Adaptive Virtual Impedance Control Scheme to Eliminate Reactive Power Sharing Errors in Islanded Microgrid

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***Abstract*—This paper proposes an enhanced distributed generation (DG) unit with an adaptive virtual impedance control approach in order to solve the inaccurate reactive power sharing problem. The proposed method can adaptively regulate DG units with the aid of the equivalent impedance, and the mismatching problem of the feeder impedance is compensated by sharing the reactive power accurately. The proposed control strategy can be implemented directly without any pre-knowledge of the feeder impedances. Simulations are performed to validate the effectiveness of the proposed control approach.**

Keywords—Distributed generation (DG); droop control; microgrid; virtual impedance

I. Introduction

Recently, distributed generation (DG) has been considered as a promising solution to meet the increased electricity demand without the effects on the environment and to mitigate the stress of many existing transmission and distribution infrastructures [1]. Subsequently, high penetration of the power electronics-based DG units accompanies a few considerable problems such as power management, resonance, system stability, etc. As a best solution for these problems, the microgrid concept has been developed. The microgrid has intentionally operated in grid-connected mode. However, it has to switch to autonomously islanded operation in case of main grid faults in order to keep the load power more reliable [2].

In the autonomous islanding operation, the power sharing is achieved by adjusting voltage magnitude and frequency. In order to facilitate the power sharing requirement with a decentralized manner, the conventional real power-frequency and reactive power-voltage magnitude droop control method have been adopted [3]-[6]. The droop method uses only local measurement and does not require any communication between DG units, so that the system can be implemented easily. However, it has been pointed out that even though accurate real power sharing is always achieved at the steady-state, the reactive power sharing is significantly affected due to the mismatched feeder impedances and different local loads [7]-[9].

To solve the inaccurate power control issues, a few improved methods have been proposed. In [7], an online estimator of the voltage drop caused by the transmission lines is developed. This estimated voltage drop is then incorporated into the power control scheme to achieve an accurate reactive power sharing in islanded microgrid. However, to properly estimate the voltage drop, the microgrid should operate in grid-connected mode before islanding operation. In [10], the line impedance mismatches are compensated by controlling the reactive power in proportion to the voltage derivative. Although this method minimizes the reactive power sharing error, it cannot completely eliminate the sharing errors. In [11], the power control instability and inaccurate power sharing are addressed at the same time and the virtual impedance control approach is considered to improve the control performance of the microgrid. In [12], by introducing the proper virtual impedance, the equivalent DG unit impedance is designed to be inversely proportional to the DG rating, and the reactive power sharing errors are eliminated. However, the virtual impedance control methods are developed based on the pre-knowledge of physical feeder impedance, which is not often readily available. Especially, the microgrid has no fixed configuration because of the "plug-and-play" feature of DG units and loads [1]. Therefore, the real-time information of the feeder impedances is important to implement the virtual impedance control.

In this paper, an adaptive virtual impedance control method is applied to DG units in islanded microgrids, and the communication is employed to exchange the desired information between DG units and microgrid central controller (MGCC), which is utilized to tune the virtual impedances adaptively in order to compensate the mismatch in the feeder impedance. Once the virtual impedance is tuned for a given load operating point, the accurate reactive power sharing is achieved. The proposed control strategy is verified by the digital simulation.

II. Operation Principle of Islanding Microgrid

A. Operation of Microgrid

Fig. 1 illustrates the configuration of a microgrid, where the microgrid is composed of a number of DG units and loads. Each DG unit is constructed by a DC-link, inverter, and LC filter; the inverters are controlled by the local controllers. The MGCC monitors the microgrid and main grid status to define whether the microgrid is operating in grid-connected mode or

