A Hierarchical Control Scheme for Reactive Power and Harmonic Current Sharing in Islanded Microgrids

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Keywords

« Islanded microgrid», « Hierarchical control », « Instantaneous circulating currents », « Reactive power sharing », « Harmonic currents sharing ».

Abstract

In this paper, a hierarchical control scheme consisting of primary and secondary levels is proposed for achieving accurate reactive power and harmonic currents sharing among interface inverters of distributed generators (DGs) in islanded microgrids. Firstly, fundamental and main harmonic components of each inverter output current are extracted at primary level and transmitted to the secondary controller. Then, instantaneous circulating currents at different frequencies are calculated and applied by the secondary level to generate proper control signals for accurate reactive power and harmonic current sharing among the inverters. Consequently, these signals are sent to the primary level and inserted as voltage references after passing the control blocks. In contrast to the conventional virtual impedance schemes, where reactive power and harmonic current sharing are realized at the expense of introducing additional voltage drop and distortion, the proposed control strategy effect on the amplitude and waveform quality of DGs' voltage is negligible. Meanwhile, it is able to provide accurate harmonic current sharing even if nonlinear loads are directly connected at the terminal of DG units. Control system design is described in detail and simulation results are provided to demonstrate the effectiveness of the proposed control method.

Introduction

Due to the increasing application of renewable energy-based distributed generations (DGs) and the advances in power electronic technologies, the concept of the microgrid has been introduced as an attractive way for future smart distribution grids [1]. Most of the DGs are often consisting of a prime mover connected to the microgrid or utility grid through a power electronic interface converters, which are mainly voltage source inverters (VSIs). Compared to traditional power distribution systems, the microgrid can operate in both grid-connected and islanding modes. Consequently, it offers a more reliable power supply to critical loads through coordinated control among paralleled DG interfacing converters.

In the autonomous islanding operation condition, the total load demand in the microgrid also must be properly shared in proportion to their power ratings. Usually to achieve this and regulate the voltage and frequency of the microgrid, the voltage-controlled DG inverters manage through the active power-frequency (*P-f*) and the reactive power-voltage magnitude (*Q-V*) cooperative droop control [2]. The droop method can control the DG units solely by the local measurements in an independent and decentralized manner without using any critical communication link between them. This will increase the reliability and plug-and-play capability [3]. However, there is an inherent limitation in conventional droop scheme which is the trade-off between the output voltage regulation and the sharing accuracy. As a result, it can affect the stability of the microgrid and also seamless transition between the islanded and grid-connected operation modes [4].

It is worth noting that by adopting a proper P - f droop control, the real power sharing is always accurate because the frequency is a global parameter and it remains constant in microgrid once the steady-state condition is achieved. In contrast, the reactive power sharing performance under Q - V droop control is extremely dependent on the impedance of DG feeders and output-side impedance of *LCL* filters connected to interface inverters [3]. Thus, the proportional reactive power sharing accuracy is often declined owing to mismatch between feeder impedances of DG units and due to different ratings of DG units. In addition, in a microgrid with severe nonlinear loads, the conventional droop control exhibit poor harmonic currents sharing and cannot directly address the harmonic current circulation problem among DG units. Consequently, overcoming the problem of inaccurate reactive power sharing and harmonic current sharing in droop-controlled islanded microgrids has attracted considerable attention in the literature.

To solve these challenges, the various techniques based on the virtual output impedance shaping [6]-[7], the modified droop control [8]-[10], and the signal injection techniques [11], [12], have been proposed. It should be noted that the output impedance of inverters plays an essential role in droop controller and power sharing performance. The virtual impedance can have an important contribution to improve system stability and reactive power sharing accuracy. This can be achieved by compensating the asymmetry physical impedances. Virtual impedance is realized through modifying the output voltage reference by means of a load current feed-forward loop [3]. Nevertheless, there is a trade-off between sharing accuracy and DG output voltage regulation [4]. The proposed approaches are mainly based on the assumption that the impedances of the feeder are small and dominated by the virtual impedance at fundamental frequency. Although this approach has the features of good stability and easy implementation, in weak islanded microgrids with large physical feeder impedances, very large virtual impedances are required to mitigate errors in reactive power sharing, which subsequently the power sharing dynamics and output voltage regulation are inevitably affected. Furthermore, in this method, to ensure accurate harmonic currents sharing, in addition to the need to extraction of line harmonic currents, harmonic frequency responses of DG feeder impedances are also required. It means that the harmonic power sharing is also affected due to mismatched feeder impedances even when the virtual impedance is used.

