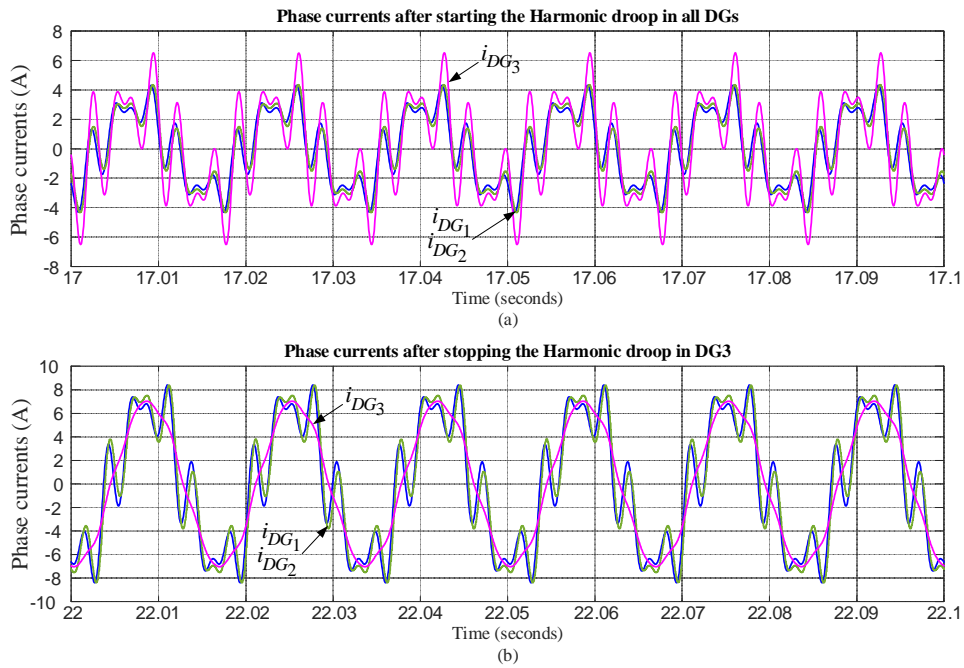


Fig. 13. Simulation Results of Case B: (a) Phase currents after harmonic compensation in all DG units; (b) Phase currents after harmonic compensation in DG₁ and DG₂.

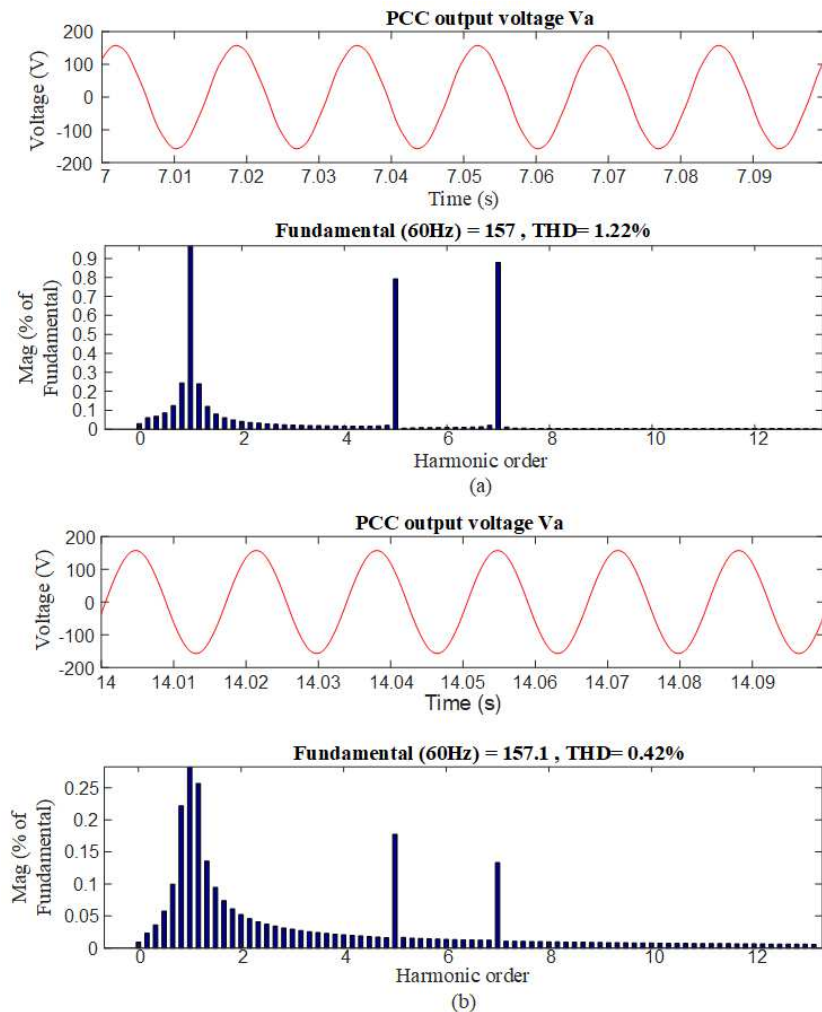


Fig. 14. Simulation Results of Case B: (a) PCC output voltage and its harmonic order analysis before starting the harmonic droop; (b) PCC output voltage and its harmonic order analysis after starting the harmonic droop.

