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Power Quality Control Strategy of Islanding Microgrid Under Distorted and Unbalanced Conditions

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Abstract: This paper presents a novel power quality control strategy for islanding microgrid contains multiple DG units under both distorted and unbalanced conditions. Actually the power quality of microgrid bus and the point of common coupling (PCC) are the main concerns due to the determination of high-quality power energy to the main grid and sensitive loads connected to microgrid bus. To tackle this problem, three control schemes based on PIR cascaded structure for DG units are developed to realize different control objectives. In these categories, the fundamental voltage is regulated by conventional PI controller to ensure direct voltage support and smooth operation mode transition while the harmonics or unbalanced variables are compensated with resonates controller in synchronous reference frame without sequential sequence decomposition. The proposed power quality control strategy that comprehensively utilization of these control schemes can satisfy power quality requirements of islanding microgrid, which is confirmed by simulation results considering both unbalance and distortion.

Keywords: Microgrid, distributed generation, power quality, resonant controller, harmonics, unbalance, distortion

1. INTRODUCTION

In the past decade, there has been significant increase in the research, development, and utilization of distributed resource system. The large penetration of distributed resource (DR) system in form of distributed generation (DG), distributed storage (DS) has brought about the conception of microgrid. A microgrid defined as a cluster of DR units and loads, can operate in the grid-connected mode, the islanding mode and transfer between the two modes [1]. The idea of forming microgrid is that it could provide adequately reliable, economical and high-quality power energy to better the localized load demand [2].

In reality, consumer loads usually contain both unbalanced loads and nonlinear loads, which cause unbalance and distortion that may propagate throughout microgrid. If these influences are not taken into account and fully compensated, they will cause adverse impacts on equipments and power system, such as considerably degrading the operation efficiency of DG units, the performance of loads connecting to the microgrid bus, even the stability of power system [3]. Therefore, IEEE Standard Coordinating Committee specifies and recommends the power quality of distributed resource system and microgrid [4].

Several control strategies are aimed to eliminate the unfavorable effects [5]. The unbalance or distortion can be usually improved by series active power filter through injection of negative sequence or harmonic voltage [6], or shunt active filter through compensating the line current [7]. However, extra power converters need to be equipped and it may interfere with the active and reactive power supply by the DG units. Some approaches are presented to use grid-connected interfacing converters with current control scheme (CCS) for unbalance or harmonic compensation, which results in the emerging conception of multi-functional DG unit [8, 9].

Based on the aforementioned research motivations, this paper develops three control schemes of DG unit based on PIR controllers implemented in synchronous reference frame to simultaneously regulate fundamental and harmonic components. Based on their features, a specific power quality enhancement strategy that comprehensively utilization of these control schemes is designed in islanding operation mode under both unbalanced and nonlinear loads.

The paper is organized as follows. Section II analysis the impacts of nonlinear load and unbalanced loads on microgrid. Section III, section IV and section V describe the implementation and performance of these three proposed control schemes, respectively. Section VI discusses the power quality enhancement strategy of islanding microgrid in details verified by simulation results. Finally, Section VII draws the conclusion.

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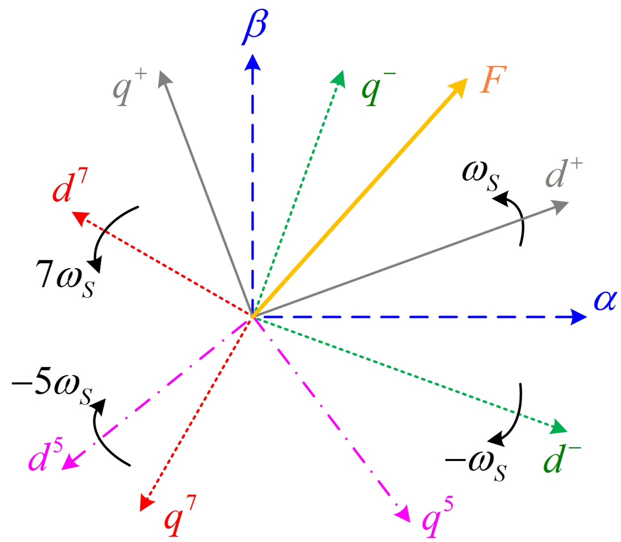

Fig. (1). Relationship of control variable vectors in various reference frame.