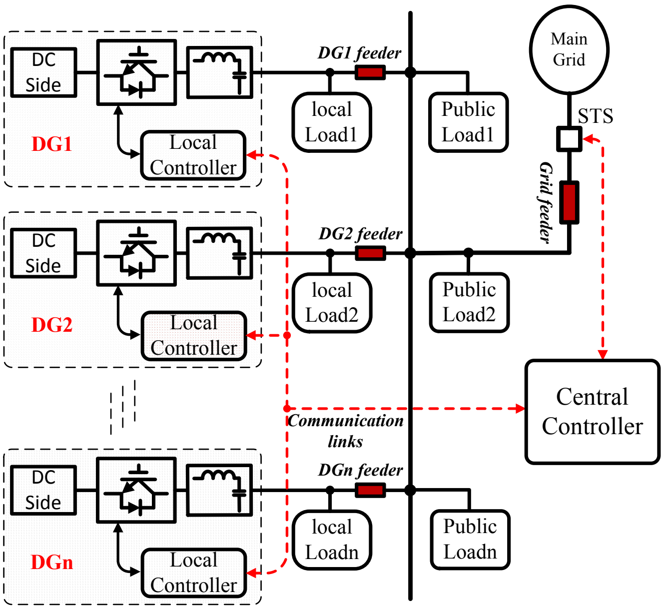

Fig. 1. Illustration of a single-phase microgrid.

islanded mode by controlling the static transfer switch at the point of common coupling (PCC). The MGCC and DG units exchange required information through the low-bandwidth communication links.

During the grid-connected operation, the real and reactive power references are normally assigned by the central controller, and the power sharing is not concerned. When the microgrid is switched to the islanding operation, the voltage and frequency of the microgrid are supported by the inverters, and the total load demand of the microgrid must be properly shared by these DG units.

For simple analysis, the physical feeders are regarded as inductive impedances because DG units are generally connected to distribution system with the isolation transformers, which have highly leakage inductance. Even for the case of DG units coupled to the PCC with only LC filters or through a resistive impedance, a fixed value of the inductive virtual impedance is introduced at the DG unit output to ensure equivalent inductive DG impedance [7].

B. Frequency and Voltage Droop Method

In islanded microgrid, the inverters operate as a voltage source inverter (VSI) so as to regulate the voltage and frequency of the microgrid, and the frequency and voltage magnitude droop control has been conventionally adopted [3]-[6]. Fig. 2 shows the real power-frequency (P-ω) droop characteristic for two DG systems. Preferably, these droop characteristics should be coordinated to make each DG system supplying the real power proportionally to its power capacity, and the following relationship is obtained:

$$\omega = \omega_0 - m\,P \tag{1}$$

$$m = \frac{\Delta\omega}{P_{\max}} \tag{2}$$

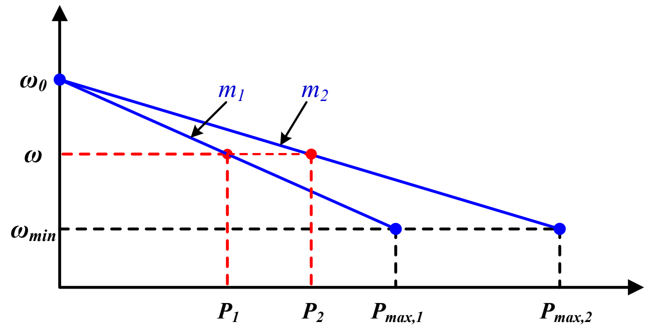

Fig. 2. Illustrated frequency droop control.

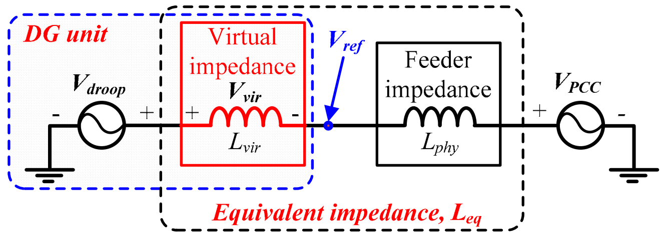

Fig. 3. Illustration of series virtual impedance control.

where ω_0 and ω are the nominal and the reference angular frequency of the DG unit, respectively; m is the droop coefficient for frequency; $\Delta\omega$ is the maximum frequency deviation allowed by the inverter; P and P_{max} are the actual and maximum real output power of the DG unit, respectively.

