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Power Sharing Scheme in an Enhanced Islanded Microgrid

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ABSTRACT: Power sharing problems are associated with DG reactive power, imbalance power and harmonic power. An enhanced droop control method through online virtual impedance adjustment is used to solve power sharing problems. DG reactive power, imbalance power, and harmonic power is added to the conventional real power-frequency droop control. The transient real power variations caused by this are used to realize DG series virtual impedance tuning. With the regulation of DG virtual impedance at fundamental positive sequence, fundamental negative sequence, and harmonic frequencies, an accurate power sharing can be realized at the steady state. In order to activate the compensation scheme in multiple DG units in a synchronized manner, a low-bandwidth communication bus is adopted to send the compensation command from a micro-grid central controller to DG unit local controllers, without involving any information from DG unit local controllers. The feasibility of the proposed method is obtained by simulation results from a low-power three-phase microgrid with two parallel DG units with the same power rating.

KEYWORDS: Virtual impedance, microgrid, Distributed generation, droop control, islanding operation, renewable energy system, power sharing, voltage control.

I.INTRODUCTION

In islanding operation, the load demand must be properly shared by parallel DG units. To facilitate the power sharing requirement without using any communications between DG units, the real power–frequency and reactive power–voltage magnitude droop control method is developed. In this control category, real power and reactive power in the power control loop are calculated using low pass filters (LPF). The reactive power sharing performance is dependent on the impedance of DG feeders. In a DG unit is equipped with dominate inductive virtual impedance the reactive power sharing errors can be reduced. An improved droop control method was proposed to realize the power sharing in proportion to DG power rating. Compared to the standard droop control method, the power sharing performance is improved via the measurement of point of common coupling (PCC) voltage. Furthermore, virtual, real, and reactive power concept was introduced to improve the stability of droop control. Similarly, the concept of virtual frequency and virtual voltage magnitude concept was also proposed to prevent instability operation of islanding microgrids. A central controller is implemented at a microgrid to detect the PCC voltage or load/grid current. These measured steady state PCC signals are modulated to dc quantities at their corresponding synchronous rotating frames. At each DG unit local controller, dc signals are switched back to ac signals by a few signal demodulators. An important advantage of this method is that harmonic signals can be transmitted to a DG unit local controller by using a low-bandwidth communication system with around 1000 Hz sampling frequency. To identify the reactive power sharing error without measuring PCC voltage, the real power and reactive power control are coupled by using a modified droop control. When the reactive power sharing errors are detected, it can be eliminated by using a simple intermittent integral term that adjusts the DG voltage magnitude. For an islanding microgrid with a large number of nonlinear or imbalanced loads, developing a schematic compensation method to realize accurate reactive, imbalance, and harmonic power sharing is very necessary.

In this paper, an adaptive virtual impedance control method is applied to DG units in islanding microgrids. The virtual impedance at fundamental positive sequence, fundamental negative sequence, and harmonic frequencies are determined according to transient real power variations. To activate small amount of transient power variations, a transient control term is added to the conventional real power–frequency droop control. Through interactions between real power variations and the virtual impedance regulation, a microgrid reactive power, imbalance power, and harmonic power sharing errors can be compensated at the steady state.

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II. MICROGRID POWER SHARING

Principle of Microgrid Power Sharing: Fig.1 shows a simplified diagram of an islanding microgrid, where a few DG units are integrated into the microgrid with LC filters. For each DG unit, the backstage power is provided by a RES or an energy storage system. To simplify the discussion, an infinite dc link with fixed dc voltage is assumed in this paper. There are a few linear, imbalanced, and harmonic loads placed at the PCC. A microgrid central controller is also placed at PCC. To realize the proposed compensation scheme in DG units in a synchronized manner, a central controller is adopted to send synchronized compensation flag signals to DG local controllers.

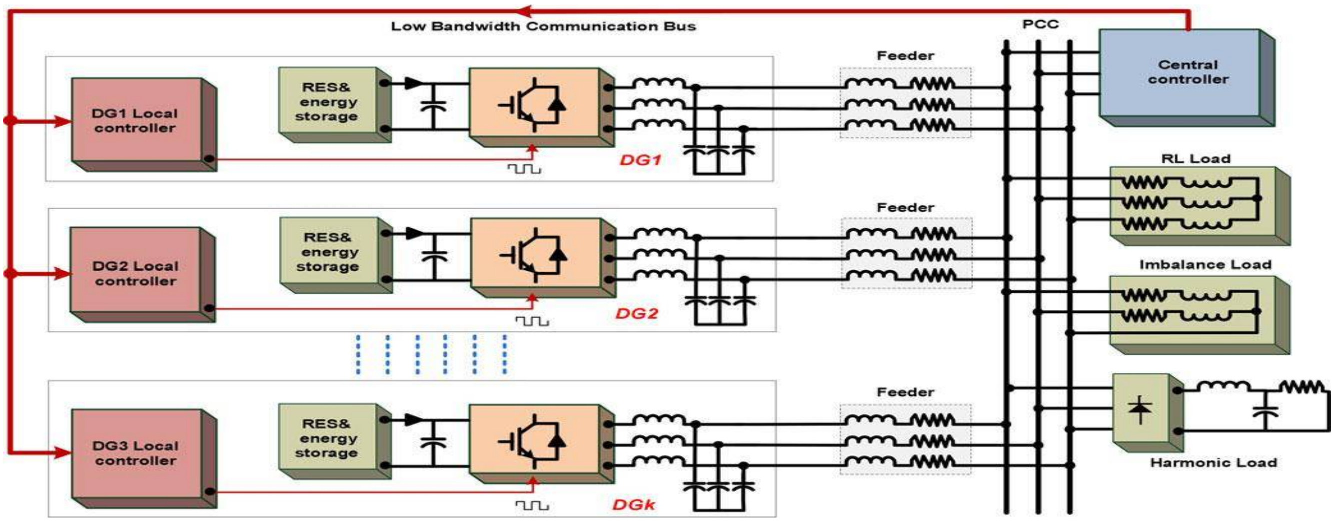

Fig.1. Diagram of an islanding microgrid with one way low bandwidth communication.