2. SYSTEM ANALYSIS

2.1. Relationship of Control Variables in Various Reference Frames

For a three phase three wire microgrid system with no neutral point connections, the zero-sequence components are ignored during unbalanced or distorted condition, and the positive-sequence and negative-sequence quantities of fundamental and harmonics alternating at -5 and 7 multiple of synchronous frequency are considered in the analysis. The proposed control scheme in micrgrid under both unbalanced loads and nonlinear loads is implemented in the positive synchronous reference frame. Consequently, In order to investigate the relationship of control variables in various reference frames, Fig. (**1**) presents a vector diagram that represents the spatial relationship among various reference frames including a stationary reference frame $(\alpha\beta)$, a positive synchronous reference frame $(dq)^+$ rotating with an angular speed of ω_s, a negative synchronous reference frame $(dq)^-$ rotating with an angular speed of $-\omega_s$, a negative fifth harmonic reference frame $(dq)^5$ rotating with an angular speed of $-5\omega_s$ and a positive seventh harmonic reference frame $(dq)^7$ rotating with an angular speed of $7\omega_s$. The vector F stands for voltage, current or power of DG unit. According to this figure, the transformations among these various reference frames can be obtained as follows:

$$F_{\alpha\beta} = F^+_{dq} e^{j\omega_s t} = F^5_{dq} e^{-j5\omega_s t} = F^7_{dq} e^{j7\omega_s t} \tag{1a}$$

$$F^+_{dq} = F_{\alpha\beta} e^{-j\omega_s t} = F^-_{dq} e^{-j2\omega_s t} = F^5_{dq} e^{-j6\omega_s t} = F^7_{dq} e^{j6\omega_s t} \tag{1b}$$

where the superscripts +, -, 5, 7 represent the $(dq)^+$, $(dq)^-$, $(dq)^5$, $(dq)^7$ reference frames, respectively.

Under unbalanced loads, the vector F in the positive synchronous reference frame is composed of both positive and negative sequence components, expressed as

$$F^+_{dq} = F^+_{dq+} + F^+_{dq-} = F^+_{dq+} + F^-_{dq-} e^{-j2\omega_s t} \tag{2a}$$

For nonlinear loads, F can be expressed in terms of their positive sequence of the fundamental and the harmonics components of $-5\omega_s$ and $7\omega_s$ in the positive synchronous reference frame:

$$F^+_{dq} = F^+_{dq+} + F^+_{dq5} + F^+_{dq7} = F^+_{dq+} + F^5_{dq5} e^{-j6\omega_s t} + F^7_{dq7} e^{j6\omega_s t} \tag{2b}$$

where subscripts +, -, 5, 7 represent the positive-sequence and negative-sequence quantities of fundamental and harmonics components alternating at -5 and 7 multiple of synchronous frequency, respectively. Thus, the negative sequence component behaves as the ac component pulsating at the frequency of $2\omega_s$ in the positive synchronous reference frame while the harmonics components of $-5\omega_s$ and $7\omega_s$ perform as the ac components alternating at the frequency of $\pm 6\omega_s$ in the positive synchronous reference frame.