In a similar manner, the magnitude set point of each DG output voltage to control the reactive power can be achieved according to the specified Q-E droop scheme. The Q-E characteristics can be expressed as following:

$$E = E_0 - n\,Q \tag{3}$$

$$n = \frac{\Delta E}{Q_{\max}} \tag{4}$$

where E_0 and E are the nominal and reference voltage magnitudes of the DG unit, respectively. ΔE is the maximum voltage deviation allowed by the inverter; n is the droop coefficient for voltage amplitude; Q and Q_{max} are the actual and maximum reactive power output of the inverter, respectively.

From Fig. 2, a larger capacity DG unit provides more power due to its smaller droop slopes under the same frequency and voltage magnitude. In the steady-state, due to the consistent frequency among DG units, the P-ω droop control always achieves accurate real power sharing. However, the Q-V droop control always suffers the reactive power sharing issues because the voltage magnitudes of DG units can hardly be unified due to the effect of mismatched feeder impedances.

III. Proposed Control Approach

A. Virtual Impedance

Virtual impedance control method is based on the virtual

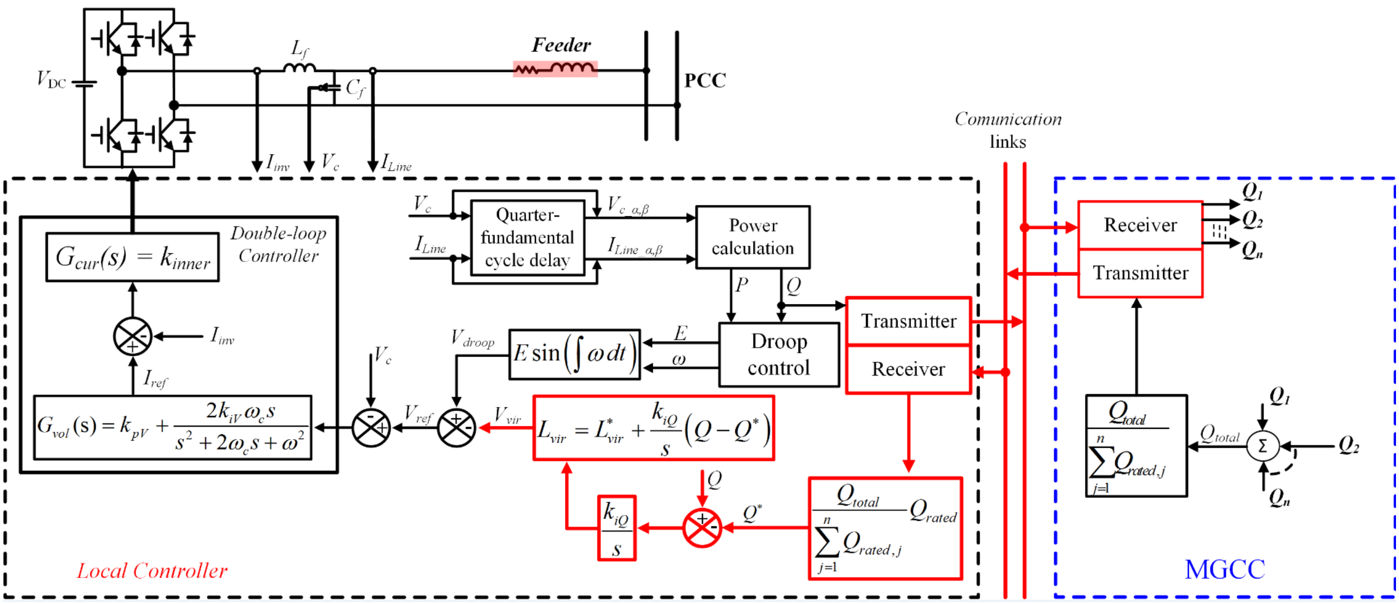

Fig. 4. Diagram of proposed control scheme.

