

An Enhanced Instantaneous Circulating Current Control for Reactive Power and Harmonic Load Sharing in Islanded Microgrids

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Abstract

To address the inaccurate load demand sharing problems among parallel inverter-interfaced voltage-controlled distributed generation (DG) units in islanded microgrids (MGs) with different DG power ratings and mismatched feeder impedances, an enhanced voltage control scheme based on the active compensation of circulating voltage drops is proposed in this paper. Using the proposed strategy, reactive power and harmonic currents are shared accurately and proportionally without knowledge of the feeder impedances. Since the proposed local controller consists of two well-separated fundamental and harmonic voltage control branches, the reactive power and harmonic currents can be independently shared without having a remarkable effect on the amplitude or quality of the DGs voltage, even if nonlinear (harmonic) loads are directly connected at the output terminals of the units. In addition, accurate load sharing can also be attained when the plug-and-play performance of DGs and various loading conditions are applied to MGs. The effects of communication failures and latency on the performance of the proposed strategy are also explored. The design process of the proposed control system is presented in detail and comprehensive simulation studies on a three-phase MG are provided to validate the effectiveness of the proposed control method.

Key words: Circulating currents, Islanded MG, Reactive power and harmonic currents sharing, Voltage-controlled DG

I. INTRODUCTION

Since most distributed generations (DGs) are linked to a power distribution system via power electronics interfaces, the coordinated control of these interfacing converters is crucial for ensuring the robust interconnection of DGs [1], [2]. Accordingly, the microgrid (MG) notion has emerged as an appealing approach for forming future smart distribution

grids [3]. When compared with the traditional power distribution systems, the islanding performance capability of MGs can enhance the quality and availability of the power supplied to customers [4].

In the islanding mode, in addition to the direct frequency and voltage support by inverter-interfaced DG systems, the total load in the MG must also be shared among the DGs in proportion to their power ratings [5]-[7]. To achieve this and to enhance the reliability of MG systems, the voltage-controlled DG inverter is mainly managed by cooperative and decentralized frequency and voltage droop control methods [5]-[8], thanks to the faster responses due to local measurements. However, recently, communication has been used for further improvement of MG performance without reducing reliability [9]-[11]. This is significant progress in terms of achieving a standard MG performance,

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similar to what has been achieved for large power systems [10].

By adopting a proper frequency droop method, accurate proportional active power sharing is always obtained. In contrast, reactive power cannot be accurately and proportionally shared by only the voltage droop technique due to a mismatch in the feeder impedances between the DGs and the loads considering the different ratings of the DG units [12]-[14]. Additionally, in a MG with intensive nonlinear loads, the conventional droop control method presents poor harmonic currents sharing and leads to circulation of the harmonic currents among the DG units [7]. The mitigation of circulating currents is a precondition for maintaining the stability of an islanded MG and for increasing the quality of demand load sharing. In conclusion, overcoming the inaccurate sharing of the reactive power and harmonic currents in droop-controlled islanded MGs is a very important and essential issue.

Since DGs interfacing inverters commonly have a wider high control bandwidth than distributed synchronous generators, they can provide coordinated ancillary services such as load sharing accuracy enhancement via regulating control references without using any additional equipment. To this end, many control methods [12]-[19] have been developed for the inverter-interfaced voltage-controlled DGs in islanded MGs. Regarding virtual impedance-based techniques [12]-[16], load sharing improvement is achieved by the compensation of the asymmetric closed-loop output impedances of the inverters and mismatched feeder impedances in a lossless circuit-oriented control way. In [11]-[13], the presented approaches are based on the presumption that the feeder impedances are small and that they are dominated by the virtual impedance at the fundamental frequency [15], [19]. Meanwhile, a practical power-electronics-based weak LV islanded MG can include multiple VSI-based DG units and loads that are connected together through large mismatched feeder impedances with wide variations due to the use of low power transformers and long feeder wires. In this case, if the feeder impedances are large, unknown and change over a wide range, very large virtual impedances are needed to mitigate reactive power sharing error, while the output voltage regulation and power sharing dynamics are inevitably affected [16].

Recently, communication has been used for the tuning of virtual impedances by utilizing the PCC voltage harmonics [15], [16] and compensation of the mismatch in the voltage drops across the feeders [14]. In addition, to achieve better harmonic currents sharing among parallel units, the DG equivalent harmonic impedance is adjusted by applying selective harmonic virtual impedance loops into the present DG voltage control loop. However, when using this technique, in addition to a deterioration of the DG output voltage quality, the harmonic frequency responses of the DGs feeder

impedance are also required; since the line inductance may weaken at the harmonic frequencies [15]. This means the assumption of a fixed physical feeder inductance at harmonic frequencies can result in a capacitive DG equivalent harmonic impedance due to over compensation. This issue can adversely affect the stability of a MG. Generally, in practice, due to the introduction of weaknesses such as additional voltage drops, significant harmonic distortions in the DG output voltage, high dependence on the estimation of the DGs feeder impedance at different frequencies and poor performance in the presence of local loads, the virtual impedance approaches still cannot be properly accepted. In [17], to increase the accuracy of the reactive power sharing, the output voltage of each DG is varied by adding two terms for voltage restoration and sharing error reduction. Nevertheless, it is difficult to adjust the coefficients of the terms in different DG ratings and to generalize this method for achieving proper harmonic currents sharing. By injecting a small transient active-reactive powers disturbance coupling term, an improved power sharing strategy using an error estimation of reactive power sharing was proposed in [18]. The sharing error is then eliminated by an integral controller. However, due to the event-triggered-based control, its stability cannot be easily insured. Moreover, load variations during the compensation process may result in undesired power sharing [14]. A hierarchical control method to proportionally share reactive power and harmonic currents was recently proposed in [19]. In this method, the load sharing errors are compensated by the control of instantaneous circulating currents through a series of proportional controllers that can only be considered as virtual circulating resistances, not as virtual circulating inductances. Hence, in this way, to achieve accurate nonlinear load sharing and to reduce the harmonic circulating current among the DGs in islanded MGs with large inductive feeder impedances, very large proportional controller coefficients are required. However this may jeopardize the system stability and compromise the voltage quality of the DGs. This issue is due to the fact that the harmonic circulating currents, which appear owing to the mismatch of the DG equivalent harmonic impedances corresponding to the DG rated powers, cannot be effectively mitigated by only small proportional gains. In addition, the effects of communication failures and latency, as well as the plug and play capability of the DG units to validate effectiveness and flexibility of the method proposed in [19] have not been studied.

In response to these problems, this paper proposes an enhanced voltage control scheme based on the active compensation of the dominant circulating voltage drops. This is done to improve the load sharing accuracy and to mitigate the fundamental and harmonic circulating currents among voltage-controlled DGs in islanded MGs. The enhancement of reactive power and harmonic load sharing is achieved

without knowledge of the feeder impedances and without having a significant impact on the amplitude or quality of the DGs voltage, even when nonlinear loads are placed locally at the output of the units. In addition, the performance of the proposed load sharing control strategy is validated under several practical case studies. These studies are carried out in the MATLAB/SimPower Systems Toolbox, including the plug-and-play performance of DGs, and load changes. One of the main challenges related to the control of MGs is the plug-and-play functionality of DGs. DGs are frequently added to and leave power generation systems due to the availability and intermittency of renewable energies, such as sunlight and wind, increases in energy demand, faults, maintenance, and so on [20]. Under this operation, different DGs are arbitrarily plugged-into or pulled-out from MGs. However, the feasibility and performance of the proposed control method to provide faster transients without creating instability in the system should be evaluated. This concept is called Plug-and-Play capability. By fulfilling this important feature, the automatized and stability of islanded MGs is always preserved [21]-[23]. In addition, the effects of communication failures and latency on the presented load sharing method are also investigated.