2.2. Impact of Unbalanced Loads and Nonlinear Loads on Microgrid

Fig. (**2**) shows the circuit representation of microgrid system consists of n inverter-based DG units. The nonlinear loads connect to DG1 terminal as local loads through an LC

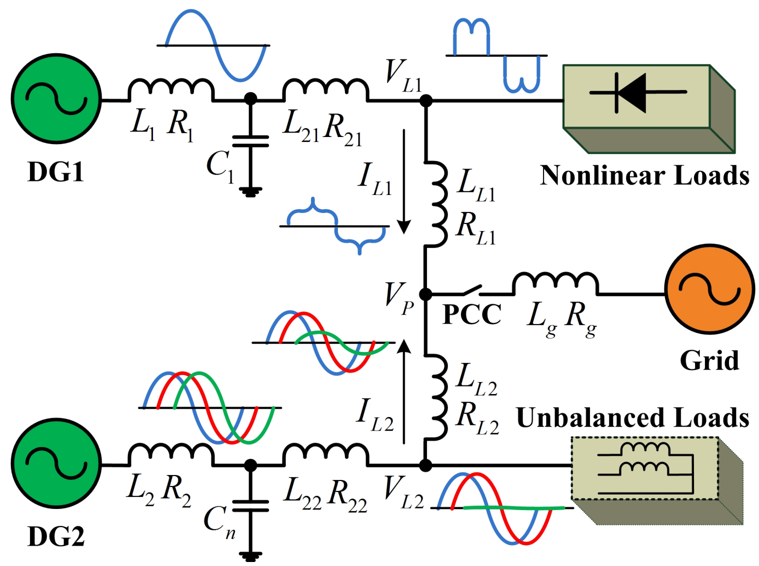

Fig. (2). The circuit representation of microgrid system.

filter with a coupling inductor, which cause distorted current I_{L1} and voltage V_{L1} in microgrid bus [10]. The harmonics seriously degrade the performance of other loads connected to microgrid, even the main grid during grid-connected mode, due to the deteriorative power quality at PCC.

Under distortion condition, the voltage at PCC is composed of a fundamental and two harmonic components (fifth and seventh) at the same frequency of $6\omega_s$, as expressed in the positive and negative synchronous rotating frames

$$E_{Pdq+} = R_{L1}I_{L1dq+} + j\omega L_{L1}I_{L1dq+} + V_{L1dq+} + R_{L1}I_{L1dq6+} + j\omega L_{L1}I_{L1dq6+} + V_{L1dq6+} + e^{-j6\omega t}R_{L1}I^*_{L1dq6+} - e^{-j6\omega t}j\omega L_{L1}I^*_{L1dq6+} \quad (3a)$$

$$E_{Pdq-} = R_{L1}I_{L1dq-} - j\omega L_{L1}I_{L1dq-} + V_{L1dq-} + R_{L1}I_{L1dq6-} - j\omega L_{L1}I_{L1dq6-} + V_{L1dq6-} + e^{j6\omega t}R_{L1}I^*_{L1dq6-} + e^{j6\omega t}j\omega L_{L1}I^*_{L1dq6-} \quad (3b)$$

where $E_{Pdq+} = E_{Pd+} + E_{Pd6+} + jE_{Pq+} + jE_{Pq6+}$,

$V_{L1dq+} = V_{L1d+} + V_{L1d6+} + jV_{L1q+} + jV_{L1q6+}$,

$I_{L1dq+} = I_{L1d+} + I_{L1d6+} + jI_{L1q+} + jI_{L1q6+}$,

$E_{Pdq-} = E_{Pd-} + E_{Pd6-} + jE_{Pq-} + jE_{Pq6-}$,

$V_{L1dq-} = V_{L1d-} + V_{L1d6-} + jV_{L1q-} + jV_{L1q6-}$,

$I_{L1dq-} = I_{L1d-} + I_{L1d6-} + jI_{L1q-} + jI_{L1q6-}$,

$I^*_{L1dq6+} = I_{L1d6+} - jI_{L1q6+}$, $I^*_{L1dq6-} = I_{L1d6-} - jI_{L1q6-}$.

