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Enhanced Power Quality and Minimized Peak Current Control in An Inverter based Microgrid under Unbalanced Grid Faults

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Abstract— **The microgrid inverter experiences the power oscillations and current harmonics in case of the unbalanced grid voltage faults. However, there is a trade-off between power oscillations and current harmonics should be considered in three phase three wire inverter systems during the conventional fault ride through control. In order to solve this problem, a novel control strategy is proposed to enhance the output current quality while mitigating the active and reactive output power oscillations. Moreover, a simple current-limited control strategy can be achieved without the necessity of the voltage/current positive/negative sequence extraction. Finally, the simulation tests of the conventional and proposed control solutions are carried out. The results verify the effectiveness of the proposed strategy.**

Keywords—microgrid inverter; unbalanced; fault ride through; current-limited

I. INTRODUCTION

Microgrid integrated with renewable energy resources (RES) has attracted considerable attentions due to its economic aspects and flexible controllability [1-4]. In general, power electronic inverters which act as the interfaces between RESs and grid should have the ability to enhance power quality and ride though the short-term gird faults or disturbances, especially under unbalanced grid conditions as so called fault ride through (FRT) capacity [5]. FRT control requires grid-connected inverters to withstand grid voltage sags and remains connected and avoid sudden tripping and the loss of power generation. The voltage collapse should be avoided by introducing active and reactive power injection to support the grid voltage [6]. Under these requirements, a wide range of FRT control strategies has been proposed to ensure the inverters operate flexibly under grid faults conditions.

The flexible power control concept, which facilitates multiple choices for FRT with different current references, has been proposed in [7-10]. An interesting FRT solution focused on the flexible power quality regulation by considering the instantaneous power ripples and current harmonics has been proposed and the current harmonic can be eliminated at the expense of active and reactive power oscillations [11]. Another FRT solution is fully flexible since positive and negative, active and reactive power/current can be simultaneously injected to improve the reliability of ride through services of grid-connected inverters [12]. However, for three-phase three-wire grid-connected inverter system, the control freedoms seems not enough to eliminate instantaneous power oscillations and current harmonics at the same time from the viewpoint of the conventional Instantaneous Power Theory [13-15]. Another new series of control strategies which utilize the zero sequence components are proposed to enhance the power control ability under unbalanced grid conditions. But the current reference generator based on a six dimensional matrix which is greatly increasing computational burden [16].

Further, advanced control algorithms for FRT are mainly based on symmetric sequences to achieve particular control objectives related to the current harmonics, power oscillations, dc bus ripples ,voltage support and complex peak current limitation during the unbalanced grid voltage faults have been proposed in [17-20]. In fact, the excessive and harmonic current in case of the unbalanced gird fault ride through significantly affects the system operation reliability [21]. The power oscillations will damages continuity of power supply for inverters based microgrid system [22]. However, few works have been developed for both power quality control and peak current-limited capacity for grid-connected inverter especially under unbalanced grid faults. On the one hand, in contrast to conventional Instantaneous Power Theory, the active and reactive power should be estimated accurately while the current harmonics are reduced [23]. On the other hand, it is more complex to control the amplitude of three phase currents during unbalanced grid faults, mainly because of the trend of simultaneously injecting both active and reactive powers coupling positive and negative sequence components. In such cases, the injection of positive and negative sequence power inherently induces different amplitudes in the injected phase current [24]. Therefore, the FRT solutions focuses on the enhanced power quality and minimized peak current control are attractive and needs further investigation.

In this paper, a novel control strategy based on delayed voltage is proposed to suppress the current harmonics while mitigating the active and reactive output power oscillations for three phase three wire systems. Moreover, it can achieve currents limitation in a simple control structure without any necessity of voltage/current positive and negative sequence extraction.

II. THE SYSTEM WORKING PRINCIPLE AND CONTROL STRATEGY

Fig.1 illustrates the schematic diagram of inverters-based microgrid system [25]. It comprises of the energy sources with optional energy storages and some dc/ac inverters. The inverters can operate both in autonomous mode and grid connected mode for different specific applications. This paper will focus on the latter case, especially for the FRT control under unbalanced grid voltage faults condition.