The rest of this paper is organized as follows. The proposed control structure for a three-phase islanding MG with multiple voltage-controlled DG units is explained in Section II. Section III provides details of this structure and the design of the proposed load sharing improvement strategy. To verify the effectiveness of this load sharing method, comprehensive simulation studies are shown and discussed for an islanded three-phase MG in Section IV. Lastly, this paper is concluded in Section V.

II. STRUCTURE OF THE PROPOSED CONTROLLER

Fig. 1 illustrates the proposed control scheme for three-phase islanding MGs, where N parallel inverter-interfaced DG units are connected to the PCC through LC filters and feeder impedances Z_{Fi} , which can include the impedances of an isolation transformer and feeder cables. Furthermore, the system consists of both linear and nonlinear loads which can be placed at the common AC bus (PCC) and locally at the DG output terminal. As shown in Figs. 1 and 2, in the proposed control scheme, the output current fundamental and main harmonics components for each of the DG inverters are extracted at the DGs local controllers and sent to the “*Circulating Currents Calculation*” block in the dq frame by means of a low bandwidth communication (LBC) bus. The LBC can be provided at a relatively low cost and applied to prevent dependence on high bandwidth availability which may adversely affect the system stability [19], [24]. Using this information, instantaneous circulating currents at different frequencies are calculated and

transmitted back to the local controllers in the dq frame. More details regarding the “*Circulating Currents Calculation*” block will be discussed in Section III.B. The superscripts “+1,” “-5” and “+7” exhibit the fundamental positive sequence and the main harmonic components that include the fifth harmonic negative sequence and seventh harmonic positives sequence. In most studies related to the selective harmonic compensation approaches [16], [24]-[26], the fundamental, the 5th and 7th harmonics are usually considered as the compensation main harmonics. Moreover, for special distorting loads, such as a three-phase diode rectifier under balanced conditions, which has been selected as a nonlinear load in this paper, the 5th and 7th harmonics have only negative and positive sequence components, respectively [26].

As shown in Fig. 2, the instantaneous fundamental and main harmonics circulating currents are then transformed to the $\alpha\beta$ frame and fed to the “*Reactive Power and Harmonic Currents Sharing Error Compensation*” blocks, to generate the updated voltage reference signals so that they can virtually compensate the fundamental and selective harmonics circulating voltage drops. Finally, the outputs of these compensation blocks are injected as a reference for DG fundamental and harmonics voltage controllers. In this way, the mitigation of circulating currents and accurate reactive power and harmonic currents sharing among DGs can be achieved without knowledge of feeder impedances. Furthermore, as is evident from Fig. 2, the DGs local controller is composed of an enhanced voltage control scheme with two parallel decoupled control branches in order to independently share the reactive powers and harmonic currents. The first voltage control branch is responsible for controlling the DG fundamental voltage and sharing improvement of the steady-state reactive power, and the second branch is used to eliminate the DG output voltage harmonics and to enhance the harmonic currents sharing accuracy among the DG units. The proposed load sharing improvement strategy is discussed in detail in the next Section.

III. PROPOSED CONTROLLER STRATEGY FOR COMPENSATION OF LOAD SHARING ERRORS

In this section, the design and performance of the proposed improved voltage control scheme-based load sharing errors compensation method are presented in detail. This can be achieved without knowledge of the physical feeder impedances values and loading conditions. This feature is very important for achieving the “plug-and-play” operation of DGs and loads in the MG applications.

A. Voltage Controllers Design

As is clear from Fig. 2, the local control system is designed and implemented in the $\alpha\beta$ frame. Thus, the well-known

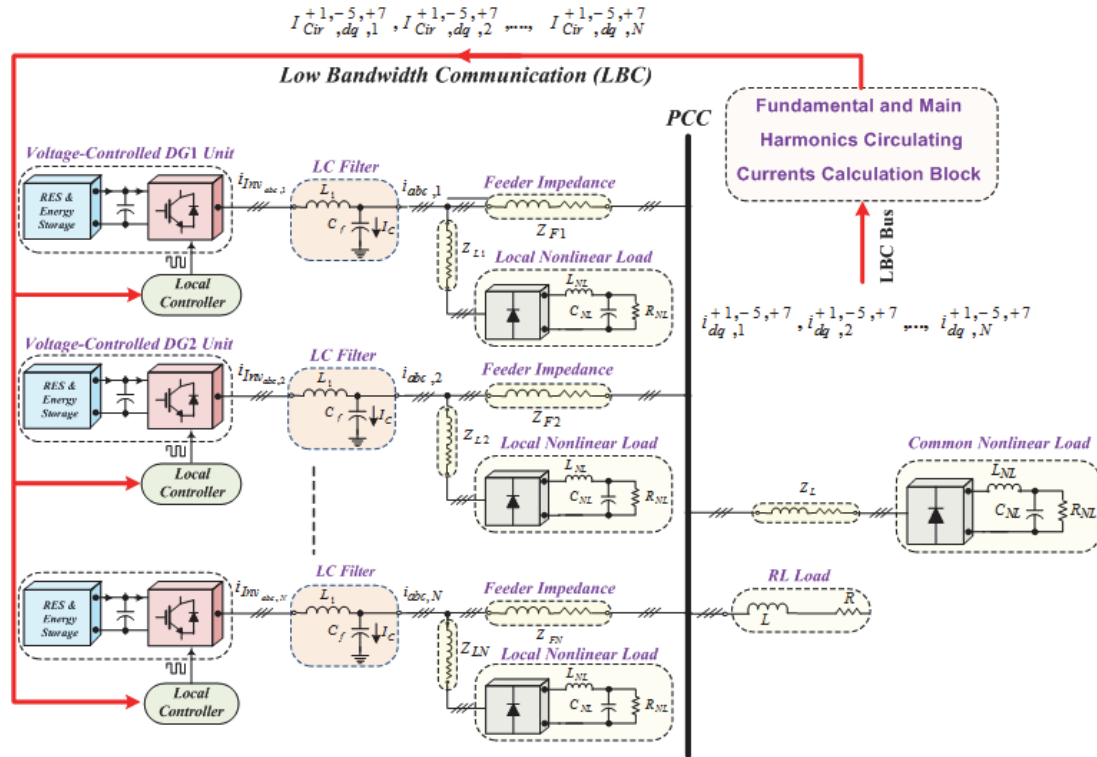


Fig. 1. Proposed control structure for a three-phase islanding MG with multiple voltage-controlled DG units.