impedance at the DG unit output terminal as shown in Fig. 3, whereby the equivalent DG unit impedance is regulated to eliminate the reactive power sharing errors affected by the mismatched feeder impedances [12]. In Fig. 3, the instantaneous voltage reference V_{droop} of the inverter can be obtained as following by using the derived angular frequency and voltage magnitude in (1) and (3):

$$V_{droop} = E\sin\left(\int \omega dt\right) \tag{5}$$

As shown in Fig. 3, the equivalent impedance L_{eq} is defined as the series combination of the existing physical feeder impedance L_{phy} and the virtual impedance controlled L_{vir} by the DG unit:

$$L_{eq} = L_{phy} + L_{vir} \tag{6}$$

To emulate the behavior of virtual impedance, its corresponding voltage drop V_{vir} is calculated as

$$V_{vir} = -\omega L_{vir} I_{Line\_\beta} \tag{7}$$

where I_{Line_β} is obtained by delaying the DG line current I_{Line} for a quarter fundamental cycle.

Finally, the voltage reference for the voltage control loop is obtained as following:

$$V_{ref} = V_{droop} - V_{vir} \tag{8}$$

B. Adaptive Virtual Impedance

The virtual impedance is determined classically based on the knowledge of physical feeder impedance which is not often available. Moreover, because the microgrid has variable configuration, it is necessary to estimate the online feeder impedance, which makes the digital controller more complex. In order to solve this problem, an algorithm to automatically regulate virtual impedance is proposed without any feeder impedance information.

The adaptive virtual impedance control diagram is shown in Fig. 4. The inverter transmits the information of the respective reactive power outputs (Q_1, Q_2,…, and Q_n) to the MGCC. The MGCC determines the total reactive power supplied by the inverters in the microgrid by considering the total rated reactive power of the inverters. The calculated value is transmitted to all inverters, and each inverter determines its reactive power demand ($Q_1^*, Q_2^*, \ldots,$ and Q_n^*) by multiplying the received value with its rated power. Hence, the reactive power demand for each inverter can be calculated as:

$$Q^* = \frac{Q_{total}}{\sum_{j=1}^{n} Q_{rated,j}} Q_{rated} \tag{9}$$

As shown in Fig. 4, the difference between the measured reactive power Q and the reactive power demand Q^* is obtained in order to adjust the DG virtual impedance through the integral controller, and the virtual impedance of DG unit L_{vir} is obtained adaptively:

$$L_{vir} = L_{vir}^* + \frac{k_{iQ}}{s}\left(Q - Q^*\right) \tag{10}$$

where L_{vir}^* is a fixed virtual inductance; k_{iQ} is the integral gain to adjust the virtual inductance.

C. Double-Loop Voltage Tracking Scheme

As an excellent voltage tracking technique, the double-loop voltage controller is applied in this paper to track the modified voltage reference V_{ref} in (7). In double-loop voltage controller, the outer loop uses a non-ideal proportional-resonant (PR) controller tuned at the fundamental frequency:

$$G_{Vol}(s) = k_{pv} + \frac{2k_{iv}\omega_c s}{s^2 + 2\omega_c s + \omega_{DG}^2} \tag{11}$$

where k_{PV} is the outer loop proportional gain, k_{iV} is the resonant

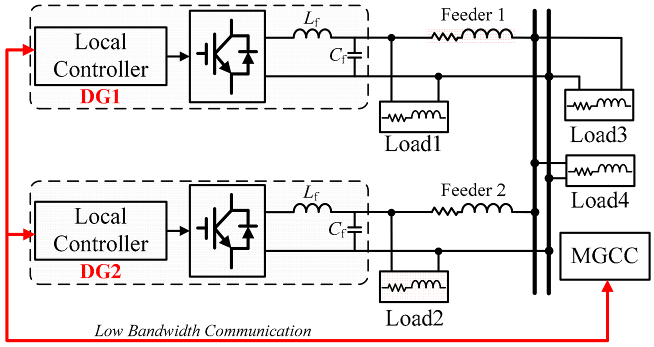

Fig. 5. Simulated microgrid configuration.