To avoid the using of virtual impedance loop, the concept of virtual active/reactive power and virtual frequency/voltage magnitude was reported, respectively, in [8], [9], to improve the stability of droop control and operation of islanding microgrids based on the modified droop control methods. However, these concepts can hardly improve both of the powers decoupling and power sharing accuracy at the same time [7].Also, In [10] for improving the reactive power sharing performance, the output voltage of each DG unit is changed by adding two terms of sharing error reduction and voltage restoration. The voltage restoration term has been realized to compensate the voltage decrease caused by the error reduction term. Nevertheles, adjusting the compensation coefficients of these terms in different power rating conditions of DG units, as well as generalization of the proposed method to address power sharing problem on harmonic currents, are difficult and complex.

In [11] to reduce the reactive power sharing error and to improve harmonic current sharing accuracy, a small non-characteristic high frequency harmonic voltage signal is injected into the output voltage reference of each DG units. However, injection of such AC signals will cause power quality problems. Furthermore, a control strategy based on estimation of reactive power sharing error by injecting a small transient real-reactive power disturbance coupling term has been proposed in [12]. Then, the reactive power sharing errors are eliminated using an integral control term. Nevertheless, due to using the event-triggered-based control method in this strategy, its stability cannot be guaranteed. Moreover, load changes during the compensation process may lead to inaccurate power sharing [6].

Although, significant control algorithms have been made to improve power sharing accuracy in the same power rating conditions, but there is a need to develop a systematic way to further increase the reactive power and harmonic currents sharing accuracy considering the different power ratings of parallel inverters and feeder impedances mismatches in a islanded microgrid with a large number of nonlinear loads. Another important issue of which has been less emphasized in these strategies, is effectiveness of them in damping circulating currents among parallel DG inverters. It should be noted that the circulating current control is a prerequisite to maintain the stability of an islanded microgrid and increasing quality of load sharing because it desire to create overloads in some parallel inverters and can damage to them [3]. Thus, this paper proposes a hierarchical control approach including primary and secondary control levels to proportionally share the reactive power and harmonic currents among paralleled DG units based on control of the instantaneous circulating currents.

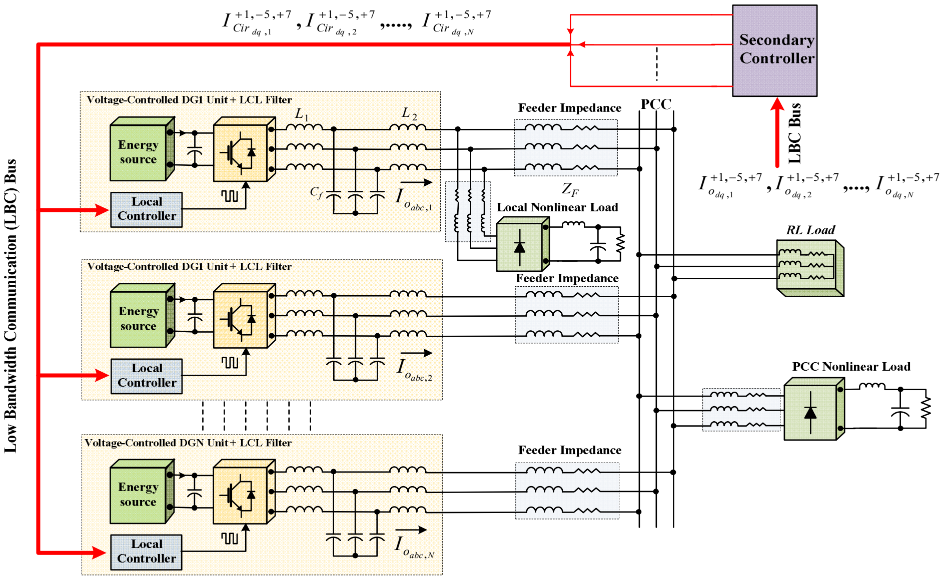


Fig. 1: Proposed hierarchical control scheme for a three-phase islanding microgrid

Proposed hierarchical control structure for islanded microgrids

Fig. 1 shows application of the proposed hierarchal control scheme to a three-phase islanding microgrid, where a number of electronically interfaced DG units are clustered together and connected to PCC through *LCL* filters and feeder impedances. Furthermore, the system is consisting both linear and nonlinear loads which can be considered at PCC and in DG output as locally. For each DG unit, the backstage power is supplied by power generators and/or energy storage systems. The DC-links of DG units are assumed to be controlled separately and kept constant. The hierarchical control scheme is consist of local and secondary controllers. The secondary control level is a central controller which first receives the instantaneous output currents signals of all DG units by means of low bandwidth communication (LBC). Afterwards, it sends the proportional instantaneous circulating currents signals corresponding to the fundamental ad selective harmonics components to the primary controllers of the DG units in order to achieve accurate reactive and harmonic power sharing and mitigation of circulating currents among the DG units. In Fig. 1, superscripts "+1," "–5," "+7" represent fundamental positive sequence and the dominant harmonic components which can be 5th and 7th harmonic, respectively. Low communication bandwidth is applied in order to avoid dependence on the high bandwidth availability which may jeopardize the system stability [13]. On the other hand, LBC can be provided at a relatively low cost. In order to ensure LBC adequacy, the fundamental and selective harmonic currents components should be extracted in *dq* frame and the resultant approximately DC signals are transmitted to the secondary controller.