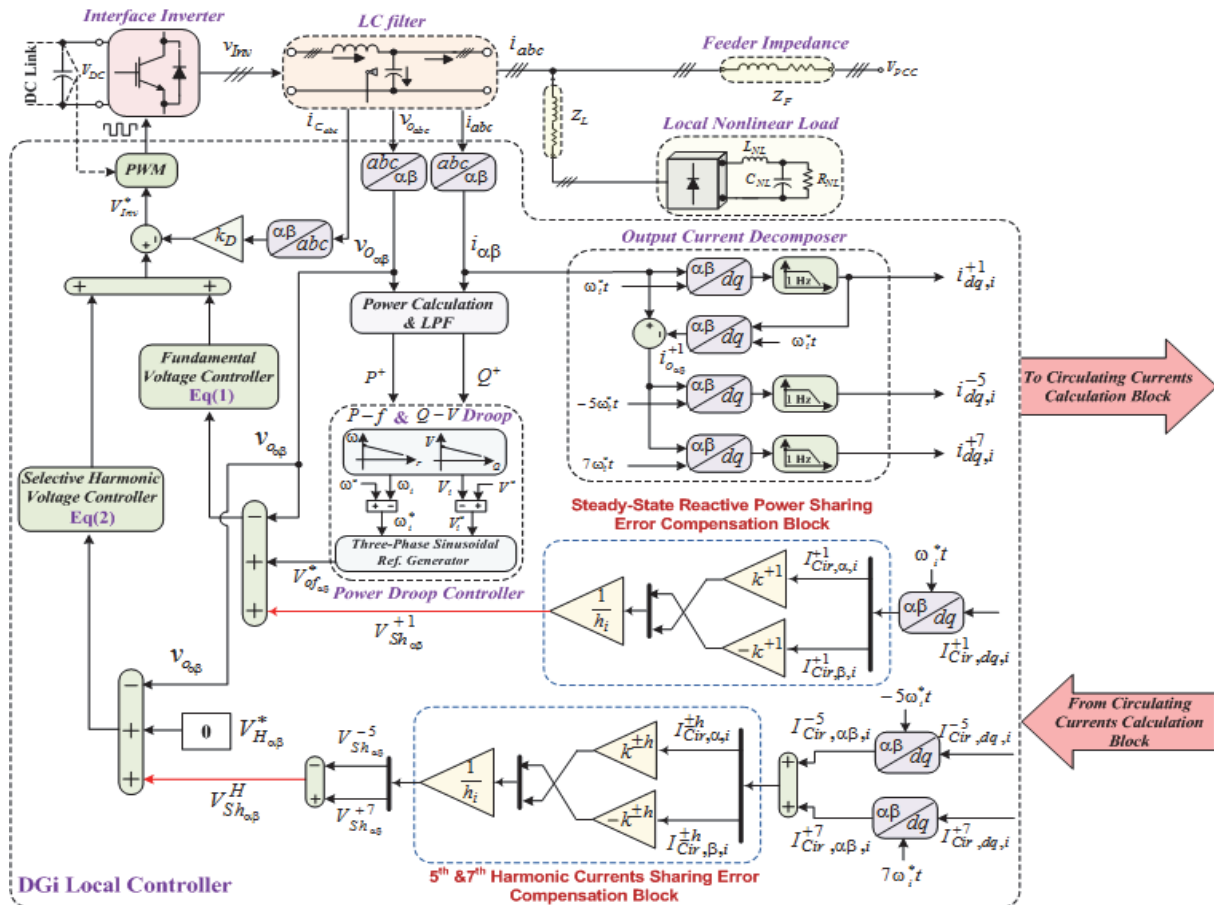


Fig. 2. Block diagram of the proposed local control system.

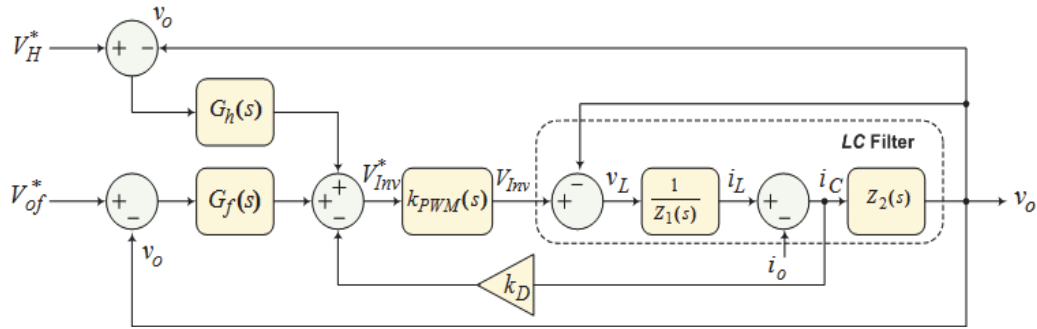


Fig. 3. Block diagram of presented DG closed-loop voltage control system.

Clarke transformation can be used to transform the variables between the abc and $\alpha\beta$ coordinates [24]. The primary function of the voltage-controlled DGs is to participate in the regulation of the grid voltage amplitude and frequency close to their rated values by controlling the active and reactive power delivered to the grid [27]. Therefore, droop control methods are mainly adopted for adjusting the fundamental reference values of the DG output voltage angular frequency (ω^*) and amplitude (V^*) according to the control of the power flows. Details and additional explanation of the power droop controller design and fundamental powers calculation have been sufficiently presented in [6], [12] and will not be repeated here. Consequently, with knowledge of the fundamental voltage reference parameters, the DG instantaneous sinusoidal reference voltage can be easily obtained through a three-phase reference generator, as shown in Fig. 2.

To ensure accurate voltage tracking and to avoid any interference between the performance of the reactive power and the harmonic currents sharing error compensation loops, an improved voltage control method based on independent control of the fundamental and harmonic components is realized in this paper. Thus, with regard to this matter, the conventional cascaded double-loop controller structure [6], [24] is not useful for the proposed control scheme. In addition, since droop-based DG output power flows are obtained through regulation of the filter capacitor fundamental voltage, the control of this component can be realized only by a fundamental proportional-resonant (PR) controller ($G_f(s)$). High bandwidth PR controllers are commonly preferred for the control of voltage and current disturbance variables in the $\alpha\beta$ frame, due to the difficulties experienced when using PI controllers to track non-dc variables [6]. Meanwhile, to provide further harmonic compensation of the filter capacitor voltage against intensive nonlinear loads, parallel main harmonics PR controllers ($G_h(s)$) are also considered. These controllers can be defined as follows [24]:

$$G_f(s) = k_{pf} + \frac{2k_{if}\omega_c s}{s^2 + 2\omega_c s + (\omega^*)^2} \quad (1)$$

$$G_h(s) = k_{ph} + \sum_{h=5,7} \frac{2k_{ih}\omega_c s}{s^2 + 2\omega_c s + (h\omega^*)^2} \quad (2)$$

Where k_{pf} , k_{ph} , k_{if} and k_{ih} are the fundamental and harmonic proportional and resonant coefficients, ω_c is the cutoff frequency, and ω^* is the fundamental angular frequency which is generated by the active power droop controller. It is worth noting that the presence of the high-order harmonic compensators of the PR controller requires a remarkable voltage control system bandwidth, otherwise it may lead to system instability [28]. In addition, for precise tracking of the fundamental voltage reference, the voltage harmonic reference ($V_{H,\alpha\beta}^*$) set to 0, as shown in Fig. 2. A simple proportional control loop k_D is also used to further improve the stability and dynamic response of the DG control system [28]. It has been demonstrated that filter capacitor current feedback provides better damping performance in the introduction of the virtual damping term than inverter-side inductance current feedback [30], [31]. As a result, the inverter voltage reference signal can be determined as:

$$V_{inv}^*(s) = G_f(s) \cdot (V_{of}^* - v_o) + G_h(s) \cdot (0 - v_o) - k_D \cdot i_C \quad (3)$$