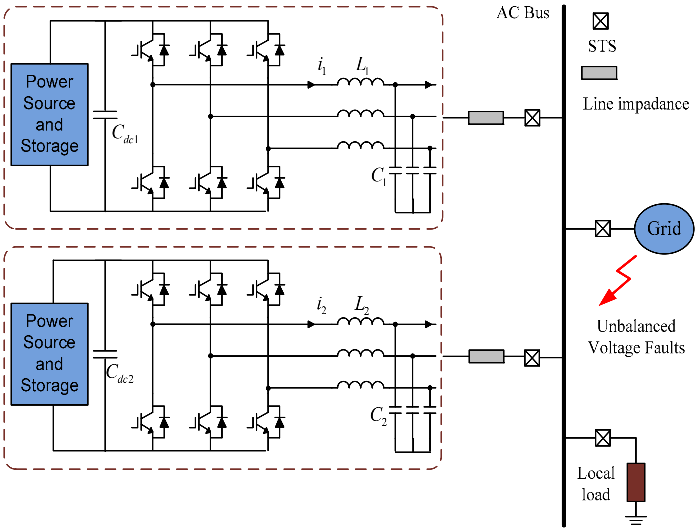


Fig.1. Schematic diagram of grid-connected inverter

A. Inherent reason for current distortion and power oscillation

For the sake of analysis, only one inverter based microgrid is considered to explain the working principle of the system. The three-phase grid voltage can be expressed as follows

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} U^+\sin(\omega t+\theta_p)+U^-\sin(\omega t+\theta_n) \\ U^+\sin(\omega t+\theta_p-120^\circ)+U^-\sin(\omega t+\theta_n+120^\circ) \\ U^+\sin(\omega t+\theta_p+120^\circ)+U^-\sin(\omega t+\theta_n-120^\circ) \end{bmatrix} \quad (1)$$

where U^+, U^-, θ_p ,θ_n and ω represents the positive and negative sequence voltage amplitude, phase angle and angular frequency respectively.

With the Clarke transformation, equation (1) can be expressed in stationary frame as follows

$$\begin{cases} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \dfrac{2}{3}\begin{bmatrix} 1 & -\dfrac{1}{2} & -\dfrac{1}{2} \\ 0 & \dfrac{\sqrt{3}}{2} & -\dfrac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} u_\alpha^+ + u_\alpha^- \\ u_\beta^+ + u_\beta^- \end{bmatrix} \\ \begin{bmatrix} u_\alpha^+ \\ u_\beta^+ \end{bmatrix} = \begin{bmatrix} U^+\sin(\omega t+\theta_p) \\ -U^+\cos(\omega t+\theta_p) \end{bmatrix} \quad \begin{bmatrix} u_\alpha^- \\ u_\beta^- \end{bmatrix} = \begin{bmatrix} U^-\sin(\omega t+\theta_n) \\ U^-\cos(\omega t+\theta_n) \end{bmatrix} \end{cases} \quad (2)$$

According to the conventional Instantaneous Power Theory, active and reactive power can be expessed as [13-15]

$$\begin{bmatrix} p \\ q \end{bmatrix} = \frac{3}{2}\begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

Substituting (2) into (3) the current components can be obtained as follows

$$\begin{cases} \begin{bmatrix} i_\alpha^* \\ i_\beta^* \end{bmatrix} = \dfrac{2}{3}\begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix}^{-1}\begin{bmatrix} P^* \\ Q^* \end{bmatrix} = \begin{bmatrix} i_{\alpha(p)}^* + i_{\alpha(q)}^* \\ i_{\beta(p)}^* + i_{\beta(q)}^* \end{bmatrix} \\ i_{\alpha(p)}^* = \dfrac{2}{3}\dfrac{P^* u_\alpha}{(u_\alpha)^2+(u_\beta)^2} = \dfrac{2}{3}\dfrac{P^* u_\alpha}{\tilde{D}} \\ i_{\alpha(q)}^* = \dfrac{2}{3}\dfrac{Q^* u_\beta}{(u_\alpha)^2+(u_\beta)^2} = \dfrac{2}{3}\dfrac{Q^* u_\beta}{\tilde{D}} \\ i_{\beta(p)}^* = \dfrac{2}{3}\dfrac{P^* u_\beta}{(u_\alpha)^2+(u_\beta)^2} = \dfrac{2}{3}\dfrac{P^* u_\beta}{\tilde{D}} \\ i_{\beta(q)}^* = -\dfrac{2}{3}\dfrac{Q^* u_\alpha}{(u_\alpha)^2+(u_\beta)^2} = -\dfrac{2}{3}\dfrac{Q^* u_\alpha}{\tilde{D}} \end{cases} \quad (4)$$