DG Inverter Primary Control system

The structure of each DG local controller and power stage is shown in Fig. 2. The local control of DGs is performed in $\alpha\beta$ reference frame. Therefore, Clarke transformation is employed to transform voltage and current variables between *abc* and $\alpha\beta$ frames. As shown in Fig. 2, the control structure consists of the fundamental voltage controller, selective harmonic voltage compensation, active and reactive power controllers, and also reactive power and harmonic power sharing error compensation loops. In addition, an output current decomposer block provides for extraction output current components.

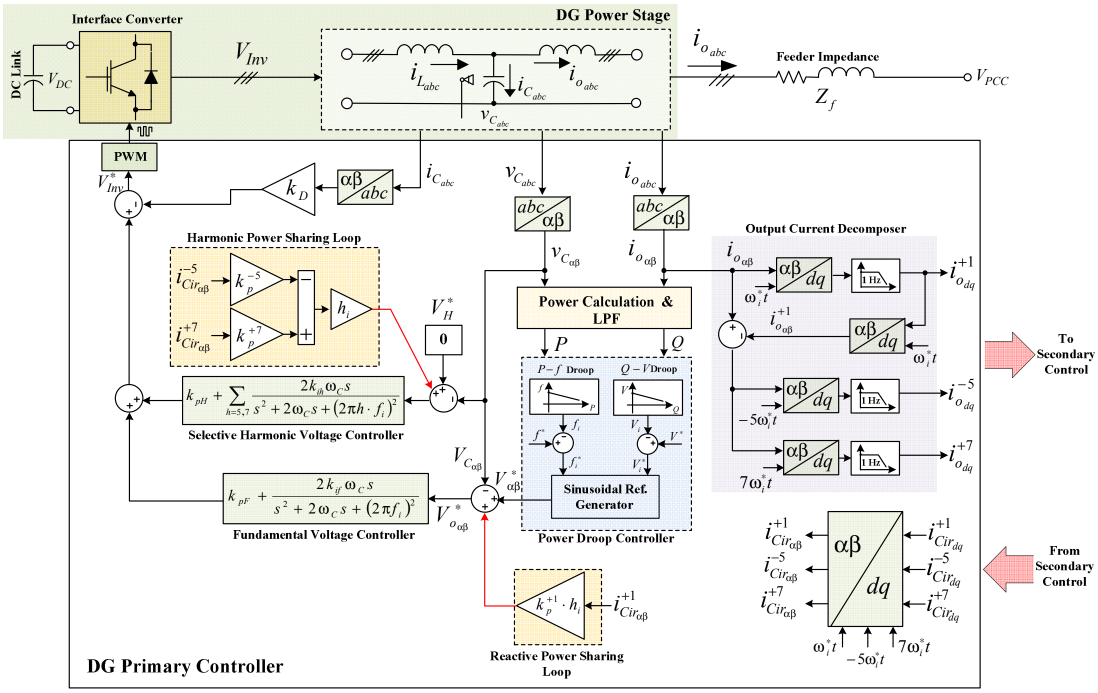


Fig. 2: Block diagram of DG primary control system strategy

Design and stability analysis of the power droop controllers is sufficiently studied in [3] and will not be discussed. The power controllers determine the reference values of DGs output voltage phase angle and amplitude for DG units. Due to inability proportional-integral (PI) controllers to track non-dc variables, proportional + resonant (PR) controllers with higher bandwidth are usually preferred in $\alpha\beta$ reference frame [2].In the structure of the controllers, the generalized integrators are utilized to get zero steady-state errors.