TABLE I
PARAMETERS IN SIMULATION

System Parameter	Values
LC filter	L_f = 1.3 mH and C_f = 20 uF
DC link voltage	150 V
Nominal operating voltage (*rms*)	110 V, 60 Hz
Switching frequency	10 kHz
Physical DG feeders	3.0mH, 0.2Ω (DG unit 1)
	1.5mH, 0.1Ω (DG unit 2)
Power Control Parameter	**Values**
Frequency droop coefficient, *m*	0.0015 *Rad/(Sec·W)*
Voltage droop coefficient, *n*	0.0015 *V/Var*
Double-Loop Voltage Control Parameter	**Values**
k_{pv}	0.1
k_{iv}	20
k_{inner}	25
ω_c	4.1 Rad/s
Virtual Impedance Control Parameter	**Values**
L_{vir}^*	1mH
k_{iQ}	0.00005
Loads	**Values**
Load1 (R/L)	20Ω/ 30mH
Load2 (R/L)	20Ω/ 30mH
Load3 (R/L)	10Ω/ 30mH
Load4 (R/L)	20Ω/ 30mH

controller gain at the fundamental frequency, and ω_c is the cutoff frequency of the resonant controller.

The inner loop has a simple proportional control gain k_{inner} with the filter inductor current feedback as

$$G_{Cur}(s) = k_{inner} \quad (12)$$

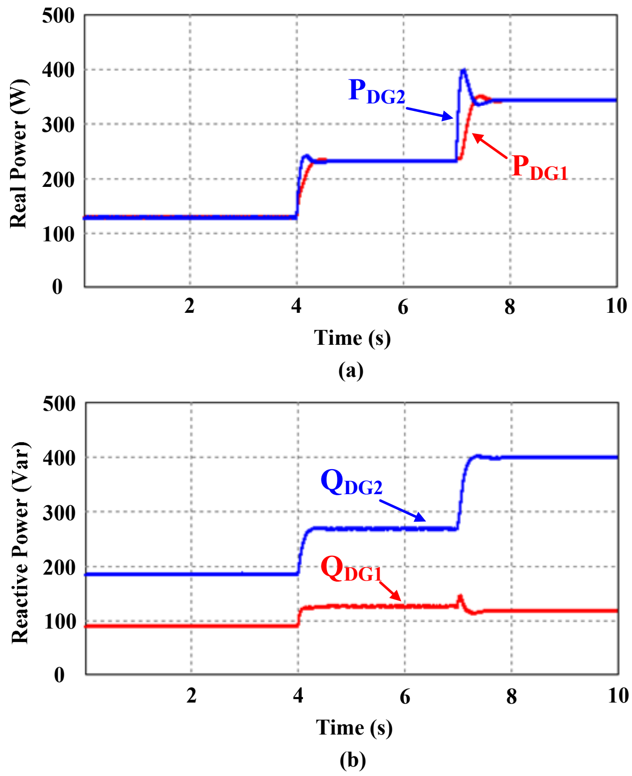

Fig. 6. Simulated power sharing performance of the conventional droop control. (a) Real Power. (b) Reactive Power.

IV. SIMULATION RESULTS

The proposed power control strategy has been verified with PSIM simulations. As shown in Fig. 5, the microgrid used in the simulation is composed of two identical DG units and several linear loads. The system parameters used in the simulation are listed in Table I. The MGCC exchanges the required information with DG local controller through a low bandwidth communication. Under the same power rating, two DG units share the load demand equally.

The performance of the system using the conventional droop control is illustrated in Fig. 6. The microgrid is originally operated without the local loads (Load1 and Load2 in Fig. 5 are disconnected) and only Load3 is applied at the PCC. At t = *4s*, Load4 is connected to the PCC in order to realize a step load change. At t = *7s*, a local load of DG2 (Load 2) is connected to the system while DG1 has no local load (Load 1 is disconnected).

As shown in Fig. 6(a), the active power demand is accurately shared between DG units under the conventional droop method at any case of operation. However, due to the effect of the mismatched feeder impedances, the reactive power sharing shows a very poor performance as can be seen in Fig. 6(b). Especially, the reactive power sharing inaccuracy becomes more severe when the local load is applied.