where $i_{\alpha(p)}^*, i_{\beta(p)}^*, i_{\alpha(q)}^*$ and $i_{\beta(q)}^*$ represent the active and reactive power current components in stationary frame respectively. $P^*$and Q^* are the inverter output active and reactive power reference and detemined by the inverter rated capacity.

It should be noted that the inverter current will not be sinusoidal because the denominator $\tilde{D}$ of (4) are not constant as expressed in (5). The detailed quantitative analysis of three phase current harmonics results can be found in [11].

$$\begin{aligned} \tilde{D} &= (u_\alpha)^2+(u_\beta)^2 = (u_\alpha^+ + u_\alpha^-)^2 + (u_\beta^+ + u_\beta^-)^2 \\ &= (U^+)^2 + (U^-)^2 - 2U^+U^-\cos(2\omega t+\theta_p+\theta_n) \end{aligned} \quad (5)$$

On the other hand, reference [11] suggests that the inverter current harmonics can be eliminated on condition that $2U^+U^-\cos(2\omega t+\theta_p+\theta_n)$ in (5) is cancelled, which can be easily achieved with a notch filter of $F(s)$. Thus, the sinusoidal inverter current references can be obtained as follows

$$\begin{cases} i_{\alpha(p)}^* = \dfrac{2}{3}\dfrac{P^* u_\alpha}{\left[(u_\alpha)^2+(u_\beta)^2\right]F(s)} = \dfrac{2}{3}\dfrac{P^* u_\alpha}{(U^+)^2+(U^-)^2} \\ i_{\alpha(q)}^* = \dfrac{2}{3}\dfrac{Q^* u_\beta}{\left[(u_\alpha)^2+(u_\beta)^2\right]F(s)} = \dfrac{2}{3}\dfrac{Q^* u_\beta}{(U^+)^2+(U^-)^2} \\ i_{\beta(p)}^* = \dfrac{2}{3}\dfrac{P^* u_\beta}{\left[(u_\alpha)^2+(u_\beta)^2\right]F(s)} = \dfrac{2}{3}\dfrac{P^* u_\beta}{(U^+)^2+(U^-)^2} \\ i_{\beta(q)}^* = -\dfrac{2}{3}\dfrac{Q^* u_\alpha}{\left[(u_\alpha)^2+(u_\beta)^2\right]F(s)} = -\dfrac{2}{3}\dfrac{Q^* u_\alpha}{(U^+)^2+(U^-)^2} \end{cases} \quad (6)$$

Substituting (6) into (3), the active and reactive power can be expressed as follows

$$\begin{aligned} p &= \frac{P^*}{(U^+)^2+(U^-)^2}(u_\alpha^2+u_\beta^2) \\ &= P^* - \frac{2P^*U^+U^-}{(U^+)^2+(U^-)^2}\cos(2\omega t+\theta_p+\theta_n) \end{aligned} \quad (7)$$

$$q = \frac{Q^*}{(U^+)^2 + (U^-)^2}(u_\alpha^2 + u_\beta^2)$$
$$= Q^* - \frac{2Q^* U^+ U^-}{(U^+)^2 + (U^-)^2}\cos(2\omega t + \theta_p + \theta_n) \quad (8)$$

It can be seen from the equation (7) and (8), the sinusoidal current references can be achieved at the expense of active and reative power oscillations. Therefore, there is always a tradeoff between current harmonics and power oscillations for three phase three wire power systems.