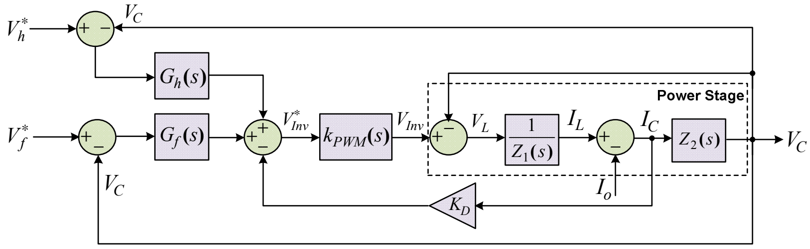


Fig. 3: Block diagram of DG voltage closed-loop voltage control system

It is known that a three-phase system can be modeled as two independent single-phase system based on the *abc*/$\alpha\beta$-coordinate transformation principle [2]. Thus, the block diagram of closed-loop control structure can be simplified as shown in Fig. 3. Z_1 and Z_2 are the filter impedances and k_{PWM} (s) is PWM delay, which are expressed as follows, respectively:

$$Z_1(s) = L_1 s + R_1 \tag{1}$$

$$Z_2(s) = \frac{1}{sC_f} \tag{2}$$

$$k_{PWM}(s) = \frac{1}{1+1.5T_s s} \tag{3}$$

where T_s is the sampling time. In order to design these controllers at fundamental and harmonic frequencies based on closed-loop dynamics of control system, the mason's theorem is applied. As a result, the closed-loop transfer functions related to tracking of fundamental and harmonic voltage reference and output impedance can be easily derived, respectively, as

$$G_{cl\_f}(s)=\frac{V_C(s)}{V_F^*(s)}\bigg|_{i_o=V_H^*=0}=\frac{G_{V-F}(s)\cdot Z_2(s)}{(G_{V-F}(s)+G_{V-H}(s))\cdot Z_2(s)+K_D+Z_1(s)+Z_2(s)} \quad (4)$$

$$G_{cl\_h}(s)=\frac{V_C(s)}{V_H^*(s)}\bigg|_{i_o=V_F^*=0}=\frac{G_{V-H}(s)\cdot Z_2(s)}{(G_{V-F}(s)+G_{V-H}(s))\cdot Z_2(s)+K_D+Z_1(s)+Z_2(s)} \quad (5)$$

$$Z_O(s)=\frac{V_C(s)}{-I_o(s)}\bigg|_{V_F^*=V_H^*=0}=\frac{Z_2(s)}{(G_{V-F}(s)+G_{V-H}(s))\cdot Z_2(s)+K_D+Z_1(s)+Z_2(s)} \quad (6)$$

where $G_{V\text{-}F}$(s) and $G_{V\text{-}H}$ (s) are fundamental and selective harmonic PR controllers, which are shown in Fig. 2. Z_1 and Z_2 are the inverter-side and filter capacitor impedances, respectively. It is worthy note that by adjusting the system parameters, it can be easily obtained a unity gain and zero phase for closed-loop transfer functions at fundamental and harmonic frequencies. Also, the magnitude of inverter's output impedance should be approximately zero at these frequencies. It means that the proper tracking voltage references are guaranteed in this way.

Secondary controller

As it can be found in Fig. 2, extraction of the output current at the fundamental and main harmonics frequencies is important for sending the proper signals to the secondary controller. Various types of harmonic signal decomposition methods [14] have been presented, but the synchronous reference frame (SRF)-based detection is still considered as one of the best solutions [15], especially in communication link-based control systems. As can be seen in Fig.2, the output current decomposer at each frequency component is easily realized by a Park transformation and a first-order low-pass filter (LPF) with 1Hz cut-off frequency. In this block, the output current is transformed to *dq* frames rotating at ω^*t, -5ω^*t, 7ω^*t, respectively. ω^* is the DG system angular frequency which is generated by droop power controller. In the secondary controller, the instantaneous fundamental and harmonic circulating currents are calculated and transmitted to the primary control level. The non-zero-sequence circulating currents between multiple parallel DG inverters with distinct DC links are generated automatically whenever the inverters act in different switching patterns due to the component tolerance and parameter drifts [16]. In addition, the mismatched feeder impedances affect on increasing the circulating current. This will result in line current distortion; unbalanced load sharing; and increase the DC link voltage level. We can define the circulating current for each phase of each inverter as [16]:

$$I_{ck,j}=I_{k,j}-i_{ok,j}=h_j\cdot\sum_{m=1}^{N}i_{ok,m}-i_{ok,j},\quad k\in\{a,b,c\};\quad j\in\{1,2,....,N\};\quad \sum_{m=1}^{N}h_m=1. \quad (7)$$

where $I_{ck,\ j}$ is the circulating current of the *j*th DG inverter and *k, j* indicate the inverter phase and number, respectively. $I_{ok,\ j}$, $I_{k,\ j}$ and h_j are the actual output current, ideally shared current and load distribution factor, respectively. Assuming that the DG$_j$ desired power loading and the total power loading of the microgrid DGs are S_j and S_T, respectively, the load distribution factor is defined as follows:

$$h_j=\frac{S_j}{S_T}=\frac{S_j}{\sum_{m=1}^{n}S_m} \quad (8)$$

Thus, based on the equations of (7) and (8), the secondary controller generates the instantaneous fundamental and harmonic circulating currents for the primary controller in order to achieve accurate steady state reactive power and harmonic current sharing among inverters.