The FFT analysis is done to interpret the efficiency of the proposed harmonic droop controller in compensating the voltage distortion at PCC. Fig. 14 shows the study and the distribution of harmonic contents of the PCC output voltage before and after starting the harmonic droop. The total harmonic distortion (THD) drops from 1.22% to 0.42% after compensation.

5. Experimental Results

A microgrid with two DGs connected to a common R-L load and a non-linear full bridge rectifier load is constructed in the laboratory as shown in Fig. 15. The system parameters used in this test are given in Table III. The experiment test bench allows to examine the effectiveness and performance of the proposed harmonic droop controller in sharing the harmonic power and compensating the voltage distortions even in microgrid with more inductive feeder lines. For case 1, Fig. 16 shows the 5th and 7th harmonic Var for the two DG units before and after starting the harmonic droop. The same figure shows the output gains time response of the harmonic droop that is responsible on adding the reference harmonic voltage of each DG to regulate the harmonic output currents.

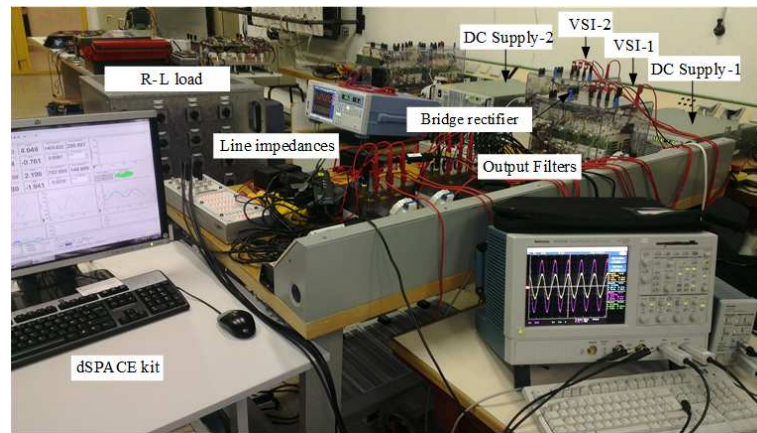


Fig. 15. Laboratory test bench with all equipment.

TABLE III. SIMULATION PARAMETERS FOR TWO DGs CONFIGURATION

System Parameters				
Fundamental Line voltage (V)/frequency (Hz)	110V/60Hz			
Feeder impedance $Z_{DG_1} (R_1, L_1)$	(0.1 Ω , 1 mH)			
Feeder impedance $Z_{DG_2} (R_2, L_2)$	(0.2 Ω , 5 mH)			
Max. Harmonic distortion HD_{max} (%)	1%			
DG Droop Characteristics				
Control parameter	Case 1: Equal harmonic power ratings		Case 2: Different harmonic power ratings	
	DG ₁	DG ₂	DG ₁	DG ₂
m_i (rad/W)	5×10^{-5}	5×10^{-5}	5×10^{-5}	5×10^{-5}
n_i (V/Var)	6.7×10^{-3}	6.7×10^{-3}	6.7×10^{-3}	6.7×10^{-3}
$Q_{i_rated}^h$ (Var)	500	500	500	250
b_i (1/Var)	0.1	0.1	0.1	0.2