B. Delayed voltage control strategy

As discussed in the previous section, the inherent reason of current harmonics are caused by $\tilde{D}$ to keep the output power constant, and the active and reactive power oscillations are caused by $\bar{D}$ to keep the output current sinusoidal. To solve this problem, the active and reactive instantaneous power $\hat{p}$ and $\hat{q}$ can be expressed as a new estimation formula as follows

$$\begin{bmatrix} \hat{p} \\ \hat{q} \end{bmatrix} = \frac{3}{2}\begin{bmatrix} u_\alpha & u_\beta \\ \hat{u}_\alpha & -\hat{u}_\beta \end{bmatrix}\begin{bmatrix} \hat{i}_\alpha \\ \hat{i}_\beta \end{bmatrix} = \begin{bmatrix} \hat{i}_{\alpha(p)} + \hat{i}_{\alpha(q)} \\ \hat{i}_{\beta(p)} + \hat{i}_{\beta(q)} \end{bmatrix} \quad (9)$$

where $\hat{u}_\alpha$ and $\hat{u}_\beta$ represent the delayed grid voltage components, which can be achieved by T/4 delay signal processor [26-28]. Assuming that $\theta_p = 0$ and $\theta_n = 0$, the delayed voltage can be expressed as

$$\begin{cases} \hat{u}_\alpha = u_{\alpha\_delay(-T/4)} = -(U^+ + U^-)\cos(\omega t) \\ \hat{u}_\beta = u_{\beta\_delay(T/4)} = (U^+ - U^-)\sin(\omega t) \end{cases} \quad (10)$$

With the same control target, active and reactive power references are P^* and Q^* without fluctuation. The microgrid inverter output current references can be derived from (9) as follows

$$\begin{cases} \begin{bmatrix} \hat{i}_\alpha^* \\ \hat{i}_\beta^* \end{bmatrix} = \frac{2}{3}\begin{bmatrix} u_\alpha & u_\beta \\ \hat{u}_\alpha & -\hat{u}_\beta \end{bmatrix}^{-1}\begin{bmatrix} P^* \\ Q^* \end{bmatrix} = \begin{bmatrix} \hat{i}_{\alpha(p)}^* + \hat{i}_{\alpha(q)}^* \\ \hat{i}_{\beta(p)}^* + \hat{i}_{\beta(q)}^* \end{bmatrix} \\ \hat{i}_{a(p)}^* = \frac{2}{3}\frac{P^*\hat{u}_\beta}{u_\alpha\hat{u}_\beta + \hat{u}_\alpha u_\beta} = \frac{2}{3}\frac{P^*\hat{u}_\beta}{\bar{D}_d} \\ \hat{i}_{a(q)}^* = \frac{2}{3}\frac{Q^* u_\beta}{u_\alpha\hat{u}_\beta + \hat{u}_\alpha u_\beta} = \frac{2}{3}\frac{Q^* u_\beta}{\bar{D}_d} \\ \hat{i}_{\beta(p)}^* = \frac{2}{3}\frac{P^*\hat{u}_\alpha}{u_\alpha\hat{u}_\beta + \hat{u}_\alpha u_\beta} = \frac{2}{3}\frac{P^*\hat{u}_\alpha}{\bar{D}_d} \\ \hat{i}_{\beta(q)}^* = -\frac{2}{3}\frac{Q^* u_\alpha}{u_\alpha\hat{u}_\beta + \hat{u}_\alpha u_\beta} = -\frac{2}{3}\frac{Q^* u_\alpha}{\bar{D}_d} \end{cases} \quad (11)$$

Note that the denominator $\bar{D}_d$ in (11) has become a constant component, which means the current references of inverter are sinusoidal without any harmonics. In this way, with proportional resonant (PR) controller, the inverter output currents only consist of the fundamental positive and negative gird voltage components, excluding the harmonic components. However, the inverter system faces the risk of overcurrent phenomenon, which may lead to the switches burned, seriously affect the system reliability and result in the failure of FRT control.