Sharing errors compensation loops at primary level

The objectives of these loops are to realize a compensation method that can eliminate the steady-state reactive power and harmonic currents sharing errors without the knowledge of the detailed microgrid structure such as the values of the feeder impedances and loading conditions. This feature is very vital to attain the "plug-and-play" operation of loads and DG units in the microgrid applications. As observed in Fig. 2, the fundamental and main harmonic circulating currents generated using the secondary controller in *dq* frame are transformed to *αβ* frame and fed to the error compensation blocks of each DG primary controller. Afterwards, in order to compensate the sharing errors a set of proportional (P) controllers are applied for fundamental and main harmonic circulating currents. These P controllers can be also considered as circulating current compensators like the virtual resistances [17]. By multiplying the P controllers output by the load distribution factor, the reactive fundamental power and harmonic current sharing errors compensation effort will be proportionally shared according to the its rated capacity. It is important to note that in order to have correct performance of the harmonic sharing block; output of the P controller related to 5th harmonic order must be applied with a negative sign, considering the rotation of this component in negative sequence. Finally, the reactive power and harmonic current sharing errors compensation signals are independently added to fundamental and harmonic voltage references, respectively. With the modification of the voltage references, accurate reactive power and harmonic current sharing can be proportionally achieved. It should be noted that unlike the conventional virtual impedance schemes, since the proposed compensation loops are applied in the feedback paths of fundamental and harmonic circulating currents instead of the large linear and nonlinear loads currents, the proposed control strategy effect on the amplitude and waveform quality of DGs' voltage is insignificant.

Table I: Power stage and control system parameters

System Parameter	Value
LCL Filter	L_1=1.8mH, C_f=27μF, L_2=1.8mH
DC Link Voltage	V_{DC} = 650 V
DG Feeder Impedance	Z_{F1}= 0.2Ω + j1.13Ω, Z_{F2}= 0.3Ω + j1.69Ω, Z_{F1}= 0.1Ω + j0.566Ω
Nonlinear Load Tie Line	Z_L= 0.1Ω + j0.566Ω
Nonlinear Load	C_{NL} = 235μF, L_{NL} = 0.84μH, R_{NL1} = 200Ω, R_{NL2} = 100Ω
Linear Load	Z_1 = 30Ω + j3.14Ω, Z_2 = 50Ω + j9.43Ω
Power and Voltage Controllers Parameters	**Value**
$m_{P3} = 2m_{P1} = 2m_{P2}$, $m_{I3} = 2m_{I1} = 2m_{I3}$, $n_{P3}=2n_{P1}= 2n_{P2}$	4×10^{-5}, 4×10^{-4}, 0.2
k_{pF}, k_{if}, ω_C	1, 1000, 2
k_{pH}, k_{i5}, k_{i7}	1, 600, 800
Reactive Power and Harmonic Current Sharing Controller Parameters	**Value**
k_P^{+1}, k_P^{-5}, k_P^{+7}	50, 100,100

Simulation Results

To verify the performance of proposed approach, a three-phase islanded microgrid has been established as the system test using MATLAB/Simulink. As shown in Fig. 4, the simulated microgrid consists of three voltage-controlled DG units with LCL filters and different power ratings. To demonstrate the effectiveness of the proposed control in general case, two types of loading are considered in the studied system as local and common loads. The PCC common loads comprise both linear and nonlinear loads and a nonlinear load is locally placed at terminal of DG1 unit. A diode rectifier and a star-connected *RL* load are adopted as the nonlinear and linear loads, respectively. DG1 and DG2 have the same nominal powers and are rated at double capacity comparing to DG3 (S_1=S_2=2S_3). Due to their power rating, three DG units shall share the total loads proportionally. The microgrid is rated at 210V (phase rms voltage) and 50Hz. Parameters of the power stage and control system are provided in Table I. As it can be seen in Table I, asymmetrical DG tie lines are assumed. Three simulation steps are considered:

- Step 1 ($0 \leq t \leq 2$s): DGs operate with only droop-based power and voltage controllers and reactive and harmonic currents sharing control schemes are not acting.

- Step 2 (2 ≤ t ≤ 4s): Hierarchical control scheme for reactive power and harmonic currents sharing is activated.
- Step 3 (4 ≤ t ≤ 6s): Load changes are applied.