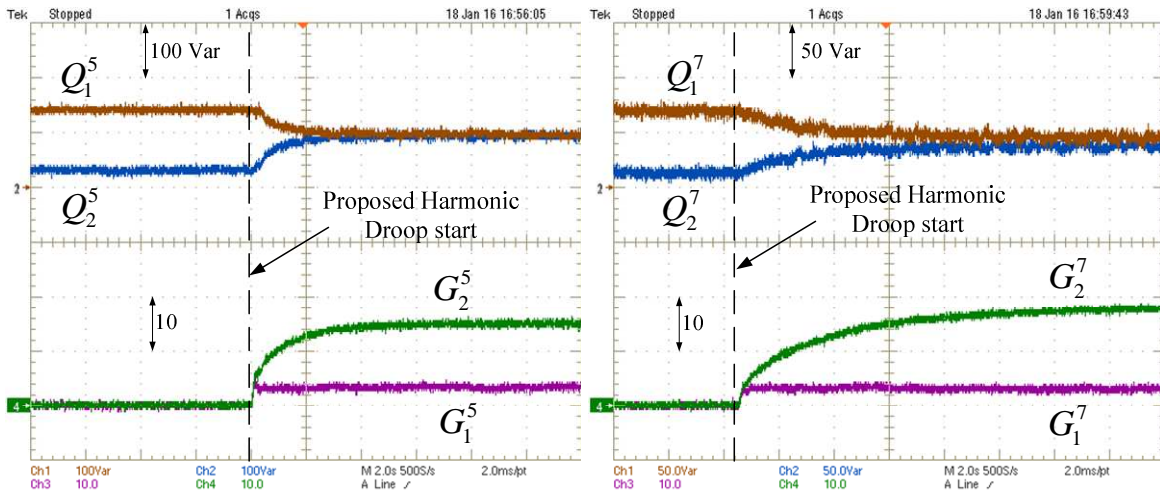


Fig. 16. Experimental results for case 1: 5th and 7th Harmonic power repartition with output gain time response for both DGs.

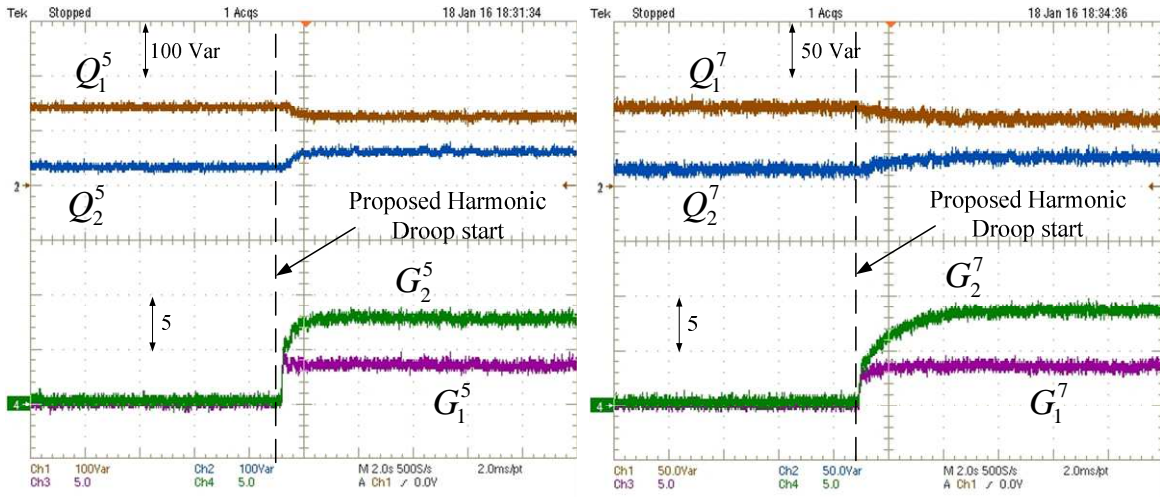


Fig. 17. Experimental results for case 2: 5th and 7th Harmonic power repartition with output gain time response for both DGs.