The system performances with the proposed control method are shown in Figs. 7, 8, and 9. At the beginning, the system operates under conventional method with only Load3 at the

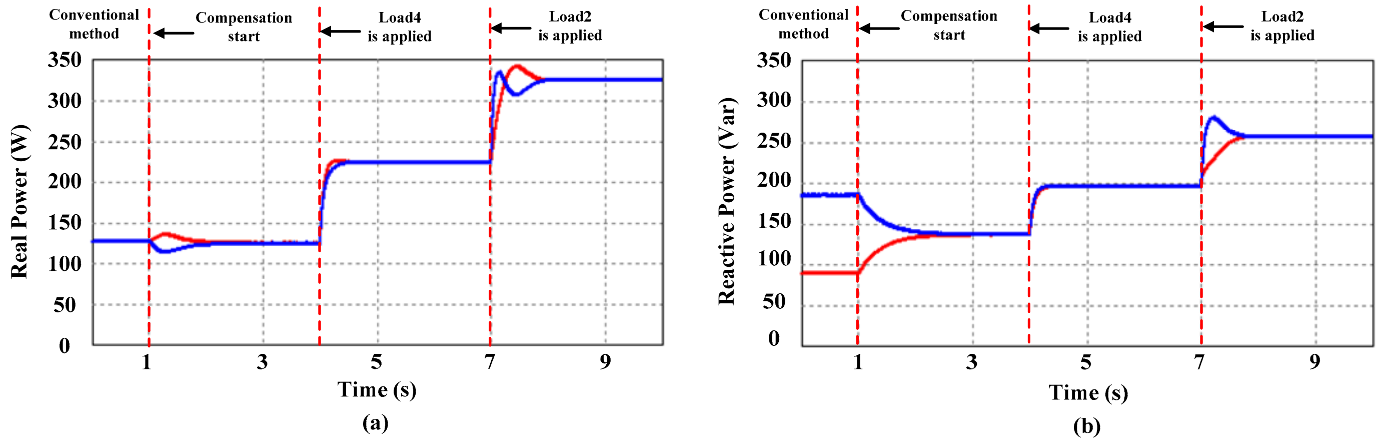

Fig. 7. Simulated performance of the proposed controller (activated at $t = 1s$). (a) Real Power. (b) Reactive Power.