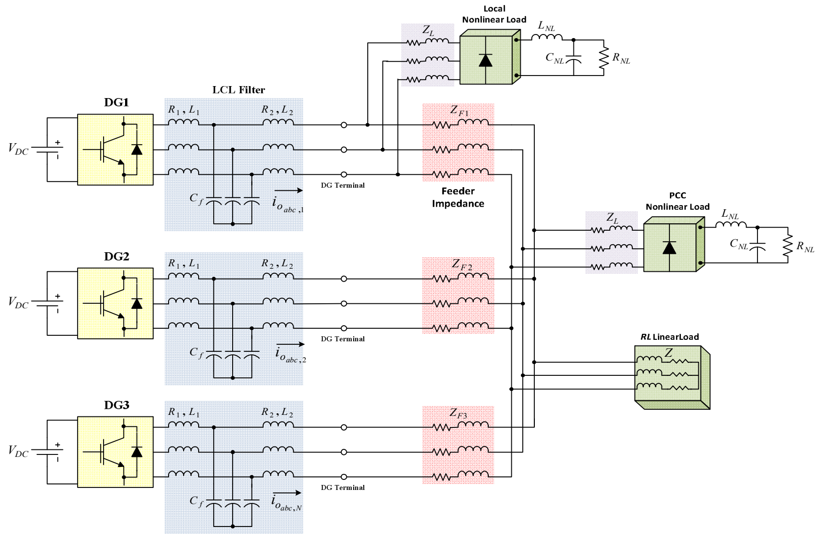


Fig. 4: Test system configuration for simulation studies

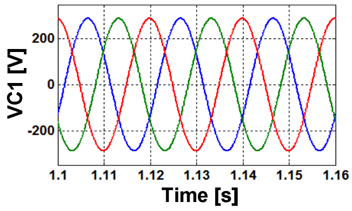
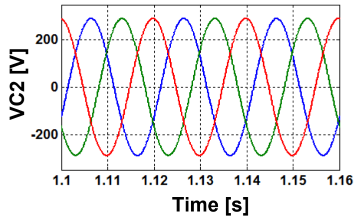
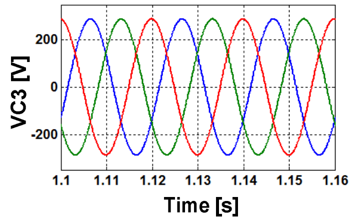
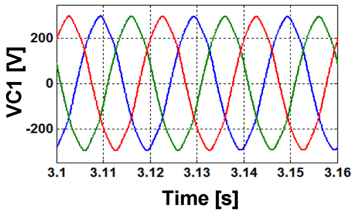
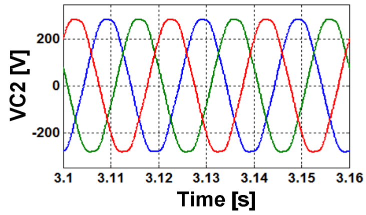
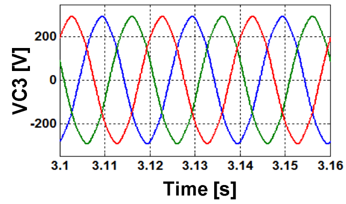
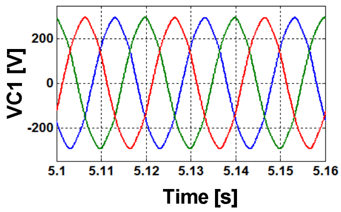
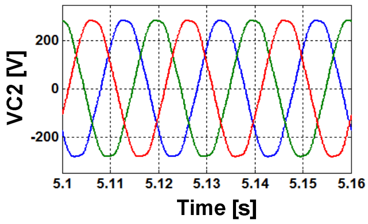
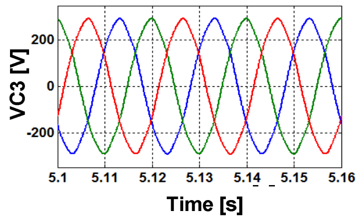
Step 1

As it can be observed in Table II, before activating the reactive power and fundamental current sharing loops, DGs output voltages are free of distortion. It indicates the effectiveness of fundamental and harmonic voltage controllers in tracking the voltage references with the presence of intensive nonlinear loads. Fig. 5 shows the sharing of P^+ and Q^+ among DGs throughout the under-study steps. But, as seen in Fig. 6, due to the feeder impedances asymmetries, there are significant errors in the proportional reactive power considering the DGs ratings. As mentioned before, the active power flow of the DG units are proportionally shared with the droop control method so that DG1 and DG2 have same active powers and are twice of the amounts of DG3 active power. Table III demonstrates the main harmonic of DGs output currents and circulating currents among them related to “a” phase in all steps of the study. It is obvious that before activating the proposed harmonic current sharing strategy, owing to mismatches of the DGs equivalent harmonic impedance, the load harmonic currents are not properly shared. Consequently, as it can be seen in Table III, the circulating harmonic currents will flow among DG units. Briefly, the above explanations reveal that the conventional droop control brings some reactive power and harmonic currents sharing errors.