At a DG unit local controller, the traditional real power–frequency droop control and reactive power–voltage magnitude droop control are adopted as

$$f_{DG} = f^* - D_P \cdot P_{LPF} \quad (1)$$

$$E_{DG} = E^* - D_q \cdot Q_{LPF} \quad (2)$$

where f^* and f_{DG} are the DG nominal and reference frequencies. E^* and E_{DG} are the DG nominal and reference voltage magnitudes. D_p and D_q are the droop coefficients for controlling DG real power P_{LPF} and reactive power Q_{LPF} respectively. With the frequency and the voltage magnitude reference, instantaneous DG voltage references $V_{droop\ \alpha}$ and $V_{droop\ \beta}$ in the two-axis stationary reference frame can be obtained by using a reference generator.

The stability and dynamic performance of the conventional droop control is a subject to the impact of DG feeders. To alleviate the impact of feeder impedance, the static virtual impedance was proposed by deducting a voltage drop term from the voltage reference as

$$V_{ref\_\alpha} = V_{droop\_\alpha} - (\omega_0 L_V I_\beta + R_V I_\alpha) \quad (3)$$

$$V_{ref\_\beta} = V_{droop\_\beta} - (-\omega_0 L_V I_\alpha + R_V I_\beta) \quad (4)$$

where $V_{ref\ \alpha}$ and $V_{ref\ \beta}$ are the voltage references considering the control of virtual impedance. L_V and R_V are the static virtual inductance and resistance, respectively. I_α and I_β are the DG unit current in the stationary two-axis reference frame. Note that the virtual impedance control mainly focuses on the performance of the DG unit at the fundamental frequency.Afterward, a high-bandwidth voltage controller is needed for tracking the voltage references.

Analysis of Reactive, Imbalance And Harmonic Power:

Sharing Errors:The previous section reviewed how the conventional droop control and the static virtual impedance regulation are applied to a DG unit. In this section, the sharing of a microgrid load demand is discussed by investigating on a simplified DG equivalent circuit.

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Fig. 2 illustrates an equivalent circuit of an islanding microgrid with two droop controlled DG units. It can be seen from Fig. 2(a) that DG units are modelled by controlled voltage sources and series virtual impedances at fundamental positive sequence. Meanwhile, the PCC load is lumped as a passive *RL* load. In order to realize accurate real and reactive power sharing, DG units at the same power rating shall design the droop control slopes . In addition, the same fundamental positive sequence equivalent impedance shall be controlled in both DG units. In the case of Fig. 3.2(a), the fundamental positive sequence equivalent impedance is defined as the series combination of existing physical feeder impedance and the virtual impedance controlled by the DG unit

$$L_f = L_{\text{phy},f} + L_{v,f} \qquad (5)$$

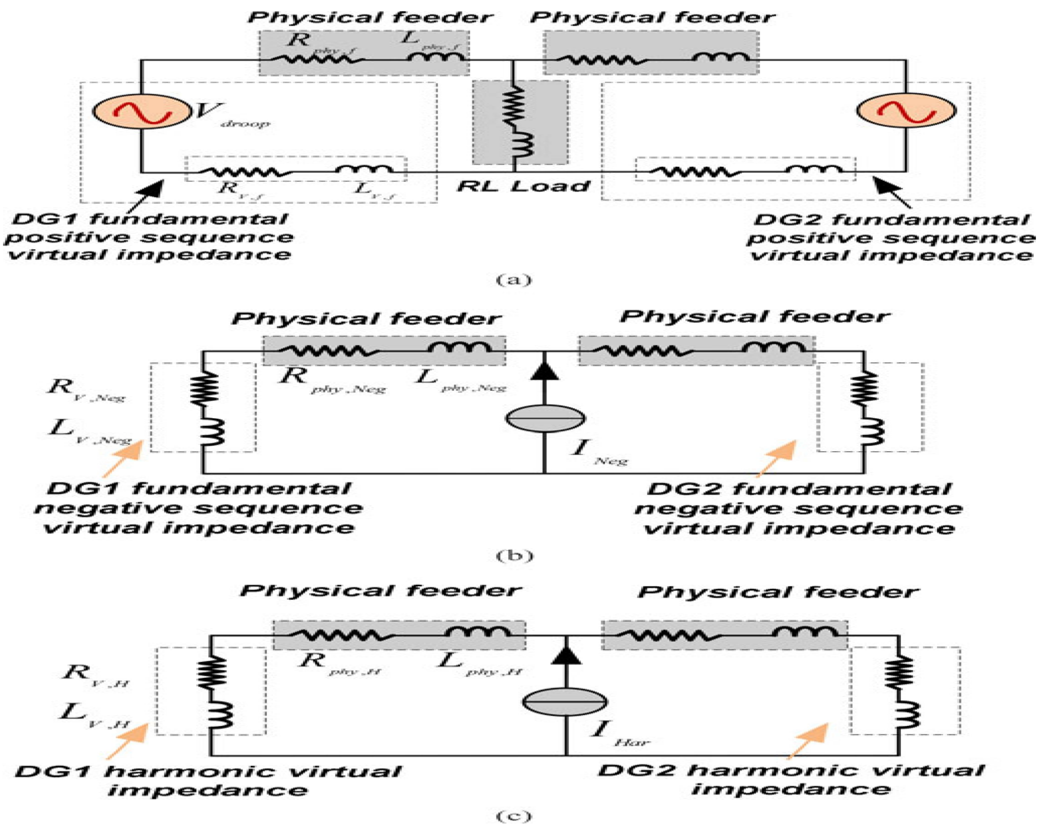
$$R_f = R_{\text{phy},y} + R_{v,f} \qquad (6)$$