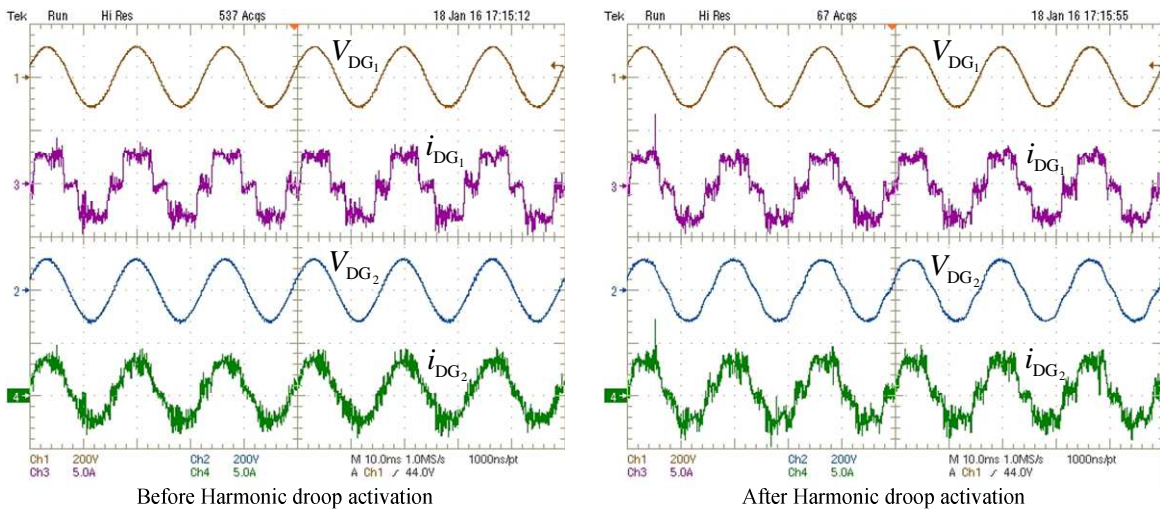


Fig. 18. Experimental results: DGs phase voltage and current before and after Harmonic droop activation.

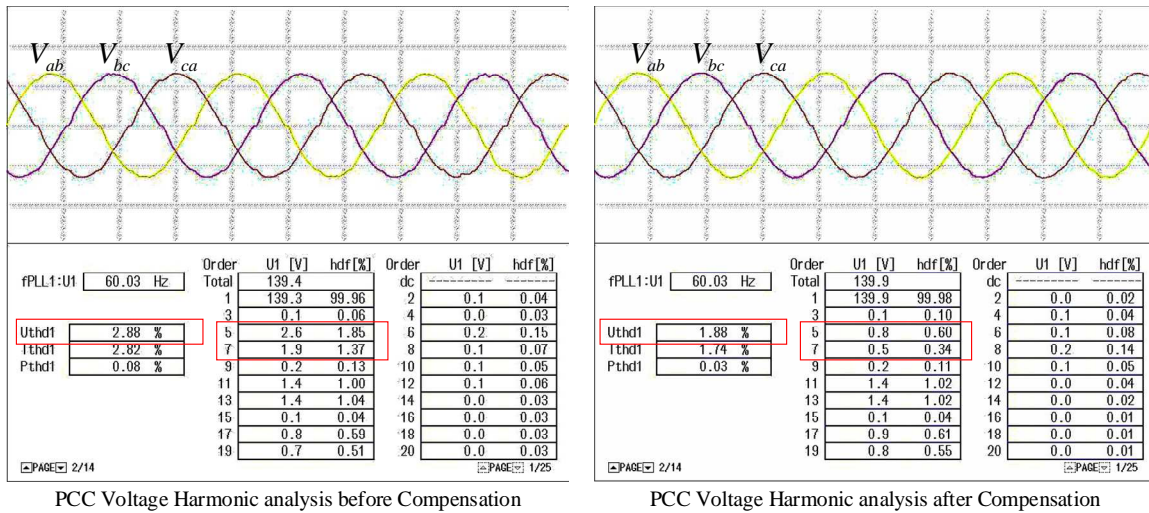


Fig. 19. Experimental results: PCC voltages with harmonic analysis before and after harmonic droop compensation.

Fig. 17 verifies the operation of the harmonic droop controller under different harmonic ratings which is related to case 2. The distribution of the average harmonic power between the two DG units shows that a proportionally share of power occur according to the ratings given in table III. In order to demonstrate more the effect of harmonic contents on the voltage and currents signals, Fig. 18 shows the voltage and current waveforms for the two DGs before and after starting the harmonic droop. The figure indicates that more harmonic contents are added to the voltage of DG₂ in order to be able to absorb more harmonic current.

The compensation of the PCC voltage distortions is demonstrated by Fig. 19. The harmonic droop allows reducing the THD from 2.88% to 1.88%. The experimental test concerns only the reduction of 5th and 7th harmonic order contents. The 5th and 7th harmonic voltage components are widely reduced since, HD5 drops from 1.85% to 0.6% and HD7 goes down from 1.37% to 0.34%.

6. Conclusion

In this paper, a new harmonic droop controller is proposed to share the harmonic power between different DG units and to compensate the voltage distortions at PCC. **The main contribution of this paper is that the proposed harmonic droop reduces the voltage distortion at the end users autonomously between different DGs in a one loop controller without the knowledge of line characteristics. The harmonic droop current sharing is unaffected by the mismatch in the line impedances.** The proposed controller is efficient, as well, when mismatch in line impedances present. The overall control strategy is discussed deeply in section II and simulation results verify the effectiveness of the proposed controller for different case studies. The proposed method works in collaboration with the fundamental droop controller without any interaction between them. Experimental tests are applied to demonstrate the performance of the harmonic droop in real application. The proposed harmonic droop works in case of resistive or inductive microgrid as realized in the simulation and experimental tests. The results show the competence of the proposed harmonic droop in compensation as compared with other controllers.

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