It is obvious from (3) that the proposed voltage control scheme includes of three parallel control branches, where the first voltage control branch is used to realize the closed-loop control of the fundamental capacitor voltage, the second voltage control branch aims to regulate the DG output harmonic voltage, and the third branch k_D is an active damping term. By modifying the voltage references of the two voltage control branches, as will be examined later, the load sharing errors can be effectively compensated. As a result, by considering (3), a block diagram of the presented closed-loop voltage control structure can be depicted as Fig. 3. Z_1 and Z_2 are the output filter components impedance and $k_{PWM}(s)$ is considered as a PWM delay [6], which can be expressed as follows, respectively:

$$Z_1(s) = L_1 s + R_1 \quad (4)$$

$$Z_2(s) = 1/sC_f \quad (5)$$

$$k_{PWM}(s) = 1/(1 + 1.5T_s s) \quad (6)$$

where T_s is the sampling time. Thus, based on Fig. 3, the closed-loop performance of the DG control system can be obtained like a Thevenin equivalent circuit, as:

$$v_o(s) = G_{CL-f}(s) \cdot V_{of}^*(s) + G_{CL-h}(s) \cdot V_H^*(s) - Z_o(s) \cdot i_o(s) \quad (7)$$

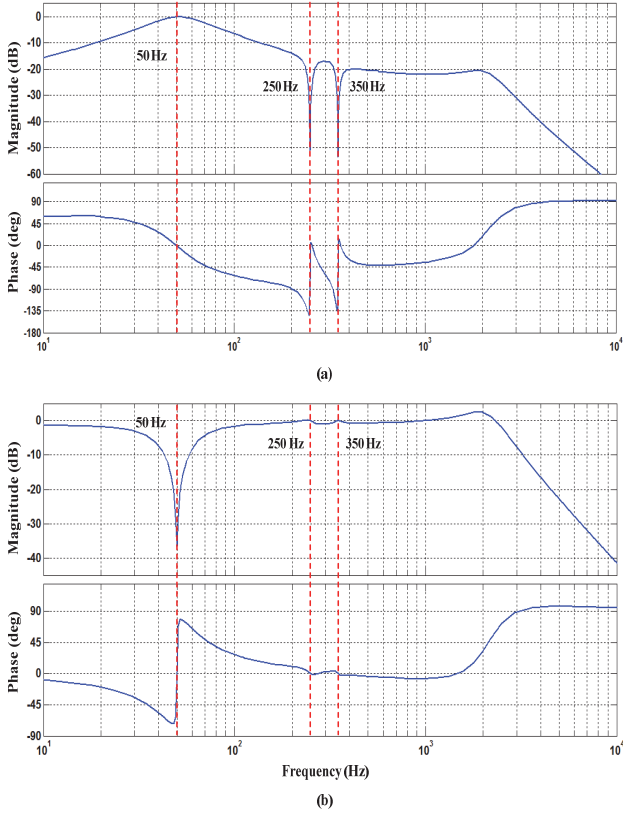


Fig. 4. Bode plots of closed-loop voltage tracking transfer functions: (a) fundamental transfer function ($G_{CL-f}(s)$); (b) main harmonics transfer function ($G_{CL-h}(s)$).

where $G_{CL-f}(s)$ and $G_{CL-h}(s)$ are closed-loop transfer functions of the fundamental and harmonic voltage references, respectively. In addition, $Z_o(s)$ represents the control system closed-loop equivalent output impedance. To design the control system parameters at the fundamental and main harmonics frequencies according to the closed-loop dynamics of the control system, Mason's theorem can be applied. Thus, the closed-loop transfer functions and equivalent output impedance are derived from Fig. 3, and expressed as equations (8) to (10).

Fig. 4 depicts Bode plots of closed-loop transfer functions using the values listed in Table I. As seen in Fig. 4(a), the gain and phase angle, are unity and zero at the fundamental frequency. At the same time, the main harmonics components have zero gain. In addition, Fig. 5 illustrates the magnitude plot of the inverter closed-loop equivalent output impedance.

$$G_{CL-f}(s) = \frac{v_o(s)}{V_{of}^*} \Big|_{i_o(s)=V_{Hf}^*(s)=0} = G_f(s) \cdot k_{PWM}(s) \cdot Z_2(s) / (k_{PWM}(s) \cdot Z_2(s) \cdot (G_f(s) + G_h(s)) + k_{PWM}(s) \cdot k_D + Z_1(s) + Z_2(s)) \quad (8)$$

$$G_{CL-h}(s) = \frac{v_o(s)}{V_H^*(s)} \Big|_{i_o(s)=V_{of}^*(s)=0} = G_h(s) \cdot k_{PWM}(s) \cdot Z_2(s) / (k_{PWM}(s) \cdot Z_2(s) \cdot (G_f(s) + G_h(s)) + k_{PWM}(s) \cdot k_D + Z_1(s) + Z_2(s)) \quad (9)$$

$$Z_o(s) = \frac{v_o(s)}{-i_o(s)} \Big|_{V_{of}^*(s)=V_{Hf}^*(s)=0} = Z_2(s) \cdot Z_1(s) / (k_{PWM}(s) \cdot Z_2(s) \cdot (G_f(s) + G_h(s)) + k_{PWM}(s) \cdot k_D + Z_1(s) + Z_2(s)) \quad (10)$$

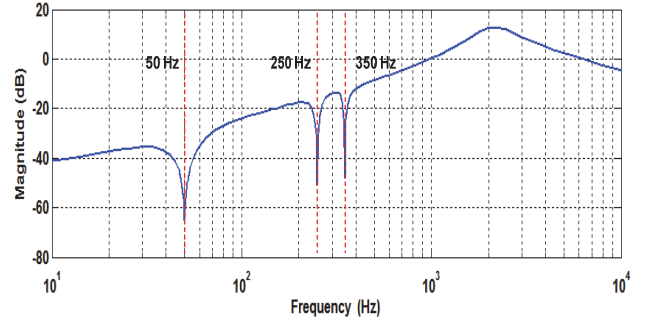


Fig. 5. Magnitude plot of DG inverter closed-loop equivalent output impedance.

It can be observed that the magnitudes are approximately zero at the fundamental and main harmonics frequencies. Thus, accurate tracking of the fundamental voltage reference is guaranteed without having any interaction with the harmonic voltage reference tracking loop. A similar description can be expressed for the Bode plot of the closed-loop main harmonics transfer function based on Fig. 4(b). Consequently, the presented voltage control method has more flexibility when compared with the conventional cascaded double-loop control in terms of adjusting the control parameters.

B. Load Sharing Error Compensation Strategy

To better understand the performance of the proposed load sharing error compensation loops, the notation of circulating currents is shortly described. The circulating currents between multiple parallel DG inverters with separate DC links are automatically raised whenever the inverters operate in different switching patterns owing to component tolerance and parameter drift [19], [31]. In addition, when multiple DGs are connected to the PCC through feeders with mismatched impedances, the fundamental and harmonic circulating currents increase which leads to unbalanced load sharing. The circulating current for each phase of a three-phase inverter is expressed as the difference between the actual output current and the allocated load current, which is given by [31] as:

$$I_{Cir_k,j} = I_{ok,j} - i_{ok,j} = h_j \cdot \sum_{m=1}^N I_{ok,m} - i_{ok,j}, \quad (11)$$

$$k \in \{a, b, c\}; \quad j \in \{1, 2, \dots, N\}; \quad \sum_{m=1}^N h_m = 1$$

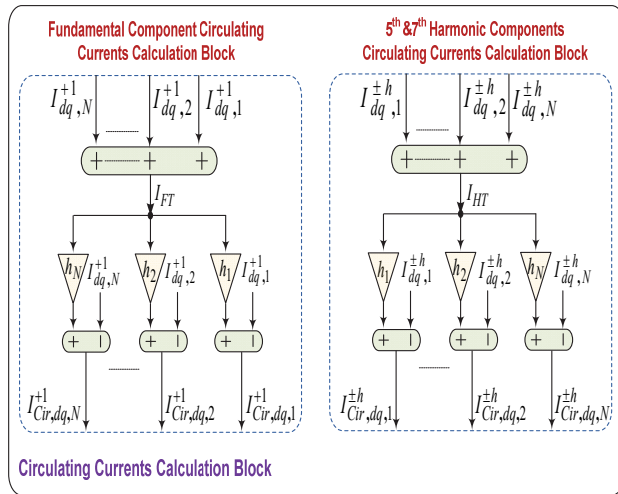


Fig. 6. Calculation of the fundamental and main harmonic components circulating currents.