where L_f and R_f are the DG equivalent inductance and resistance at the fundamental positive sequence. $L_{\text{phy},f}$ and $R_{\text{phy},f}$ are the physical feeder inductance and resistance at the fundamental positive sequence. $L_{V,f}$ and $R_{V,f}$ are the fundamental positive sequence virtual impedance controlled by the DG unit
In addition, the equivalent circuit at fundamental negative sequence is presented in Fig. 2 (b), where the PCC imbalanced load is described as a current source (INeg). In this system, the equivalent fundamental negative sequence DG impedance is

$$L_{\text{Neg}} = L_{\text{phy,Neg}} + L_{v,\text{Neg}} \qquad (7)$$

$$R_{\text{Neg}} = R_{\text{phy,Neg}} + R_{v,\text{Neg}} \qquad (8)$$

where $L_{\text{phy,Neg}}$ and $R_{\text{phy,Neg}}$ are the inductance and resistance of physical feeder at fundamental negative sequence.



Equivalent circuits of a microgrid at different frequencies and sequences.
Fig. 2 (a) Equivalent circuit at fundamental positive sequence.
Fig. 2 (b) Equivalent circuit at fundamental negative sequence.
Fig. 2 (c) Equivalent circuit at harmonic frequencies

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To share the imbalance load current using multiple DG units, the equivalent fundamental negative sequence impedance L_{Neg} and R_{Neg} are regulated by controlling DG virtual impedance $L_{V,Neg}$ and $R_{V,Neg}$ at the fundamental negative sequence.

Finally, the equivalent circuit at harmonic frequencies is given in Fig. 2(c) as

$$L_H = L_{\text{phy},H} + L_{V,H} \quad (9)$$

$$R_H = R_{\text{phy},H} + R_{V,H} \quad (10)$$

where LH and RH are the DG equivalent inductance and resistance at harmonic frequencies. The physical feeder impedance is described as Lphy,H and Rphy,H . LV,H and RV,H are the harmonic virtual impedance controlled by DG units.

To simplify the discussion, this paper assumes that DG units in an islanding microgrid are interfaced to PCC with inductive physical feeders. This is because series coupling chokes are normally required in the droop controlled DG units, in order to ensure the stability of power sharing control. In addition, DG units are often interconnected to a distribution system with isolation transformers, which have highly inductive leakage impedance. Finally, even for some directly coupled DG units with only LC filters, the fixed value inductive virtual impedance can be pre-activated through DG unit virtual impedance control scheme. As it will be discussed later, DG unit virtual impedance in this case is the series combination of pre-activated virtual impedance and the adaptive virtual impedance that is adjusted by the proposed compensation scheme. If the ranges of adaptive virtual impedance and pre-activated virtual inductance are both properly designed, the DG equivalent impedance can be always inductive at fundamental and selected harmonic frequencies.

Based on the assumption of inductive DG equivalent impedance and slow microgrid load demand dynamics the relationship between DG output power and DG equivalent inductance can be summarized as

$$\begin{cases} L_f \uparrow & Q_{\text{LPF}} \downarrow \\ L_{\text{Neg}} \uparrow & Q_{\text{Neg}} \downarrow \\ L_H \uparrow & Q_{\text{Har}} \downarrow \end{cases} \quad (11)$$

where QLPF , QNeg , and QHar are DG unit reactive power, imbalance power, and harmonic power, respectively. Their detailed definition is given in next section. Based on the aforementioned discussion, it can be seen that the output power of a DG unit decreases when the corresponding equivalent DG inductance increases and vice versa.