C. Proposed current-limited control strategy

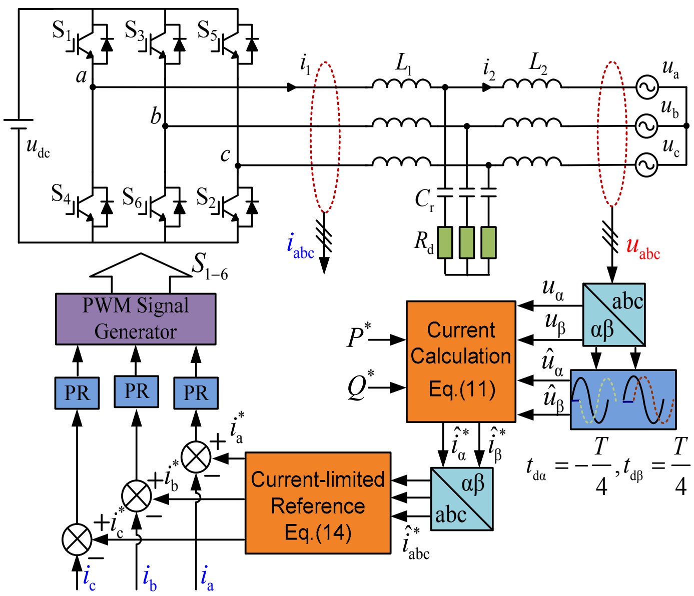


Fig. 2. Structure diagram of proposed current-limited control

The overall control structure is shown in Fig. 2. As can be seen, the three-phase current is independently controlled by three PR controllers with a single current-loop control. R_d is used to damping the potential resonance from LCL filter, and optimization of the damping resistor can be found in [29]. Note that the current-limited reference generator operates in abc frame is beneficial to the convenience of actual current peak values detection and comparison in real time. The current peak values detection can be easily estimated in a fast and accurate way as reported in [30].

Following will present the analysis of the proposed current-limited control method. As the analysis in the delayed voltage control, the current can be controlled as sinusoidal waveforms. Substituting the sinusoidal current reference (11) into the Clarke transformation, the actual three phase currents can be derived as

$$\begin{bmatrix} \hat{i}_a^* \\ \hat{i}_b^* \\ \hat{i}_c^* \end{bmatrix} = \begin{bmatrix} \hat{i}_{\alpha(p)}^* + \hat{i}_{\alpha(q)}^* \\ -(\hat{i}_{\alpha(p)}^* + \hat{i}_{\alpha(q)}^*)/2 + \sqrt{3}(\hat{i}_{\beta(p)}^* + \hat{i}_{\beta(q)}^*)/2 \\ -(\hat{i}_{\alpha(p)}^* + \hat{i}_{\alpha(q)}^*)/2 - \sqrt{3}(\hat{i}_{\beta(p)}^* + \hat{i}_{\beta(q)}^*)/2 \end{bmatrix} \quad (12)$$

Substituting (2), (10) and (11) into (12), the three phase output currents peak value can be expressed as follows

$$\begin{cases} \left|\hat{i}_a^*\right| = \frac{2}{3}\frac{\sqrt{(P^*)^2 + (Q^*)^2}}{U^+ + U^-} \\ \left|\hat{i}_b^*\right| = \frac{2}{3}\frac{\sqrt{[(P^*)^2 + (Q^*)^2][(U^+)^2 + (U^-)^2 + (U^+)(U^-)]}}{(U^+)^2 - (U^-)^2} \\ \left|\hat{i}_c^*\right| = \frac{2}{3}\frac{\sqrt{[(P^*)^2 + (Q^*)^2][(U^+)^2 + (U^-)^2 + (U^+)(U^-)]}}{(U^+)^2 - (U^-)^2} \end{cases} \quad (13)$$

As can be seen form (13), it is clear that the unbalanced and excessive output currents phenomenon is caused by the negative sequence voltage component $U^{-} \neq 0$, which means the system is under unbalanced grid voltage faults.