The complex power from DG1 to PCC can be depicted by the positive sequential and negative sequential vectors in the synchronously rotating frame

$$S_P = \frac{3}{2}(e^{j\omega t}E_{Pdq+} + e^{-j6\omega t}E_{Pdq6-})(e^{j\omega t}I_{L1dq+} + e^{-j6\omega t}I_{L1dq6-})^* \quad (4)$$

Substituting (3a) and (3b) into (4) and decomposing the real and reactive powers into the components with various alternating frequencies yields

$$P_P = P_{P0} + P_{P\cos 6}\cos(6\omega t) + P_{P\sin 6}\sin(6\omega t) + P_{P\cos 12}\cos(12\omega t) + P_{P\sin 12}\sin(12\omega t) \quad (5a)$$

$$Q_P = Q_{P0} + Q_{P\cos 6}\cos(6\omega t) + Q_{P\sin 6}\sin(6\omega t) + Q_{P\cos 12}\cos(12\omega t) + Q_{P\sin 12}\sin(12\omega t) \quad (5b)$$

Similarly, if the unbalanced loads connect to DG2 terminal as local loads, the voltage at PCC can be described in terms of positive and negative sequence components in the positive and negative synchronous rotating frames as

$$E_{Pdq+} = R_{L1}I_{L1dq+} + j\omega L_{L1}I_{L1dq+} + V_{L1dq+} + e^{-j2\omega t}R_{L1}I^*_{L1dq+} - e^{-j2\omega t}j\omega L_{L1}I^*_{L1dq+} \quad (6a)$$

$$E_{Pdq-} = R_{L1}I_{L1dq-} - j\omega L_{L1}I_{L1dq-} + V_{L1dq-} + e^{j2\omega t}R_{L1}I^*_{L1dq-} + e^{j2\omega t}j\omega L_{L1}I^*_{L1dq-} \quad (6b)$$

where $E_{Pdq+} = E_{Pd+} + jE_{Pq+}$, $V_{L1dq+} = V_{L1d+} + jV_{L1q+}$,

$I_{L1dq+} = I_{L1d+} + jI_{L1q+}$, $E_{Pdq-} = E_{Pd-} + jE_{Pq-}$,

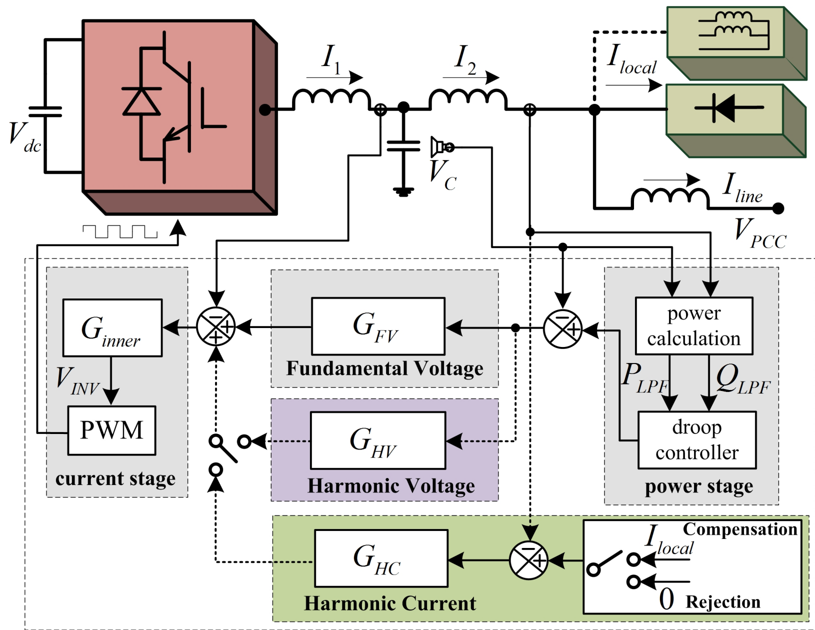

Fig. (3). The implementation of control scheme in DG unit.