III. ENHANCED POWER SHARING METHOD

DG Unit Power Calculation: First, the fundamental positive sequence, fundamental negative sequence, and harmonic components of DG current are separated by using the second-order generalized integrator and the delayed-signal cancellation based sequence decomposition method. A simplified detection diagram is sketched in Fig. 3. With the detected current components, the output power of a three-phase DG unit can be calculated as

$$P_{\text{LPF}} = \frac{3}{2(\tau s+1)} \cdot (V_{\text{DG},\alpha} \cdot I^+_{\alpha,f} + V_{\text{DG},\beta} \cdot I^+_{\beta,f}) \quad (12)$$

$$Q_{\text{LPF}} = \frac{3}{2(\tau s+1)} \cdot (V_{\text{DG},\beta} \cdot I^+_{\alpha,f} - V_{\text{DG},\alpha} \cdot I^+_{\beta,f}) \quad (13)$$

$$Q_{\text{Har}} = 3/2 \cdot E^* \cdot \sqrt{(I^-_{\alpha,5})^2 + (I^-_{\beta,5})^2 + (I^+_{\alpha,7})^2 + (I^+_{\beta,7})^2} \quad (14)$$

$$Q_{\text{Neg}} = 3/2 \cdot E^* \cdot \sqrt{(I^-_{\alpha,f})^2 + (I^-_{\beta,f})^2} \quad (15)$$

where P_{LPF} is the DG real power and Q_{LPF} is the DG reactive power. The ripples in DG real and reactive power are attenuated by using LPFs with time constant τ . Q_{Har} and Q_{Neg} are de-fined as DG harmonic power and imbalance power, respectively.

E^* is the rated DG phase voltage (peak value). $V_{DG,\alpha}$ and $V_{DG,\beta}$ are the measured DG voltages in the stationary reference frame. $I_{\alpha,f}^+$ and $I_{\beta,f}^+$ are the DG fundamental positive sequence current, $I_{\alpha,f}^-$ and $I_{\beta,f}^-$ are the DG fundamental negative sequence cur-rent. $I_{\alpha,5}^-$ and $I_{\beta,5}^-$ are the negative sequence component of DG fifth harmonic current. $I_{\alpha,7}^+$ and $I_{\beta,7}^+$ are the positive sequence component of DG seventh harmonic current. Note that in this paper, only dominate low order harmonic currents are adopted to calculate the harmonic power.

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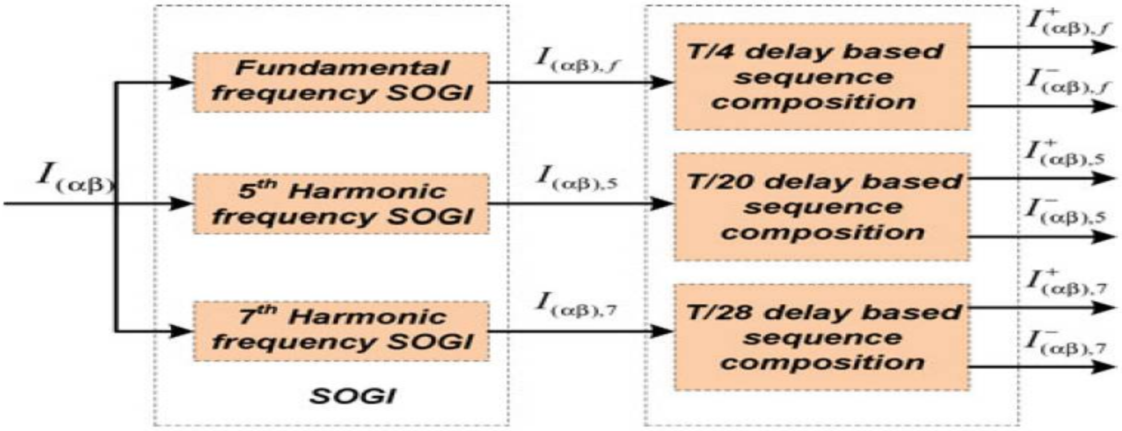

Fig. 3. Decomposition of fundamental positive sequence, fundamental negative sequence, and harmonic components. T is the fundamental cycle.

Couplings between DG Unit Virtual Impedance and Transient droop Control: It has been demonstrated that the conventional frequency droop control in (1) can realize zero steady-state real power sharing errors. Therefore, when a disturbance term associated with reactive power Q_{LPF} , harmonic power Q_{Har} , or imbalance power Q_{Neg} is added to the frequency droop control in (1), the real power sharing shall appear some variations when Q_{LPF} , Q_{Har} , or Q_{Neg} in multiple DG units are not the same. For the same reason, if these load demands are properly shared by DG units, adding the same amount of frequency disturbance to will not cause any obvious real power variations. Therefore, one can find that the transient real power variations indirectly indicate the reactive, harmonic, and imbalance power sharing errors in an islanding microgrid.

Based on the above discussions and the analysis of DG equivalent circuit in Fig. 5, it is practical to eliminate the power sharing errors by injecting couplings between the transient real power variations and the DG virtual impedance.

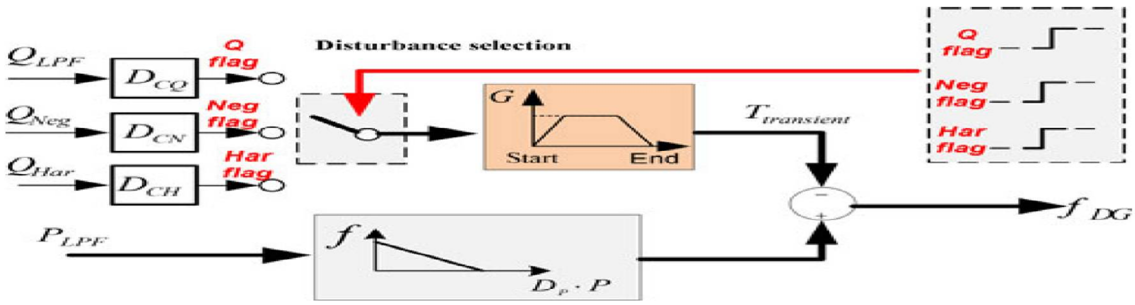

Fig. 5. Real power disturbance injection during the compensation (step 2).