On the other hand, in order to limit the output current within a rated operating range during the FRT process of the inverter and three phase output currents should be measured and calculated in real time. The current references based on (12) can be modified into equation (14) as follows

$$\begin{bmatrix} \hat{i}_a^{**} \\ \hat{i}_b^{**} \\ \hat{i}_c^{**} \end{bmatrix} = \frac{I_{rated}}{I_{\max}} \begin{bmatrix} \hat{i}_a^{*} \\ \hat{i}_b^{*} \\ \hat{i}_c^{*} \end{bmatrix} = \frac{I_{rated}}{I_{\max}} \begin{bmatrix} \hat{i}_{\alpha(p)}^{*} + \hat{i}_{\alpha(q)}^{*} \\ -(\hat{i}_{\alpha(p)}^{*} + \hat{i}_{\alpha(q)}^{*})/2 + \sqrt{3}(\hat{i}_{\beta(p)}^{*} + \hat{i}_{\beta(q)}^{*})/2 \\ -(\hat{i}_{\alpha(p)}^{*} + \hat{i}_{\alpha(q)}^{*})/2 - \sqrt{3}(\hat{i}_{\beta(p)}^{*} + \hat{i}_{\beta(q)}^{*})/2 \end{bmatrix} \tag{14}$$

where I_{rated} represents the rated current value of the inverter, $I_{\max}$ represents the maximum current value in three phase output currents.

It is clear that the current reference peak value in equation (14) will not beyond I_{rated} under the unbalanced grid voltage conditions. As for balance grid conditions, the inverter output current can be also controlled as balanced and sinusoidal waveforms with the peak value I_{rated} .

On the other hand, it would be an interesting doubt about that whether P-Q regulator could be used to this proposed control. In this case, another power loop with PI control should be integrated with the existing current loop, which may be beneficial to the power regulation but at the expense of the control complicity due to two-loop (power-loop and current-loop) structure with two PI coefficients tuning to avoid interaction between outer power loop and inner current loop. That's why the single-current-loop structure is used for most existing solutions. But for the high penetration of multi-inverters based microgrid systems under unbalanced grid faults, P-Q regulator with droop control integrated with current control might be an interesting solution but it is beyond the scope of this paper.

III. SIMULATION RESULTS

In order to verify the effectiveness of the proposed control strategy, the MATLAB/Simulink simulation test are carried on the conventional control method and proposed strategy. Assuming that the rated current of inverter is 5A, the unbalanced voltage grid fault occurs at 0.2s and the unbalanced factor is 0.3 with a common phase shift as shown in Fig.3. The detailed system parameters can be found in table. I.

TABLE. I SYSTEM PARAMETERS

parameters	*value*	*parameters*	*value*
u_{dc}/V	400	u_a/V$_{rms}$	120∠ 0°
u_b/V$_{rms}$	120∠−137°	u_c/V$_{rms}$	120∠ 137°
U^{+}/V$_{rms}$	92.5	U^{-}/V$_{rms}$	27.5
P^{*}/W	1000	Q^{*}/var	800
L_1/mH	1.8	L_2/mH	1.8
C/μF	27	I_{rated}/A	5

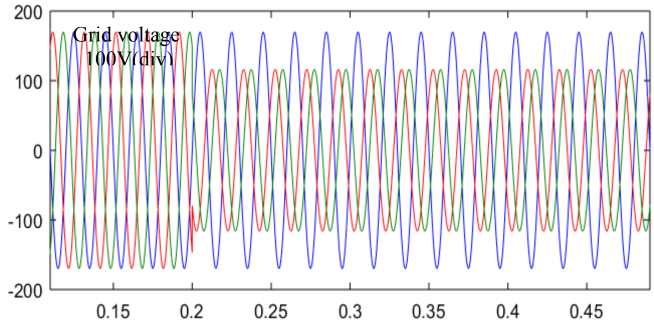
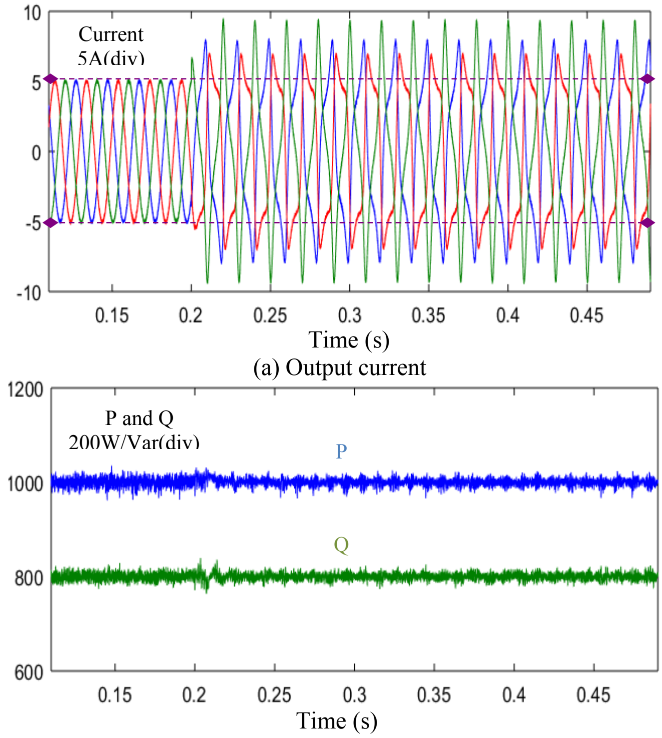