TABLE I

POWER STAGE AND CONTROL SYSTEM PARAMETERS

System Parameters	Values
LC Filter	$R_f = 0.1 \Omega, L_f = 1.8 \text{mH}, C_f = 27 \mu\text{F}$
DC Link Voltage	$V_{DC} = 650 \text{V}$
Main grid	220V(phase RMS voltage) / 50 Hz
Switching Frequency	10 kHz
DG Feeder Impedance	$Z_{F1} = 0.1 \Omega + j0.566 \Omega,$ $Z_{F2} = 0.2 \Omega + j1.13 \Omega,$ $Z_{F3} = 0.1 \Omega + j0.566 \Omega$
Nonlinear Load Tie Line	$Z_L = 0.1 \Omega + j0.566 \Omega$
Nonlinear Load	$C_{NL} = 235 \mu\text{F}, L_{NL} = 0.84 \mu\text{H},$ $R_{NL} = 200 \Omega$ (Local), 100Ω (PCC) ($0 \leq t \leq 4\text{s}$), $R_{NL2} = 400 \Omega$ (Local), 200Ω (PCC) ($4\text{s} \leq t$)
Linear Load	$Z_{L1} = 100 \Omega + j15.7 \Omega$ ($0 \leq t \leq 4\text{s}$), $Z_{L2} = 80 \Omega + j9.42 \Omega$ ($4 \leq t$).
Power and Voltage Controllers Parameters	Values
$m_{P3} = 2m_{P1}$ $= 2m_{P2}n_{Q3} = 2n_{Q1} = 2n_{Q2}$	$10^{-4} \text{W/rd.s}, 0.02 \text{VA/r/V}$
$k_{pf5}, k_{if5}, \omega_C$	1, 1000, 2
k_{ph5}, k_{i5}, k_{i7}	15, 1000, 1000
k_D	20
Load Sharing Controller Parameters	Values
$k_1^{+1}, k_2^{+1}, k_3^{+1},$ $k_1^{\pm h}, k_2^{\pm h}, k_3^{\pm h},$	15, 30, 15, 20, 40, 20,

where $I_{Cir,kj}$ is the circulating current related to the j th DG inverter and k indicates the inverter phase. $i_{ok,j}, I_{ok,j}$ and h_j are the actual output current, the allocated load current and the load distribution factor, respectively. Assuming the DG $_j$ rated power and the total power loading of the DGs are S_j and S_T , the load distribution factor is expressed as

$$h_j = S_j / S_T = S_j / \sum_{m=1}^N S_m \quad (12)$$

The allocated load current for each DG unit is obtained by multiplying the total instantaneous load current and the corresponding load distribution factor, as shown in Fig. 6. It should be noted that in the harmonic unbalanced loading condition, the determination of the circulating current for each phase is similar to the presented method (see Fig. 6). However, in addition to taking the considered harmonic sequences into account, the fundamental negative sequence, the third harmonic positive and negative sequences, the fifth harmonic positive sequence, the seventh harmonic negative sequence, etc., should also be considered. It is obvious that to achieve proportional reactive power and harmonic current sharing among DG units with different ratings, the feeders' resistance and reactance at the fundamental and harmonic components must be changed to be inversely proportional to the P and Q ratings, respectively [12], [15]. As previously mentioned, one solution to this problem is to apply virtual fundamental and harmonic impedances to match the feeder impedances. However, in practice, due to the weaknesses introduced in the introduction section, this technique cannot be properly employed.

The other method to resolve this problem, as proposed in this paper, is to virtually compensate the instantaneous fundamental and main harmonics circulating voltage drops across DG feeders through circulating currents control in order to effectively reduce the steady-state reactive power and harmonic currents sharing errors. Hence, the extraction of the DG output current at the fundamental and main harmonics frequencies is essential for sending proper signals to the "Circulating Currents Calculation" block. Different types of harmonic signals decomposition methods have been presented in [32], [33]. However, detection based on the synchronous reference frame (SRF) can be considered as one of the best solutions [32]. It is obvious from Fig. 2 that the output current decomposer is readily realized by a Park transformation and a low-pass filter (LPF) at each frequency component. To better match the response of sharing errors compensation loops and the dynamics of droop-based power controllers, the cutoff frequencies of the LPFs adopted in the load current decomposer approach and the extraction of the average active and reactive powers are designed with the same values. Moreover, since harmonics are defined as periodic steady-state waveform distortions [35], the LPF cutoff frequency used for the detection of harmonic load current can be selected as a small value [34]. Hence, in the proposed sharing error compensation scheme, a first-order LPF with a 1Hz cutoff frequency is employed.

As a result, as seen in Fig. 6, according to the received information from the local controllers and based on (11) and (12), the instantaneous fundamental and main harmonics circulating currents are calculated and send to the local

control level for each of the DGs, as shown in Fig. 2. Then, this data is transformed to the $\alpha\beta$ frame and fed to the load sharing error compensation blocks. It is noteworthy that to facilitate the use of the droop control method in low voltage distribution systems, an actual and/or a virtual interface inductor is added at the DG output in an effort to decrease the coupling between the active and reactive power flows. Thus, with regard to this issue and due to the dominant asymmetric inductive impedances at the main harmonics, a set of proportional (P) controllers with a 90° leading phase-shifting, which can be considered as virtual circulating impedances, are then applied for the fundamental and main harmonic circulating currents (see Fig. 2). These controllers can be considered as instantaneous circulating voltage drop compensators. In other words, the proposed load sharing error compensation loops are embedded in the paths of the fundamental and harmonic circulating currents feedback instead of the large linear and nonlinear loads currents, which are already considered in the conventional virtual impedance methods. Thus, by controlling the instantaneous circulating currents, the instantaneous fundamental and main harmonics voltage drops due to circulating currents across the DG feeders that lead to substantial load-sharing errors, are effectively compensated. It should be noted that the MG becomes unstable if an integral term is added to the P controllers. Through multiplying the controllers output by the inverse of the corresponding load distribution factor, the load sharing error compensation effort will be proportionally shared based on the DGs rated capacity. Finally, the load sharing error compensation signals are independently added to the fundamental and harmonic voltage control loops in order to simultaneously obtain accurate proportional reactive power and harmonic currents sharing. It is worth noting that this control method can be readily extended for sharing of unbalanced loads. Due to the rotation of 5th harmonic component in the negative sequence, the proposed controller output related to 5th harmonic must be inserted with a negative sign to achieve accurate current sharing at this harmonic component. Otherwise, it leads to a voltage drop which increases the circulating currents due to the reduction of the equivalent circulating impedance in this sequence. This, in turn, leads to instability of the system.