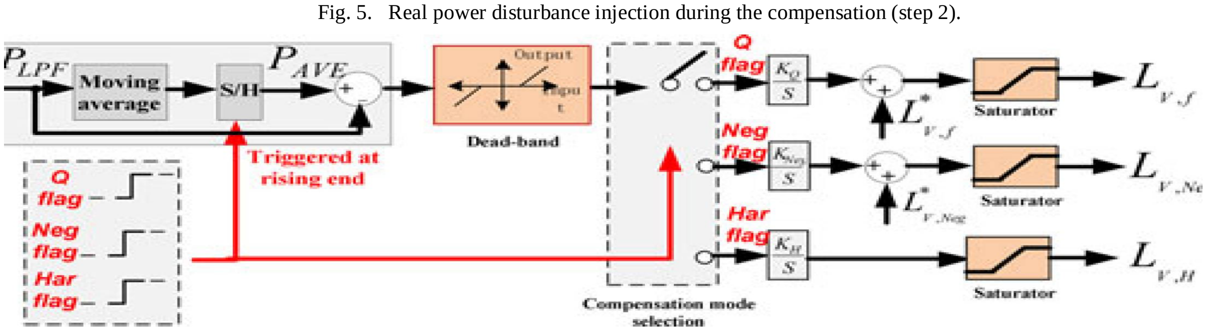

Fig. 6. DG virtual impedance adjustment during the compensation (step 3).

The power sharing error compensation scheme is composed of the following three steps.

Step 1 (Conventional Droop Control): First, the conventional droop control scheme as shown in (1) and (2) is applied to the microgrid. In this step, the DG unit monitors the compensation signals coming from the central

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controller. Once the DG unit receives a compensation signal, its control mode switches to steps 2 and 3. Note that in the first step, the ripple-free real power P_{ave} is also measured by using an additional moving average filter. And this value is recorded as a reference during the compensation in steps 2 and 3.

Step 2 (Real Power Disturbance Injection): When a compensation flag from the microgrid central controller is received by the DG unit local controller, the DG unit starts power sharing compensation by activating steps 2 and 3 at the same time. Note that the sending of one way compensation flag does not need any information of DG unit local controllers. Therefore, the communication from DG units to the microgrid central controller is not necessary. In step 2, a transient disturbance term associated with reactive power, imbalance power, or harmonic power is slowly deducted from the frequency control. Accordingly, the conventional droop control is modified as

$$f_{\mathrm{DG}} = f^* - D_P \cdot P_{\mathrm{LPF}} - T_{\mathrm{transient}} \qquad (16)$$

$$E_{\mathrm{DG}} = E^* - D_q \cdot Q_{\mathrm{LPF}} \qquad (17)$$

where the transient disturbance term $T_{transient}$ is determined by the type of compensation flag signal from the microgrid central controller. It has three options depending on how the flag signal from central controller is

$$T_{\mathrm{transient}} = \begin{cases} G \cdot (D_{\mathrm{CQ}} \cdot Q_{\mathrm{LPF}}) & \text{Reactive power flag (Q flag)} \\ G \cdot (D_{\mathrm{CN}} \cdot Q_{\mathrm{Neg}}) & \text{Imbalance power flag (Neg flag)} \\ G \cdot (D_{\mathrm{CH}} \cdot Q_{\mathrm{Har}}) & \text{Harmonic power flag (Har flag)} \end{cases} \qquad (18)$$

where G is a time-varying soft compensation factor. It in-creases slowly from 0 to 1 at the beginning of the compensation and it reduces to zero at the end of the compensation. The coefficients D_{CQ}, D_{CH}, and D_{CN} are designed to ensure that appropriate amount of disturbances is injected to the frequency control. It is important to note that the reactive, harmonic, and imbalance power sharing errors cannot be simultaneously compensated by the proposed method. In each compensation transient (steps 2 and 3), only one type of compensation flag can be generated by the microgrid central controller. Fig. 7 presents a detailed diagram of injecting real power disturbance.

Step 3 (Virtual Impedance Adjustment): When the real power variation is introduced by injecting frequency disturbances, it should be captured to adjust the DG series virtual impedance. This process is defined as step 3. The detailed virtual impedance regulation diagram is shown in Fig. 6.

First, the measured ripple free DG real power P_{ave} before receiving the compensation flag is saved to identify the real power variations. As shown in Fig. 7, if the reactive power compensation flag is received by the DG unit, the difference between the measured real power P_{LPF} and the DG real power P_{ave} saved in the end of step 1 is employed to adjust the DG virtual impedance at the fundamental positive sequence as

$$L_{V,f} = L^*_{V,f} - \frac{k_q}{s} \cdot (P_{\mathrm{LPF}} - P_{\mathrm{ave}}) \qquad (19)$$

where $L^*_{V,f}$ is the static virtual inductance at the fundamental positive sequence. As discussed earlier, this static virtual inductance is used to ensure that the DG equivalent impedance is always inductive at the fundamental positive sequence. $L_{V,f}$ is adjusted by an integral control with the transient real power variations ($P_{LPF} - P_{ave}$) as the input.