Step 2

In simulation step 2, the reactive power and harmonic currents sharing errors compensation loops are activated at t = 2 s. As seen in Table 2, unlike the conventional virtual impedance-based droop control schemes, where reactive power and harmonic current sharing are realized at the expense of introducing additional voltage drops and distortions, the proposed control strategy effect on the amplitude and waveform quality of DGs’ voltage is negligible. This fact can be justified due to that the proposed control loops are provided in the feedback paths of fundamental and harmonic circulating currents instead of the large and nonlinear loads currents. Furthermore, it can be observed in Fig. 5 that reactive powers sharing errors are accurately compensated and proportionally shared. In addition, as seen in Table 3, the harmonic currents sharing are improved noticeably in proportion to the DGs’ rated powers. It means that the harmonic currents of the loads which are supplied by the DG1 and DG2 are approximately twice of the amounts of DG3. As a result, the harmonic circulating currents among DG units are approximately zero, as illustrated in Table 3.

Table II: DGs output voltage waveforms at different simulation steps

	DG1 Output Voltage	DG2 Output Voltage	DG3 Output Voltage
Step1			
Step2			
Step3			

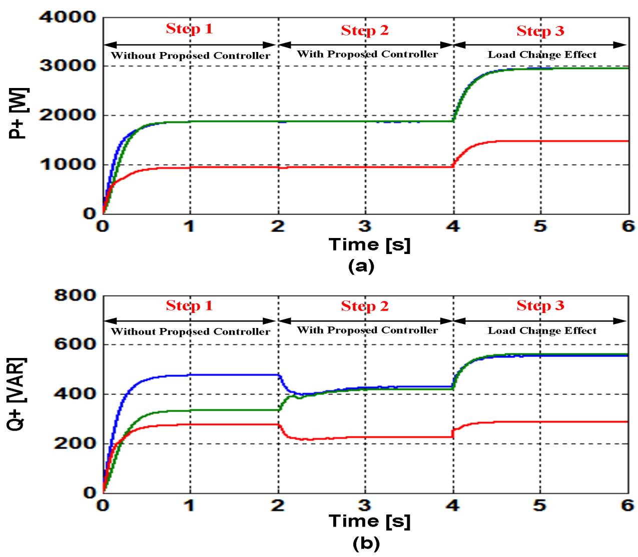
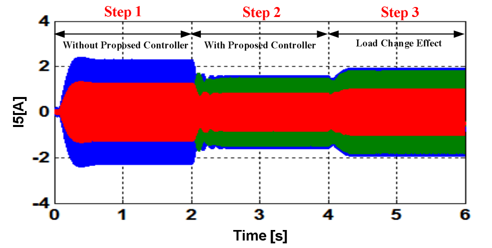
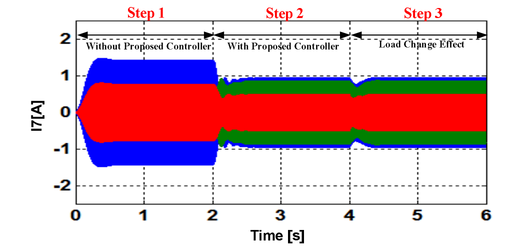
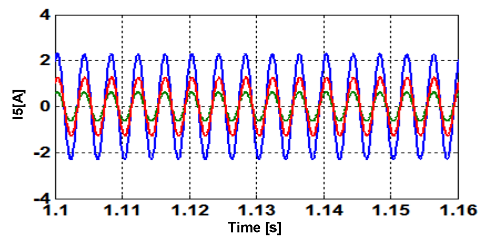
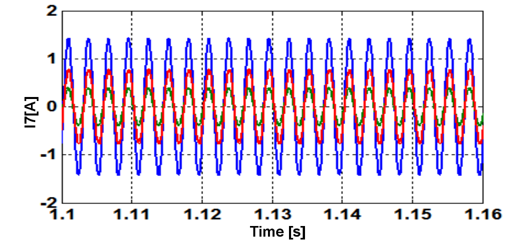
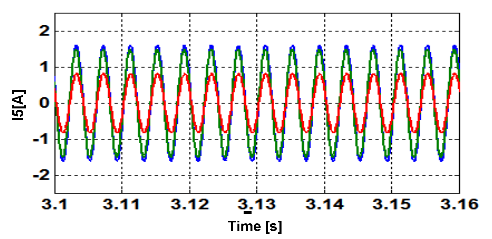
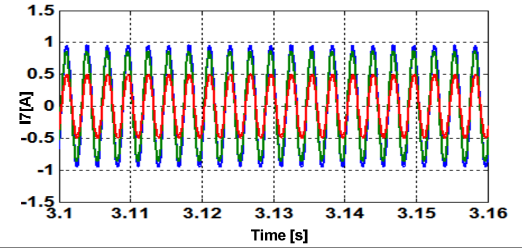
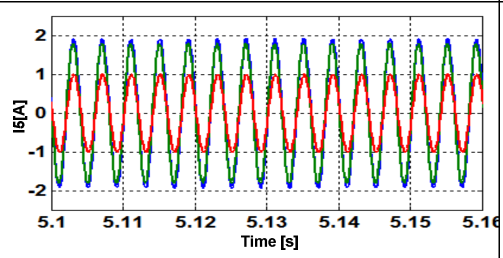
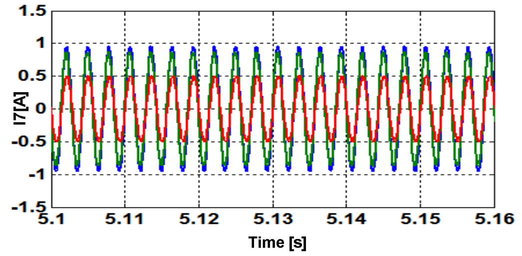
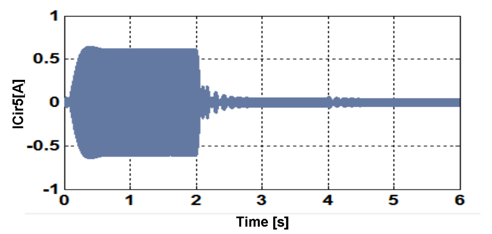
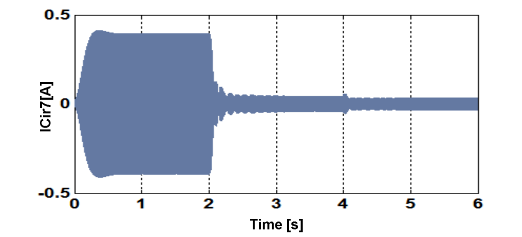