IV. SIMULATION RESULTS

The proposed reactive power and harmonic currents sharing improvement strategies are verified through Matlab/Simulink on a three-phase MG system which has been depicted in Fig. 1. The system under study consist three voltage-controlled DGs with LC filters at different ratings and mismatched feeder impedances. DG1 and DG2 have the same rated powers and twice the power capacity of DG3 ($S_1=S_2=2S_3$). To show the effectiveness and flexibility of the

proposed control in the general case, two types of loadings are regarded as local (at the output terminal of DG1) and common (at the PCC bus). A star-connected RL load and a three-phase diode rectifier are considered as linear and nonlinear loads, respectively. It should be noted that the type and bandwidth of the communication link should be carefully designed according to the control requirements. Since, the proposed load sharing strategy only needs to exchange information at a slow-rate, the LBC link is adequate for this application. In this way, the system is not dependent on high bandwidth availability which may adversely affect the system stability [37]. The needed information is sent to the circulating currents calculation block and DG local controllers using a zero-order hold block with a 1ms latency. The behavior of the LBC system in different delays is also emulated by using sample and hold blocks. In practice, communication mechanisms can be realized using smart metering protocols, power line signaling technologies, or the commercial infrastructure such as UDP/IP-based wired and wireless Ethernet links, Wi-Fi, ZigBee, and digital subscriber lines [13], [18], [38], and [39]. Since the focus of this paper is to present an enhanced reactive power and harmonic currents sharing scheme realized at the DG local controllers, further discussion on the communication system is beyond this scope.

The parameters of the power stage and control system used in the simulation are listed in Table I. To test the correctness of the proposed load sharing control method, four simulation cases have been considered:

- Case 1 ($0s \leq t \leq 2s$): The DGs are only operating based on the droop and voltage controllers.
- Case 2 ($2s \leq t \leq 4s$): The proposed load sharing schemes is activated.
- Case 3 ($4s \leq t \leq 6s$): The load changes applied.
- Case 4 ($6s \leq t \leq 10s$): The plug-and-play performance of the DG unit.

1) *Case 1* ($0s \leq t \leq 2s$): As can be seen in Figs.7(a), 7(c) and 7(e), before activating the proposed load sharing loops, the DGs output voltages are free of harmonic distortions. In addition, Table II shows the DGs output voltage total harmonic distortion (THD) for the first and second simulation steps. Thus, they indicate the effectiveness of the fundamental and harmonic voltage controllers in tracking the voltage references in the presence of severe nonlinear loads. Fig. 8 shows sharing of the fundamental active $P+$ and reactive $Q+$ among the DGs throughout the simulation cases. As expected and shown in Fig. 8(a), despite the asymmetry of the DGs feeder impedances corresponding to their power ratings, the active powers flow of the DGs are properly shared in the steady-state with the droop control method. However, as seen in Fig. 8(b), due to the mismatched feeder impedances, there are considerable errors in the steady-state reactive power sharing considering the DGs ratings. The

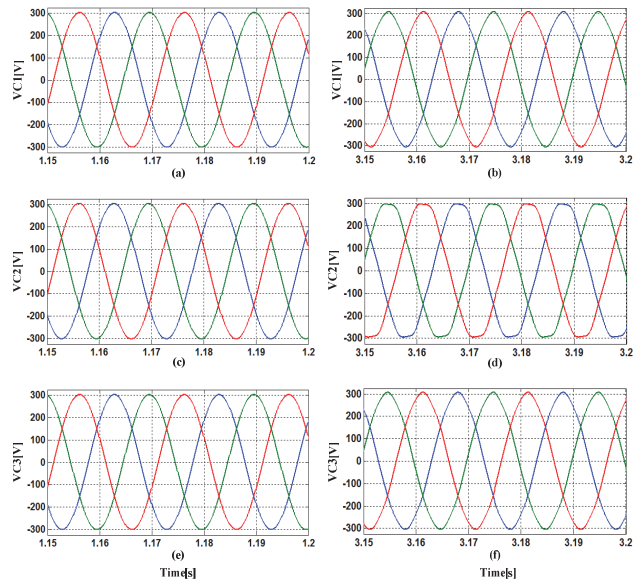


Fig. 7. Output voltages waveforms of DGs: (a) DG1 voltage in case 1; (b) DG1 voltage in case 2; (c) DG2 voltage in case 1; (d) DG2 voltage in case 2; (e) DG3 voltage in case 1; (f) DG3 voltage in case 2.

TABLE II
DGs VOLTAGE THDs IN THE SIMULATION CASES

	THD (%)		
	VC1	VC2	VC3
Case1	0.46	0.45	0.46
Case2	1.32	2.43	1.28

main harmonics of the DGs output currents related to the “A” phase in all of the cases of the simulation are shown in Fig. 9. It is obvious from Figs. 9(a) and 9(b) that before activating the proposed harmonic currents sharing strategy, owing to mismatches of the DGs equivalent harmonic impedances, the load harmonic currents are not proportionally shared. As can be seen in Figs. 10 and 11 (from 0 sec to 2 sec), the fundamental and harmonic circulating currents will flow from the “A” phase of the DG1. This fact can also be observed in Fig. 12, which indicates the three-phase output currents of the DGs. This figure clearly shows that the current waveforms of DG1 and DG2 are not the same and are twice the amount of DG3. Therefore, the above explanations reveal that the droop controllers bring significant reactive power and harmonic currents sharing errors due to mismatches in the DGs feeder and equivalent harmonic impedances.

2) *Case 2* ($2s \leq t \leq 4s$): In this case, the load sharing errors compensation loops are activated at $t = 2s$. When compared to the conventional virtual impedance-based droop control schemes, where load sharing is achieved at the expense of introducing additional voltage drops and distortions, the effects of the proposed load sharing control strategy on the amplitude and quality of the DGs voltage are insignificant according to the intended severe nonlinear loads (see Figs.

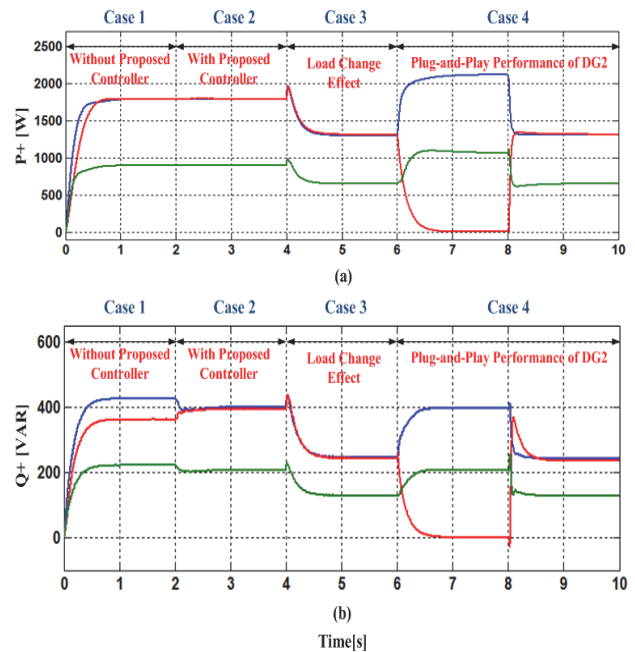


Fig. 8. Fundamental output powers of DGs: (a) Active powers; (b) Reactive powers (Blue: DG1, Red: DG2, Green: DG3).