To get a better understanding of the principle of the pro-posed compensation scheme, it is assumed that DG1 shares less reactive power in step 1. When the reactive power compensation flag is received by DG1, the real power has some overshoot due to the control scheme. As it has been pointed out that smaller equivalent fundamental positive sequence inductance increases the sharing of reactive power load in this DG unit, the real power overshoot ($P_{LPF} - P_{ave}$) are employed as an input to tune the magnitude of virtual inductance at fundamental positive sequence. When the microgrid reactive power load demand is equally shared by multiple DG units, the frequency control will automatically make the transient real power variation ($P_{LPF} - P_{ave}$) reduces to zero, as the same amount of frequency bias is injected by $T_{Transient}$.

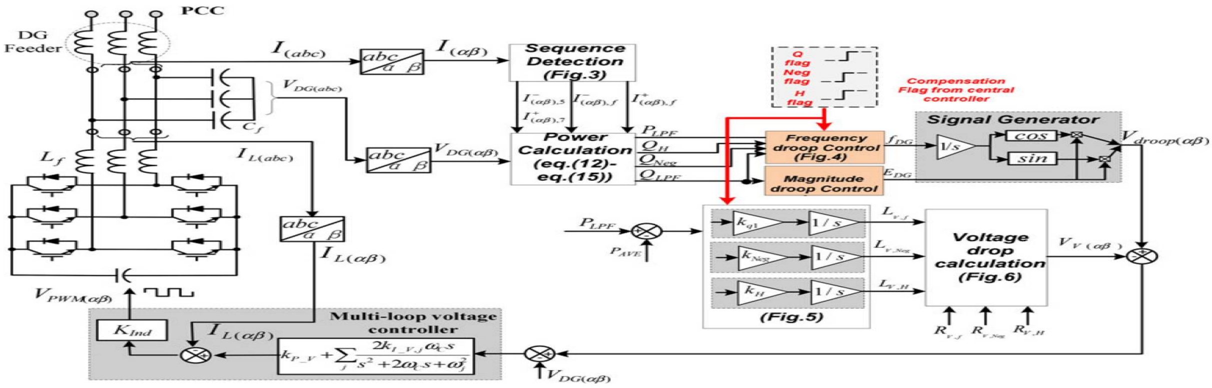

Fig. 7 Complete diagram of a DG unit using the control method.

For the same reason, if an imbalance power compensation flag is received by the DG unit local controller, a disturbance $G \cdot D_{CN} \cdot Q_{Neg}$ shall be injected to the frequency droop control and the virtual inductance $L_{V,Neg}$ at the fundamental negative sequence shall be adjusted in a similar manner as

$$L_{V,\mathrm{Neg}} = L^*_{V,\mathrm{Neg}} - \frac{k_{\mathrm{Neg}}}{s} \cdot (P_{\mathrm{LPF}} - P_{\mathrm{ave}}) \qquad (20)$$

where $L^*_{V,\mathrm{Neg}}$ is a static virtual inductance at the fundamental negative sequence frequency. k_{Neg} is an integral gain to adjust the virtual inductance.Finally, when the DG unit receives a flag signal to compensate the system harmonic power sharing errors, the real power variation due to the injection of $G \cdot D_{CH} \cdot Q_{Har}$ needs to be captured to regulate the virtual impedance at selected harmonic frequencies as

$$L_{V,H} = -\frac{k_{\mathrm{Har}}}{s} \cdot (P_{\mathrm{LPF}} - P_{\mathrm{ave}}) \qquad (21)$$

where $L_{V,H}$ is the virtual inductance at the harmonic frequencies.

Note that the proposed method is developed based on an assumption that real power load in an islanding distribution sys-tem is fixed during the compensation process. When there are some real power load demand fluctuations during steps 2 and 3, the proposed method may not be able to completely eliminate reactive power, harmonic power, and imbalanced power sharing errors. To address this concern, the proposed compensation should be activated in very few minutes. With this arrangement, the errors caused by real power fluctuations can be mitigated by other compensations. Additionally, the compensation period shall be properly designed to reduce the possibility of real power variations during the compensation. This can be achieved by tuning the integral gain in the virtual inductance adjustment loop.