$V_{L1dq-} = V_{L1d-} + jV_{L1q-}$, $I_{L1dq-} = I_{L1d-} + jI_{L1q-}$

$I^*_{L1dq+} = I_{L1d+} - jI_{L1q+}$, $I^*_{L1dq-} = I_{L1d-} - jI_{L1q-}$.

The complex power from DG2 to PCC can be depicted by the positive sequential and negative sequential vectors in the synchronously rotating frame

$$S_P = \frac{3}{2}(e^{j\omega t}E_{Pdq+} + e^{-j\omega t}E_{Pdq-})(e^{j\omega t}I_{L1dq+} + e^{-j\omega t}I_{L1dq-})^* \quad (7)$$

Substitute (6a) and (6b) to (7) and rearrange the instantaneous real power and reactive power into three terms, i.e., the dc average term, and the sine terms of twice the line frequency as given by

$$P_P = \text{Real}\{S_P\} = P_{P0} + P_{P\cos 2}\cos(2\omega_s t) + P_{P\sin 2}\sin(2\omega_s t) \quad (8a)$$

$$Q_P = \text{Imge}\{S_P\} = Q_{P0} + Q_{P\cos 2}\cos(2\omega_s t) + Q_{P\sin 2}\sin(2\omega_s t) \quad (8b)$$

It can be observed in (3) and (6) that under unbalanced or nonlinear loads, the voltage and current at PCC in the positive synchronous reference frame consist of both dc and ac components at double or six multiples of synchronous frequency. Meanwhile, both the instantaneous real and reactive power contain oscillating components of double or six and twelve times the synchronous frequency.

3. FVHV CONTROL SCHEME OF DG UNIT UNDER DISTORTION AND UNBALANCE

3.1. Principle of FVHV Control Scheme

The most characteristic of islanding microgrid is that the system itself has to generate a constant voltage and frequency irrespective of varying power source and consumer loads [11]. Therefore, fundamental voltage control scheme based on PI controller has been widely used in most of DG interfacing inverters[12]. To improve voltage quality of islanding microgrid considering distortion and unbalance, the Fundamental Voltage Harmonic Voltage (FVHV) control scheme based on PIR controller for DG units is proposed to simultaneously regulate fundamental and harmonic voltage, as shown in Fig. (**3**).

In this case, the droop controllers in the power control stage is described as

$$\omega_{DG} = \omega^* + m(P_{rated} - P_{LPF}) \quad (9a)$$

$$E_{DG} = E^* + n(Q_{rated} - Q_{LPF}) \quad (9b)$$

where ω^* and ω_{DG} are the nominal and DG reference angular frequencies. E^* and E_{DG} are the nominal and DG reference voltage magnitudes. *m* and *n* are the droop coefficients for the real power P_{LPF} and reactive power Q_{LPF} control, respectively. It should be noted that DG units can output their rated power based on the above droop control in the grid-connected mode without control schemes transition, except that the microgrid and the main grid should be properly synchronized before reconnection.

In the voltage tracking stage, the capacitor voltage is regulated by a well-known double loop controller. The outer loop can be a PIR controller at the synchronization reference frame as expressed in (9a) and (9b)

$$G_{FV}(s) = K_{pv} + \frac{K_{iv}}{s} \quad (10a)$$

$$G_{HV}(s) = \sum_{h=2,6,\ldots} \frac{K_{rvh}\omega_{ch}s}{s^2 + 2\omega_{cvh}s + (\pm h\cdot\omega_s)^2} \quad (10b)$$

where K_{pv} and K_{iv} are the proportional and integral gain that has the same function in the PI controller, K_{rvh} is the resonant gain at harmonics frequencies of $\pm h \cdot \omega_s$, ω_{cvh} is the cut-off frequencies at harmonics frequencies of $\pm h \cdot \omega_s$. The DG output power flow can be realized through fundamental voltage controller G_{FV} while the harmonic voltage can be regulated by the adoption of resonant controller G_{HV}. Note that the reference voltage contains only the fundamental component due to the low pass filter in power stage.