7(b), 7(d), and 7(f)). Moreover, as shown in Table II, the DGs voltage THDs are in accordance with *IEEE* standards [34], where the voltage THD of a MG must be less than 2.5%. In very weak islanded MGs with very large physical feeder impedances, the THD voltage may increase. However, the proposed approach still outperforms the conventional virtual impedance techniques. This is due to the fact that the proposed load sharing errors compensation loops are adopted in the paths of the fundamental and main harmonic circulating current feedbacks instead of the large and nonlinear loads current in order to actively compensate the fundamental and main harmonics circulating voltage drops across the DGs’ feeder. Additionally, by using this strategy, the reactive powers sharing errors are effectively compensated and proportionally shared (see Fig. 8(b)). At the same time, as seen in Figs. 9(c) and 9(d), the harmonic current sharing is substantially improved in proportion to the DGs rated powers. This means that the harmonic currents of the loads supplied by DG1 and DG2 are approximately double that of DG3. As a result, the fundamental and harmonic circulating currents among DGs caused by the mismatched harmonic feeder impedances are approximately zero, as illustrated in Figs. 10 and 11. These results can also be viewed in Fig. 12. It is obviously shown that the current sharing errors are effectively mitigated and DG1 and DG2 have similar current waveforms and twice the amounts of DG3. Thus, these analyses demonstrate the effectiveness and correctness of the proposed reactive power and harmonic currents sharing loops.

3) *Case 3* ($4s \leq t \leq 6s$): To investigate transient performance of a MG based on the proposed load sharing method, in this simulation case, variations in loading which occur at $t = 4s$

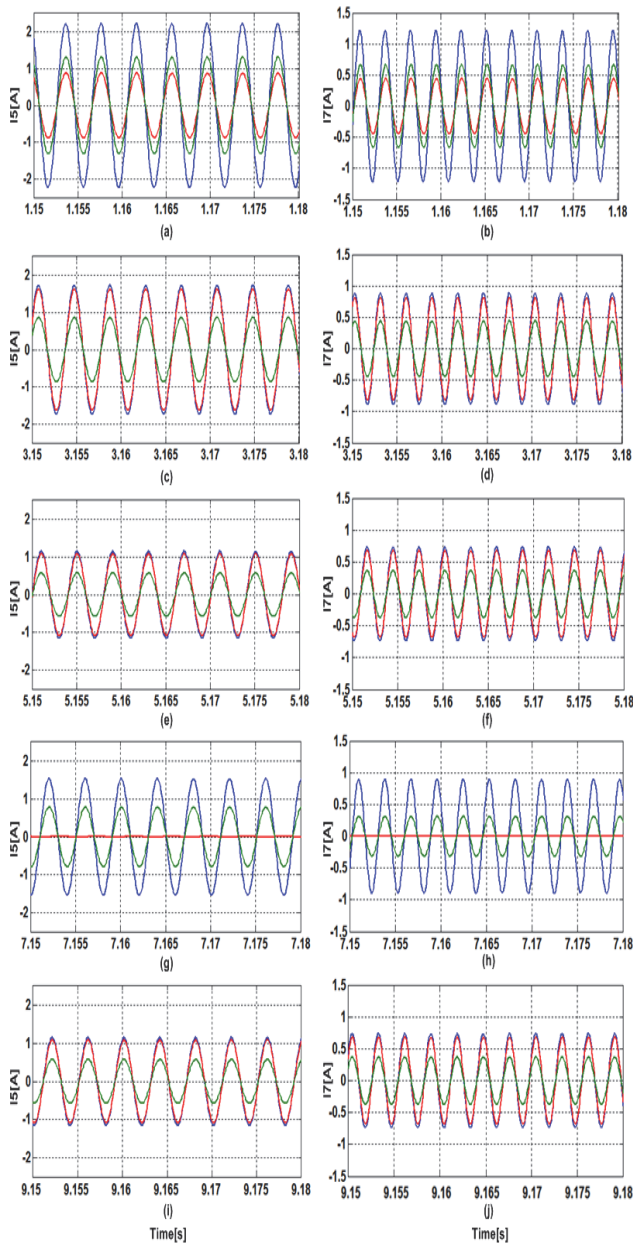


Fig.9.Harmonic components of the “A” phase output current of DGs (Left: 5th harmonic; Right: 7th harmonic): (a) , (b) case1; (c), (d) case2; (e), (f) case3; (g), (h) case4 (exit of DG2); (i), (j) case4 (entry of DG2), (Blue:DG1; Red: DG2; Green:DG3).

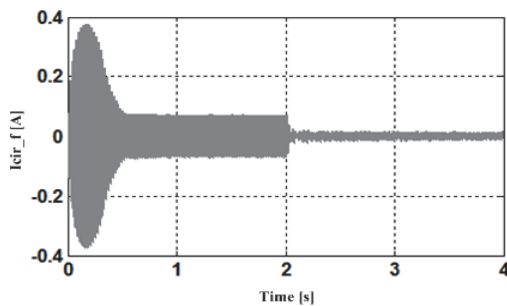


Fig.10. Fundamental circulating current related to the “A” phase of DG1.

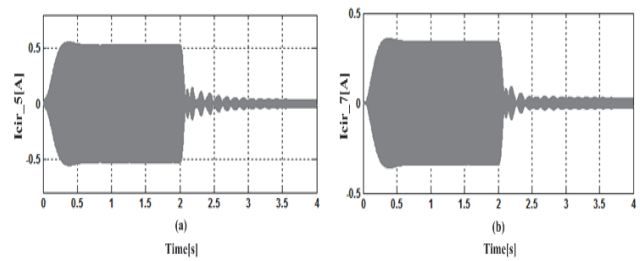


Fig.11.Harmonic circulating currents related to the “A” phase of DG1 : (a) 5th harmonic component; (b) 7th harmonic component.

(see Table I) are considered. As is obvious from Fig. 8, using the presented strategy, accurate power sharing is achieved even if different loading conditions are applied. In addition, as seen from Figs. 9(e) and 9(f), harmonic load sharing can be effectively followed in accordance with the new loading conditions.

4) *Case 4* ($6s \leq t \leq 10s$): To further evaluate the transient performance of a MG, the plug-and-play capability of DGs is conducted and verified by consideration of the case 3 loading condition. Hence, to achieve this objective, at $t = 6s$, DG2 (and its associated communication links) is intentionally disconnect from the system and at $t = 8s$, it is reconnected to the MG and operates with the other DGs in parallel. It is worth noting that for reconnecting DG2 to the MG, the synchronization process is done by using the proposed synchronization algorithm in [6]. Since each proposed local controller deals with the instantaneous measurement variables of the corresponding DG unit and the other DGs, the plugging-in or plugging-out of a DG unit can easily destabilize an entire islanded MG if the control factors are not properly updated. It is clear that in terms of plug-and-play performance, with the exit of a DG unit, its output current is zero. Hence, a zero flag signal is multiplied in the corresponding DG rated power capacity S_j . On the other hand, for other DG units with non-zero output currents, a unit flag signal is multiplied in their rated power capacity. Then, these settings are applied to (12) in order to update the load distribution factors. As can be seen from Fig. 8, by disconnecting DG2 and enabling the load sharing error compensation loops, the powers between DG1 and DG3 are accurately shared with respect to their power ratings before, during, and after the hot-swap procedure, with minimal transients. Additionally, the harmonic loads currents supplied by the DG1 and DG3 are accurately shared without any influence from the disconnecting of DG2, as shown in Fig. 9(g) and 9(h). After the reconnecting of the DG2 to the MG, as expected, the steady-state reactive power and harmonic currents are properly shared, which is similar to the case 3 results (see Figs. 8, 9(i), and 9(j)). These results illustrate the robust performance of the proposed load sharing control method when it comes to the plug-and-play functionality of DGs. These results verify that the local controllers guarantee system stability and provide a desirable performance even in