IV. RESULTS AND DISCUSSION

Fig 8, shows the simulink model of micro grid with harmonic load

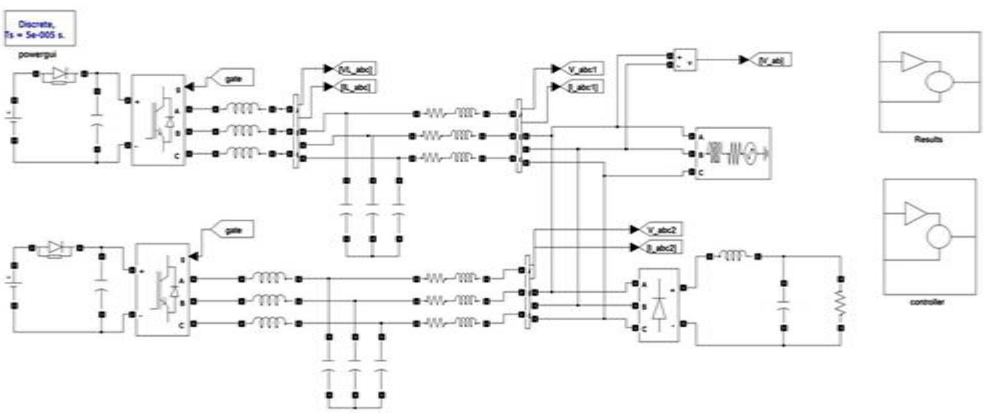

Fig 8 Simulink model of micro grid with harmonic load

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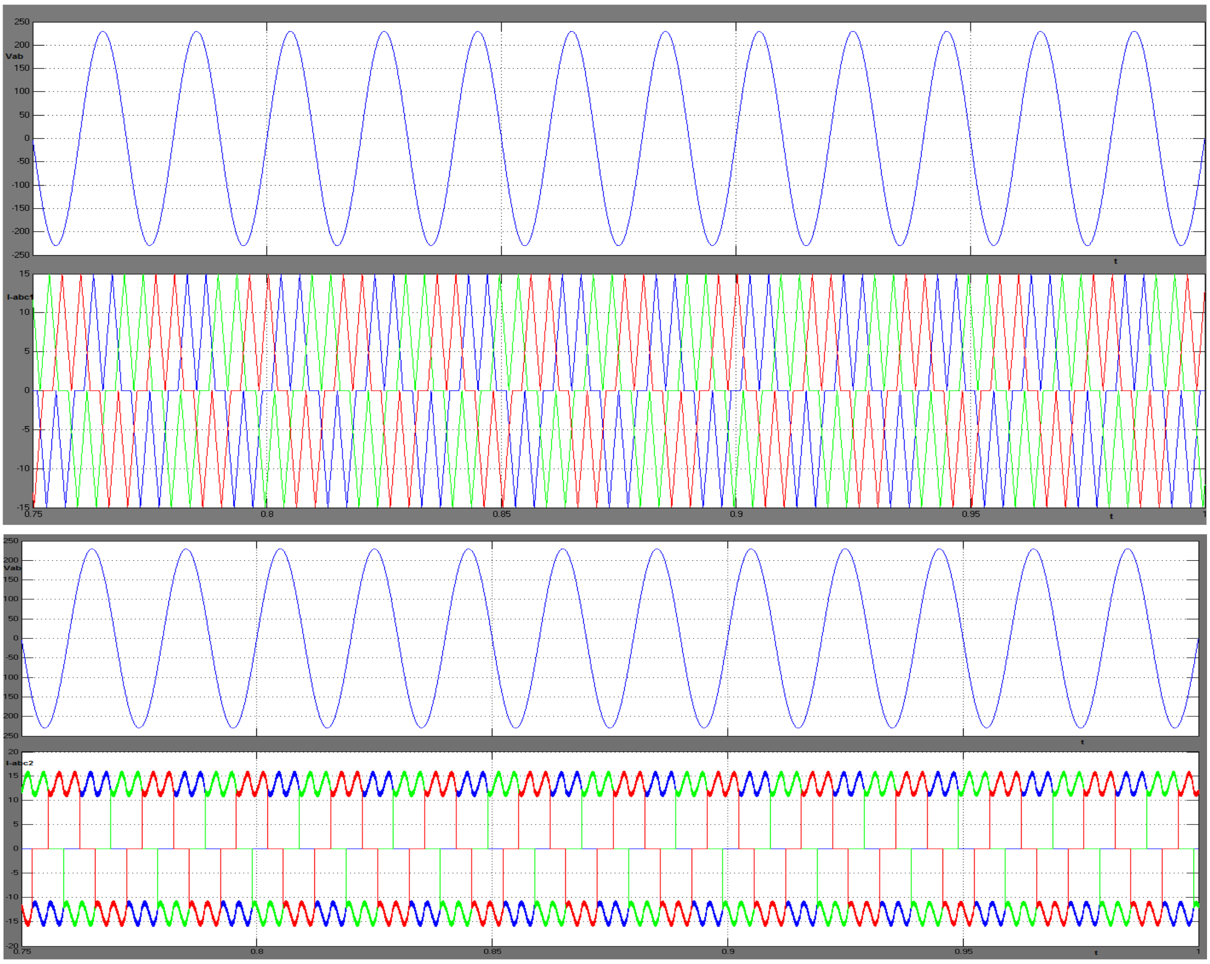

Fig 9 Simulation waveforms of the conventional droop control in a micro grid with harmonic load

The simulation waveform in fig 9 shows the PCC load is a three-phase diode rectifier and the performance of the microgrid when the control of the harmonic virtual impedance is not activated for DG1 and DG2. DG1 provides more harmonic current as it has smaller existing feeder inductance.