Fig.3. Grid voltage



(a) Output current

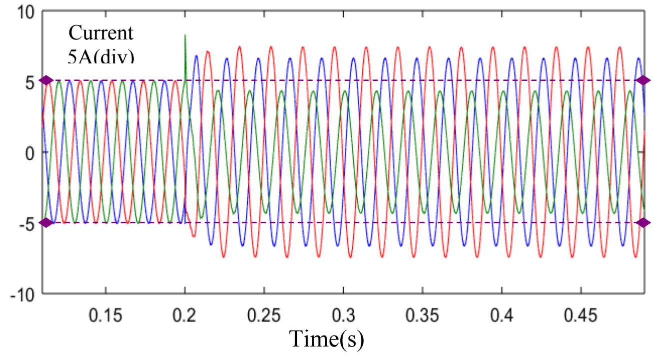
(b) Active/reactive power estimation

Fig.4. Conventional control results I

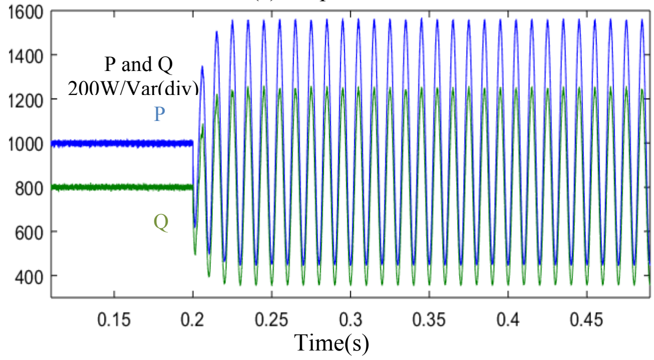
Fig.4 and Fig.5 shows the simulation results of conventional FRT control solutions. As it can be seen, the inverter output currents are distorted with a large of low-order harmonics in order to estimate constant active and reactive power normally under unbalanced grid faults. The system suffers from the unbalanced grid faults with a very fast dynamic response because the controller is not requiring a PLL for the positive and negative sequence component extraction.

On the other hand, in the Fig.5, it can be observed that the current harmonics are significantly reduce at the expense of power fluctuations at specific frequency (100Hz), the peak values of the active and reactive power fluctuations are about 546W and 437Var respectively. Therefore, the sinusoidal current waveform and constant power estimation cannot be achieved at the same time under unbalanced grid conditions, which is consistent with the traditional Instantaneous Power

Theory and the above analysis. Furthermore, the system also experiences the excessive current stress in case of the unbalanced FRT progress.