Fig. 5: (a) Fundamental active power, (b) fundamental reactive power (Blue: DG1, Green: DG2, Red: DG3).

Step 3

In order to demonstrate the flexibility of the proposed reactive power and harmonic currents sharing control approach, in the simulation step 3 at $t = 4$ s, the changes in loading conditions are applied. As seen in Table I, the values of the local nonlinear load and PCC linear and nonlinear loads are changed. It is clear from Table I that using the presented control method; the load changes would have negligible impacts on the amplitude and waveform quality of DGs' voltage. In addition, the accurate active and reactive power sharing tracking are achieved even if different loading conditions as illustrated in Fig. 5. Moreover, it can be also observed in Table III that the harmonic currents of the load are accurately shared in proportion to the DGs' rated powers without being influenced by changes in the system loads. The harmonic circulating currents among parallel DG units will remain approximately zero, as seen in Table III.

Table III: Harmonic components of 'a' Phase output and circulating currents

	5th harmonic (Blue: DG1, Green: DG2, Red: DG3)	7th harmonic(Blue: DG1, Green: DG2, Red: DG3)
General Steps		
Step1		
Step2		
Step3		
Circulating Current		

Conclusion

In this paper, a reactive power and harmonic currents accuracy sharing strategy that employs hierarchical control scheme based on control of the instantaneous circulating currents including the primary and secondary controllers has been proposed and validated for paralleled voltage-controlled DG inverters in three-phase islanded microgrids. Prominent advantage of the proposed load sharing errors compensation method compared to the conventional virtual impedance techniques is that the output voltage waveform quality of DG units is not noticeably affected; Since the proposed sharing loops embedded in the feedback paths of fundamental and harmonic circulating currents instead of the linear and nonlinear loads currents without any knowledge of the mismatched feeder impedances. As a consequence, the proposed control approach is straightforward to implement in practice. Furthermore, accurate reactive power and harmonic currents sharing performance is obtained even if the nonlinear load is placed locally at the output of DG units. Control system design is explained in detail and simulation results are provided to demonstrate the effectiveness of the proposed control method.

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