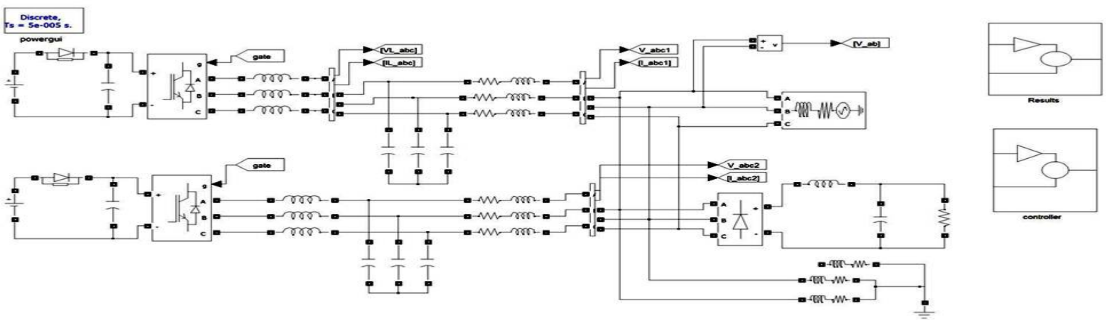

Fig 10 Simulink model of micro grid with imbalance RL load

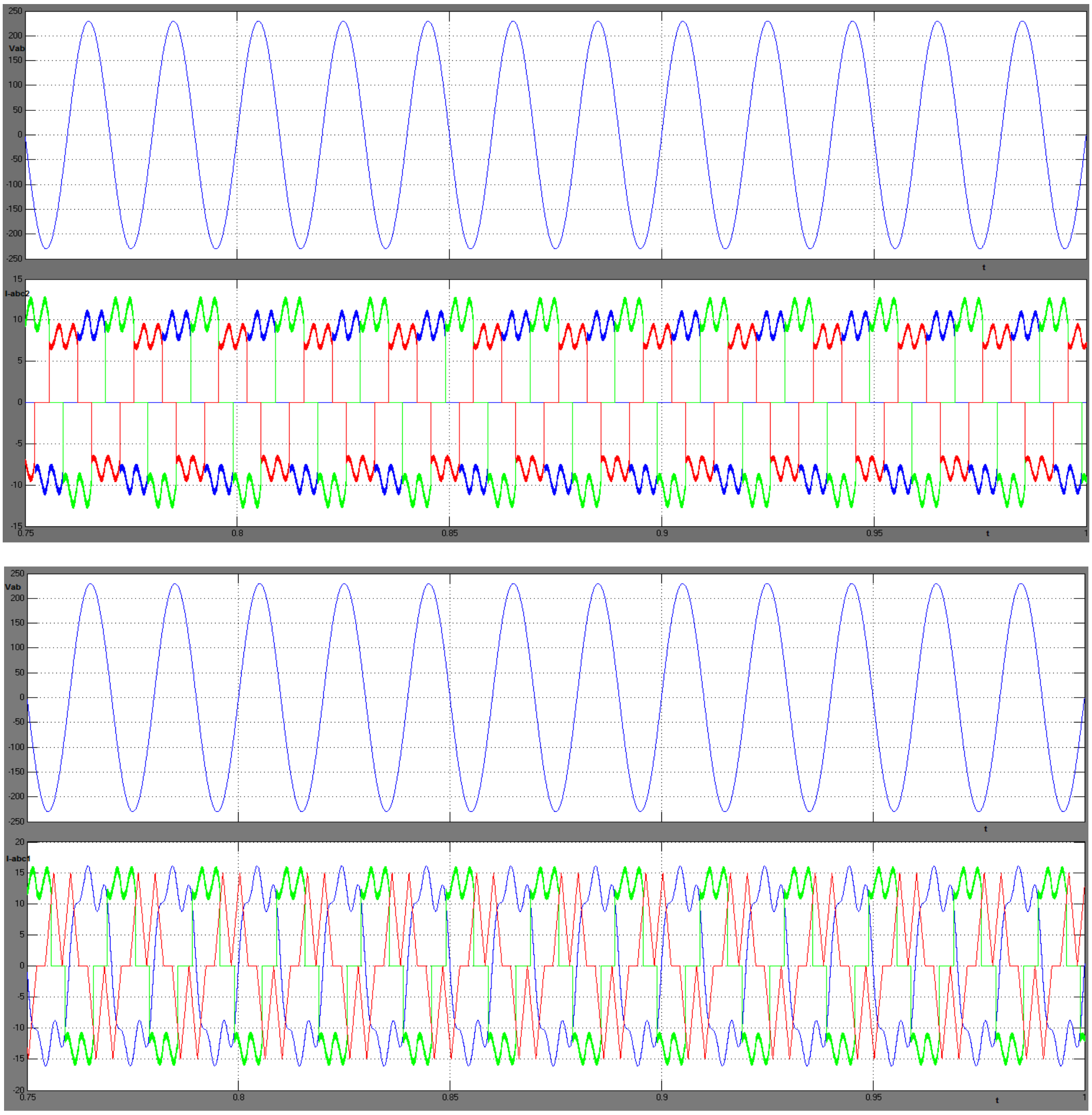

Fig 11 Simulation waveforms of the proposed compensation in a micro grid with imbalance RL load

Simulation waveforms in fig 11 show a micro grid with generalized PCC loads for DG1 and DG2. An imbalanced RL load and a three-phase diode rectifier are connected to PCC at the same time. To reduce the micro grid power sharing errors, the compensation done in reactive power compensation, imbalance power compensation, and harmonic power compensation, it is seen that the proposed method is effective to address the power sharing errors in a micro grid with generalized loads.

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V.CONCLUSION

This paper discusses an enhanced power sharing scheme for islanding microgrids. The proposed method utilizes the frequency droop as the link to compensate reactive, imbalance, and harmonic power sharing errors. Specifically, the frequency droop control with additional disturbance is used to produce some real power sharing variations. These real power variations are used to adjust the DG unit virtual impedances at fundamental positive sequence, fundamental negative sequence, and harmonic frequencies. With the interactions between the transient frequency droop control and the variable DG virtual impedance, the impact of unknown feeder impedances can be properly compensated and an accurate power sharing is achieved at the steady state. Comprehensive simulated results from a low-voltage microgrid give effectiveness of the proposed scheme.

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