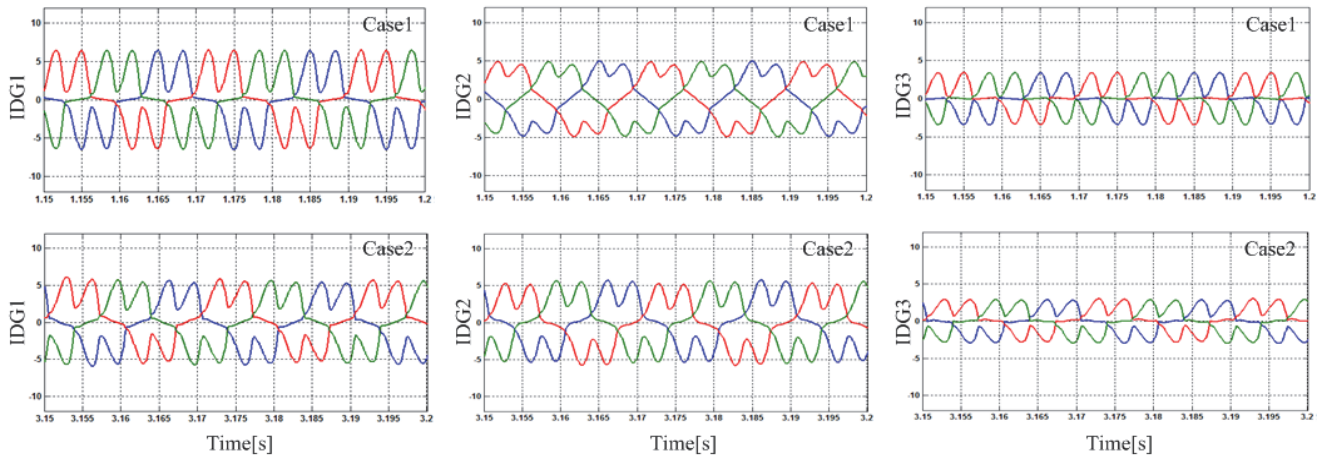


Fig. 12. DGs output currents waveforms at simulation cases 1 and 2: (Blue: DG1; Red: DG2; Green: DG3).

this case.

A. Proposed Controller Performance During Communication Failures and Latency

The scenario of communication failures is illustrated in Fig. 13 for reactive powers sharing among DG units. A communication failure at $t = 3.5s$ is applied for DG2 by disabling it in getting information from the “*Circulating Currents Calculation*” block. As can be seen, the reactive powers sharing accuracy is reduced by the communication failure. In addition, to demonstrate the local controller stability of the DG units, at $t = 5.5s$, the communication links for all of the units have been disrupted. Taking into account these changes, as shown in Fig. 13, the local controller continues to operate without instability. The effects of restoring communication are also explored at $t = 7.5s$. With the restoring of the communication links, the steady-state reactive powers sharing errors among the DGs are effectively compensated. Similar results can be achieved for harmonic current sharing. In addition, the previous simulation results have been conducted assuming a 1ms as the delay of the LBC. To emulate the behavior of the LBC system latency, it is simulated by using sample and hold blocks. To test the sensitivity of the proposed load sharing strategy to communication latency, some delays such as 5ms, 10ms, and 20ms are considered. The effects of the communication delay are observed in Fig. 14. It is obvious that with an increase of the delay, the accuracy of the reactive power sharing is adversely affected. Thus, the presented strategy is sensitive to large communication delays. This fact can be justified given that the proposed load sharing method has been realized based on the instantaneous fundamental and harmonic circulating currents among DGs. Moreover, for this reason, is clear that asynchronous communication delays between the data transmitting from the DGs local controllers to the circulating current calculation block and vice versa can lead to instability.

However, despite the fact that sampling and information

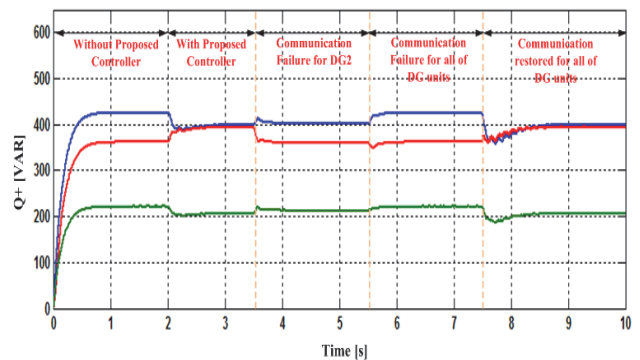


Fig. 13. Performance of the proposed reactive power sharing errors compensation method after communication failures and restoration, (Blue: DG1; Red: DG2; Green: DG3).

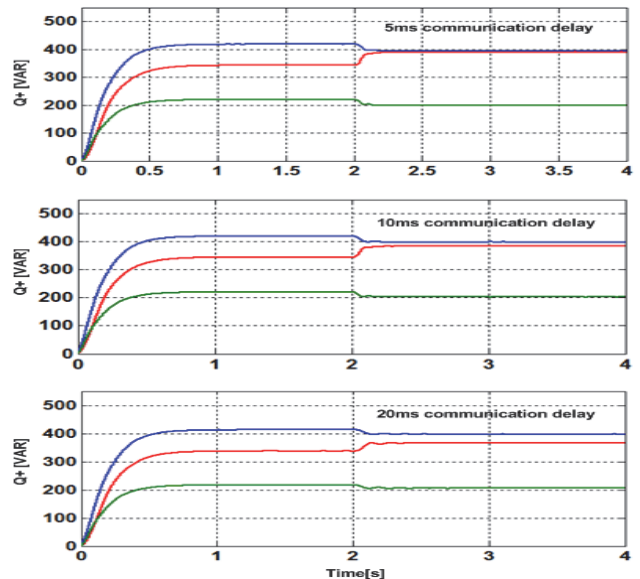


Fig. 14. Reactive power sharing error compensation method with time delays in the communication links (Blue: DG1; Red: DG2; Green: DG3).

transmitting delays due to the distance of inverters may have affects on the system control performance stability, such delays are crucial for low switching frequency applications

(high-power inverters). However, this is beyond the scope of the case studies in this paper. In addition, the impact of communication link latency can be reduced by adjusting the load sharing controller parameters $k_i^{+1}, k_i^{\pm h}$. Similar results can also be achieved for harmonic currents sharing.

V. CONCLUSIONS

In this paper, an improved voltage control scheme based on the active compensation of instantaneous fundamental and harmonics voltage drops across the DGs' feeder through circulating currents control is proposed and validated to enhance the reactive power and harmonic currents sharing accuracy. Since the proposed local controller consists of two well-decoupled fundamental and harmonic voltage control branches, the reactive power and harmonic currents can be independently shared without any knowledge of the mismatched feeder impedances even if nonlinear loads are directly placed at the output terminal of the DG units. The prominent superiority of the proposed load sharing method when compared to the conventional virtual impedance approaches is that the DGs' output voltage quality is not significantly affected. This is due to the fact that the proposed load sharing error compensation loops are embedded in the paths of the fundamental and harmonic circulating current feedbacks instead of the large linear and nonlinear load currents. The effects of load changes, communication failure and latency on the presented control strategy are also investigated. The obtained results indicate that the proposed load sharing technique is very robust with respect to communication link impairments and that it is insensitive to low time delays. The effectiveness of the proposed load sharing strategy is validated by simulation results.

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