As the inner loop controller is to improve the damping and dynamic performances of the system, either the inductor current or the capacitor current of LC filter could be chosen as the inner loop feedback [13]. The simple proportional control is normally adopted

$$G_{inner}(s) = K_{pi} \tag{11}$$

4. FVHC1 CONTROL SCHEME OF DG UNIT UNDER DISTORTION AND UNBALANCE

4.1. Principle of FVHC1 Control Scheme

Similar to FVHV, in order to simultaneously control of the DG fundamental voltage and line harmonic currents, the harmonic current resonant controller is incorporated with fundamental voltage control into the cascaded control structure. The implementation of Fundamental Voltage and Harmonic Current (FVHC) control scheme is also shown in Fig. (**3**). The fundamental voltage tracking controller is the same as G_{FV} in (10a) and the harmonic current resonant controller G_{HC} at the synchronization reference frame can be described as

$$G_{FV}(s) = K_{pv} + \frac{K_{iv}}{s} \tag{12a}$$

$$G_{HC}(s) = \sum_{h=2,6,\text{L}} \frac{K_{rih}\omega_{ch}s}{s^2 + 2\omega_{cih}s + (\pm h \cdot \omega_s)^2} \tag{12b}$$

where K_{rih} is the resonant gain at harmonics frequencies of $\pm h \cdot \omega_s$, ω_{cih} is the cut-off frequencies at harmonics frequencies of $\pm h \cdot \omega_s$. Since the line harmonic currents and DG fundamental voltage are decoupled as demonstrated later, they could be regulated separately by using G_{HC} and G_{FV}. The line harmonics currents can be eliminated by setting current reference I_{ref} to zero and the effective of local load can be rejected, so this FVHC control scheme for line current rejection is named FVHC1 here.

The configuration and major function of power stage and inner current closed-loop in FVHC1 are the same as those in FVHV, which will not be addressed here due to space limitation.

4.2. FVHC2 Control Scheme of DG unit under Distortion and Unbalance

When the reference current I_{ref} is set to be the harmonic current of local loads, the DG unit controlled by FVHC can realize the function of shunt active power filer (APF) to compensate most of the harmonic currents produced by local loads. Hence, this FVHC control scheme for load harmonic compensation is called FVHC2 here.

The configuration and implementation of FVHC2 are the same as FVHC1 except that the measured total local current I_{local} is directly used as the reference current, depicted in Fig. (**3**). It is worth mentioning that the harmonic extraction for conventional APF is not necessary in FVHC2, which could effectively reduce computation burden for low-power cost-effective DG unit [11]. Further analysis demonstrates that FVHC2 has the same frequency domain characteristics of FVHC1 as illustrated above.

4.3. Power Quality Enhancement Of Islanding Microgrid Under Unbalance And Distortion

Comprehensively utilization of FVHV, FVHC1 and FVHC2 controlled DG units to enhance the power quality of islanding microgrid system under unbalance and distortion as mentioned earlier, has been verified in this section. The detailed configuration of microgrid system is illustrated in Fig. (**4**). The microgrid system consists of three DG units at the same power rating. DG1 has a diode rectifier as local load while the unbalanced load with one phase short circuit is adopted as the local load of DG2. Two linear load are connected to DG3 terminal and PCC, respectively. In order to satisfy different power quality requirements of microgrid operation mode, different control schemes should be applied in DG units to improve the power quality of microgrid system.

When the microgrid system is disconnected to the main grid and operates in islanding mode, it is desired to ensure the minimized voltage unbalance and distortion in accordance with IEEE Std 1547.4-2011 as illustrated by Table **1**. To realize the purpose, the DG1 unit is controlled by FVHC2 control scheme to compensate its local harmonic currents produced by nonlinear load while the DG2 unit's task is to reduce the pollution of unbalanced load to microgrid bus using FVHC2. Meanwhile, the FVHV control scheme is applied to DG3 unit, leaving a clean voltage at PCC.