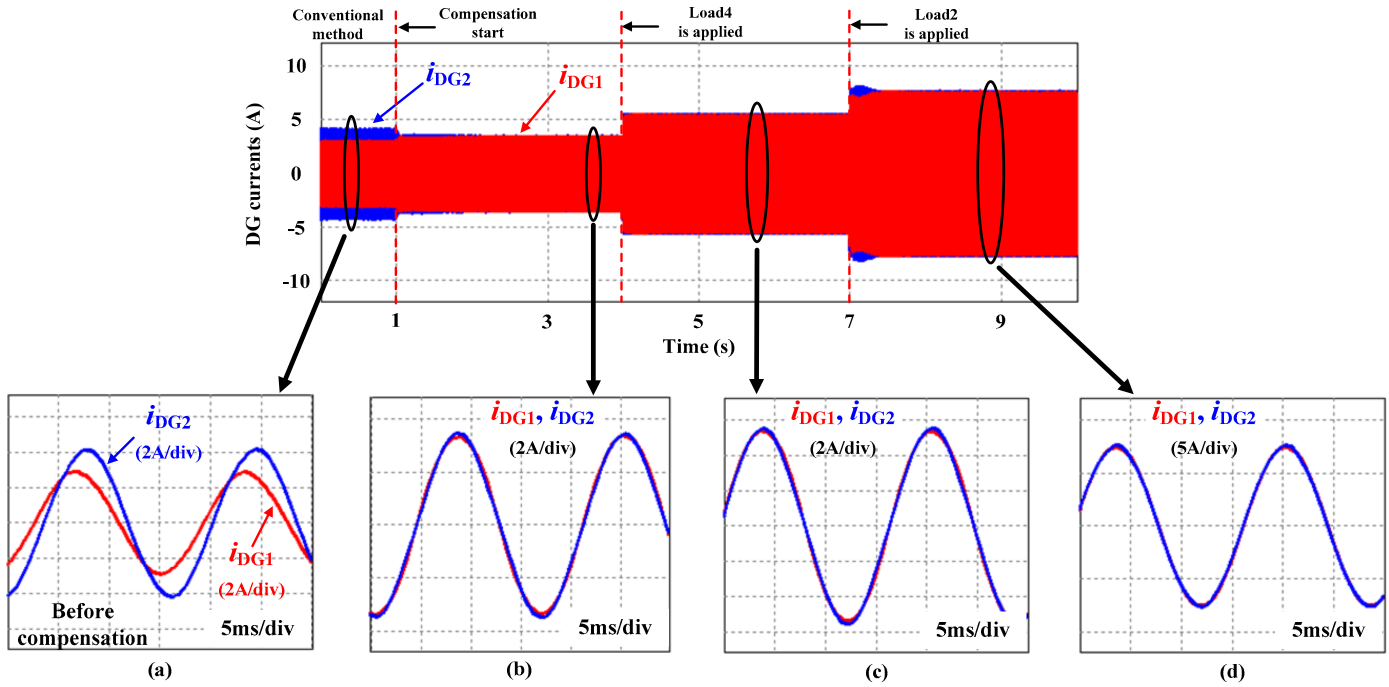

Fig. 8. Zoom-in DG current waveforms with

(a) Conventional droop method.
(b) Proposed method (activated at $t = 1s$).
(c) Proposed method under load change operation (Load 4 is connected at $t = 4s$).
(d) Proposed method under local load effect (Load 2 is connected $t = 7s$).

PCC. At $t = 1s$, the proposed adaptive virtual impedance control scheme is activated. To investigate the performance of the proposed control scheme when the load changes at $t = 4s$, Load4 is connected to the PCC. To demonstrate the effectiveness of the proposed method under the presence of the local load, Load2 (DG2's local load) is connected to system at $t = 7s$ while Load1 is remained disconnected.

As shown in Fig. 7, the proposed control scheme causes only a small transient variation for the active power sharing between DG units, and the perfect active power sharing is achieved at the steady-state with the proposed control scheme. Furthermore, the reactive power demands are equally shared without any reactive power sharing error after 1.5s transient duration even though the load changes or the local load is applied.

Fig. 8 shows the zoom-in DG line current waveforms to investigate the current sharing accuracy by the proposed control strategy compared to the conventional droop control. As shown in Fig. 8(a), with the conventional droop control method, the magnitude and the phase of DG currents are not the same. However, both of the DG line currents are almost identical with the proposed control scheme even though the

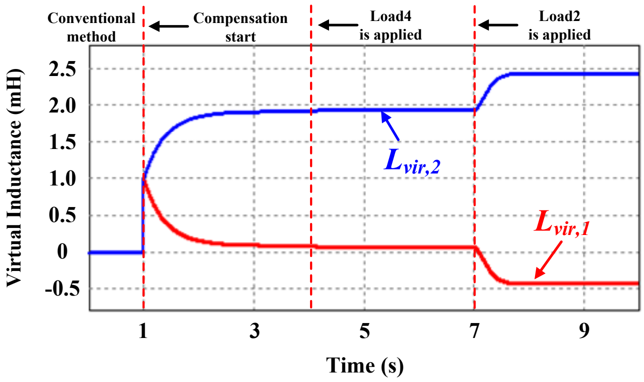

Fig. 9. Virtual inductance values under different operation points.

load or the local load changes.

Fig. 9 shows the variation of the virtual impedances when the proposed method is applied. We can say that the accurate reactive power sharing is achieved thanks to the adaptive compensation of the mismatched feeder impedances.

V. CONCLUSION

The accurate reactive power sharing in an islanded microgrid has been achieved based on the adaptive virtual impedance concept. By adjusting the virtual impedances at the outputs of DG units, the accurate reactive power sharing is achieved even though the feeder impedance or the local load mismatches with each other. The proposed control strategy does not require any feeder impedance, which eliminates the need of online feeder impedance estimator and decreases the system complexity. Moreover, the control strategy can be implemented without any local load measurement, which reduces the system cost.

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