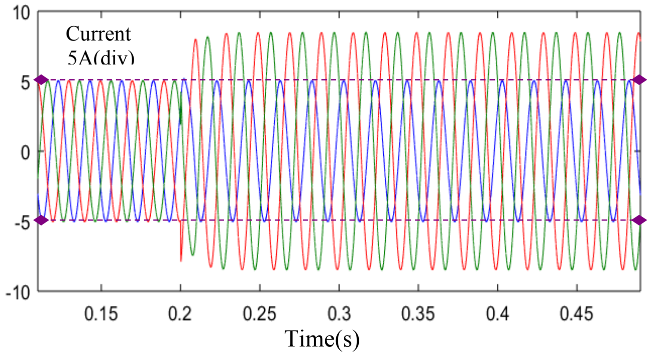


(a) Output current

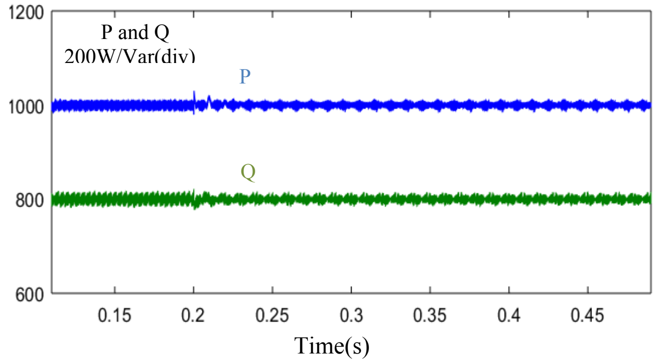


(b) Active/reactive power estimation

Fig.5. Conventional control results II



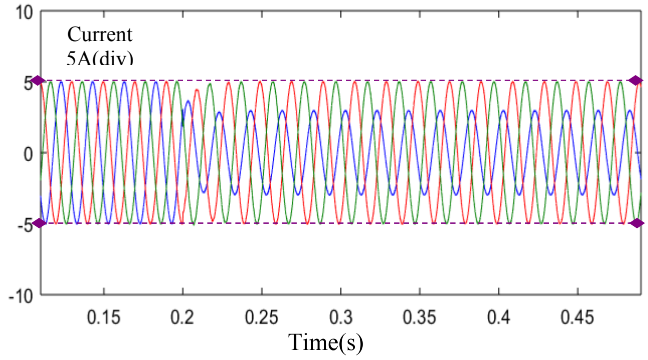
(a) Output current



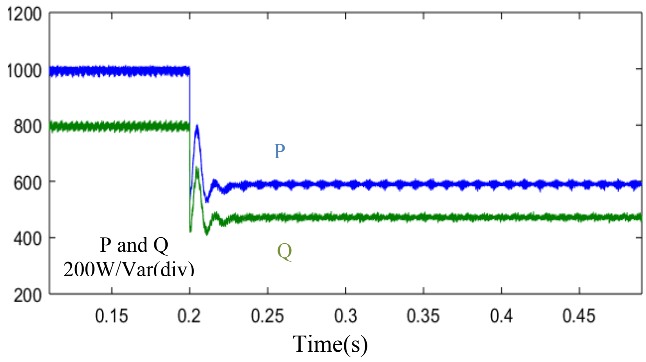
(b) Active/reactive power estimation

Fig.6. Delayed voltage control results

Fig.6 shows the simulation results of delayed voltage control solution. It can be observed that the current harmonics can be greatly reduced and the active/reactive power can be estimated accurately at the same time due to the T/4 delayed voltage are used to eliminate the fluctuant item in the denominator of current reference which is different from the traditional FRT control schemes. For the transient impact of delayed voltage control system, there will be more complex characteristics to be analyzed, which would be the subject of our future research. However, it is should be noted that the system still experiences excessive current phenomenon which may lead to the failure of FRT control under unbalanced grid faults.



(a) Output current



(b) Active/reactive power estimation

Fig.7. Current-limited control results

Fig.7 shows the simulation results of current-limited control strategy. It can be observed that the enhanced current quality and the accurate and fast estimation of active/reactive power can be achieved at the same time compared with the conventional control solutions. Further, the current peak value can be limited into 5A rated range to improve the reliability of the process of FRT control under unbalanced grid voltage conditions.

IV. Conclusion

In this paper, a novel FRT control strategy has been presented for grid-connected inverters under unbalanced grid voltage conditions. Compared with the conventional control schemes, the simulation test results reveal that the proposed strategy can enhance the inverter output current quality while mitigating the active and reactive power oscillations. Moreover, the inverter equipped with current-limited capacity will also improve the reliability of the process of FRT control under unbalanced grid faults.

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