To evaluate performance of islanding microgird controlled by three control scheme with local unbalanced load, the negative sequence component caused by unbalanced loads can be evaluated by the Unbalance Factor (UF) as expressed in (9a) and the harmonic component caused by

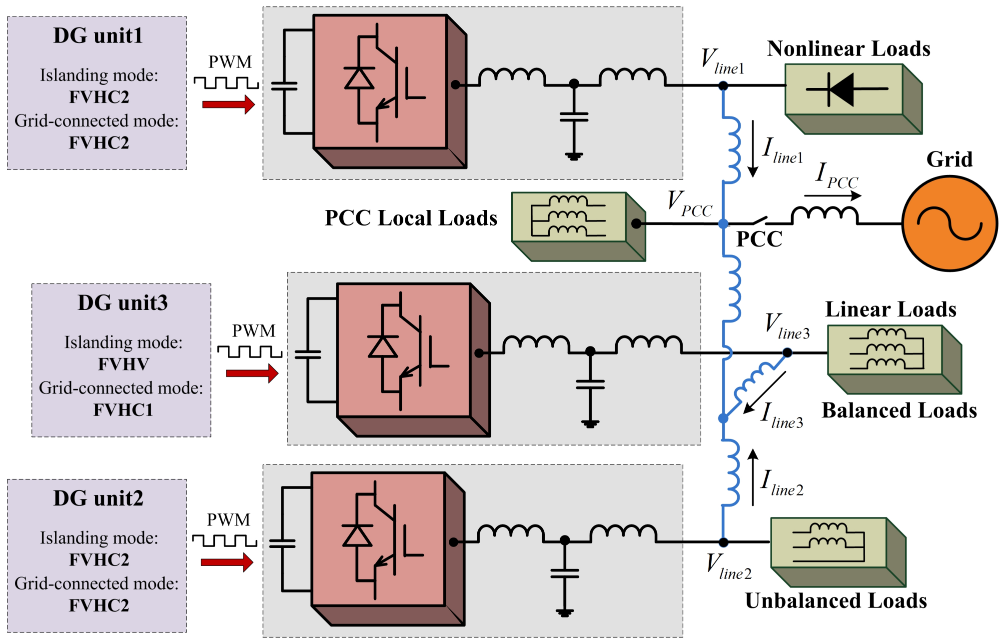

Fig. (4). The structure diagram of microgrid system with three DG units.

Table 1. Maximum harmonic current distortion.

Individual Harmonic Order	Percent (%)
h<11	4.0
11≤h≤17	2.0
17≤h≤23	1.5
23≤h≤35	0.6
h≤35	0.3
Total demand distortion (TDD)	5.0

nonlinear loads can be evaluated by Total Harmonic Distortion(THD).

$$UF = \frac{\sqrt{\left(F_d^-\right)^2 + \left(F_q^-\right)^2}}{\sqrt{\left(F_d^+\right)^2 + \left(F_q^+\right)^2}} \times 100\% \tag{13}$$

Fig. (**5**) shows the performances of islanding microgrid with conventional and proposed control schemes. the UF and THD of DG line voltage and current is obtained in Table **2**. At the beginning, the DG units in islanding microgrid are controlled by conventional method with only PI controller at the fundamental frequency. It is obvious that the unbalanced and distorted currents are shared by DG units according to their respective harmonics impedances and all the loads connected to microgrid are affected by polluted voltage. The control schemes are applied to DG units as mentioned earlier at the time of 0.7s. It can be seen that the majority of harmonic load current flow to DG units controlled by FVHC2 and the power quality of microgrid bus is considerably improved.

CONCLUSION

This paper proposed a novel power quality enhancement strategy of islanding microgrid considering distortion and unbalance conditions. This strategy comprehensively utilizes three control schemes based on PIR cascaded structure for DG units, such as FVHV, FVHC1, FVHC2. With the cascaded structure based on PIR, the FVHV control scheme can simultaneously regulate fundamental and harmonic voltage of DG unit to supply a sinusoidal voltage while the FVHC1 and FVHC2 control scheme are able to regulate fundamental voltage, meanwhile, compensate local load harmonic currents or reject microgrid bus harmonic current. DG units can seamlessly change their control schemes to satisfy different power quality requirements of islanding microgrid.

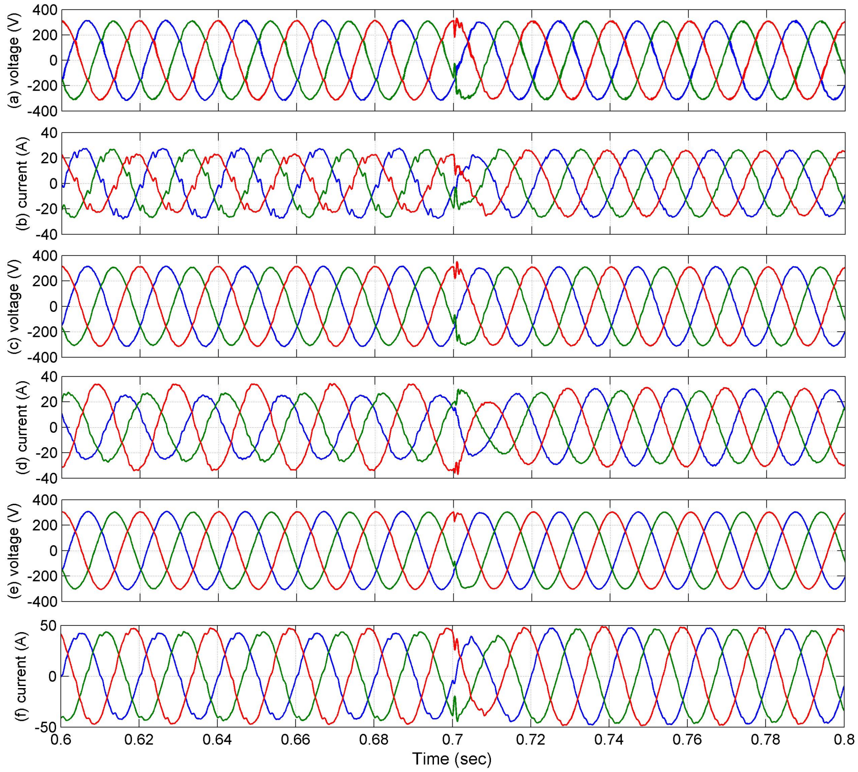

Fig. (5). The line voltage and line current of DG units in islanding microgrid (control scheme transition at 0.7s. a: DG1 line voltage; b: DG1 line current; c: DG2 line voltage; d: DG2 line current; e: DG3 line voltage; f: DG3 line current).

Table 2. UF and THD of DG untis under different operation with different control scheme.

Operation Mode		Islanding Mode	
Control Scheme		**Conventional Method**	**Proposed Method**
DG1 line voltage	UF	1.79%	0.23%
	THD	3.68%	1.02%
DG1 line current	UF	11.95%	0.81%
	THD	9.52%	2.07%
DG2 line voltage	UF	2.33%	0.39%
	THD	2.46%	0.82%
DG2 line current	UF	20.57%	5.03%
	THD	4.86%	0.76%
DG3 line voltage	UF	1.71%	0.15%
	THD	2.37%	0.44%
DG3 line current	UF	7.24%	1.74%
	THD	4.22%	1.23%
PCC voltage	UF	2.19%	0.26%
	THD	2.56%	0.72%

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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