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Control Strategy for Microgrid Inverter under Unbalanced Grid Voltage Conditions

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Abstract—This paper presents the theoretical analysis of the inherent reason of current harmonic and power oscillation phenomena in case of operating the microgrid inverter under unbalanced grid voltage conditions. In order to flexibly control the current harmonic and power oscillation, a new stationary frame control strategy is proposed. It has a simple control structure due to no need of a phase-locked loop and voltage/current positive/negative sequence extraction calculation. The coordinate control of power and current quality is achieved, which enhances the operation performance of microgrid inverter. Finally, the performance evaluation tests are carried out under unbalanced grid voltage conditions. Results verify the effectiveness of the propose method.

Keywords—microgrid, unbalanced grid voltage; inverter, current quality, power oscillation

I. INTRODUCTION

Microgrid integrated with renewable energy system receives more and more attention around the world[1-7]. In order to achieve the flexible operation of the microgrid, many technique challenges should be dealt with, and one of the most important issues is how to ride though the short-term disturbances, especially under unbalanced grid voltage conditions. Many interesting solutions have been reported in the last decades. In general, they can be clarified into two groups. One is the rotating-frame control strategy, and the other is the stationary-frame control strategy. A dual-sequence rotating frame control solution was proposed by Song and Nam in [8], which can eliminate the active power oscillations so as to achieve the constant dc voltage. An enhanced dual-frame control was presented in [9]. The dynamic response is improved by using the decoupling network. Another interesting method was proposed in [10]. The multiple-rotating-frame control was used to mitigate the effect of the grid background harmonics. The major disadvantage of the abovementioned rotating-frame solution is complex with the high computational burden. In order to simplify the solution, Etxeberria, et al presented a single-sequence rotating frame solution [11], which had a simple control structure and fast dynamic response, but still needed the positive and negative sequence separation of voltages for the current reference calculation. On the other hand, the stationary-frame solutions are more popular due to the computational saving and easy implementation. A

significant contribution made by Rodriguez, et al is the flexible power control concept [12], which facilitates multiple choices for FRT with different current references. Another interesting improvement was reported in [13], which achieved the flexible power quality regulation by considering the instantaneous power ripples and current harmonics. It should be noted that all the abovementioned solutions require a phase-locked loop (PLL) to separate the voltage positive and negative sequence components, which is complex to design, and even might degrade the system performance[14-16].

In this paper, a new control strategy for microgrid inverter under unbalanced grid voltage conditions is proposed to achieve the flexible control of power and current quality with no need of any PLL.

II. CONTROL STRATEGY

Fig.1 illustrates the schematic diagram of inverter-based microgrid [17]. It comprises of the energy sources with optional energy storages and dc/ac inverters. The inverter may either operate in autonomous mode or in grid connected mode, and this paper will focus on the latter case.

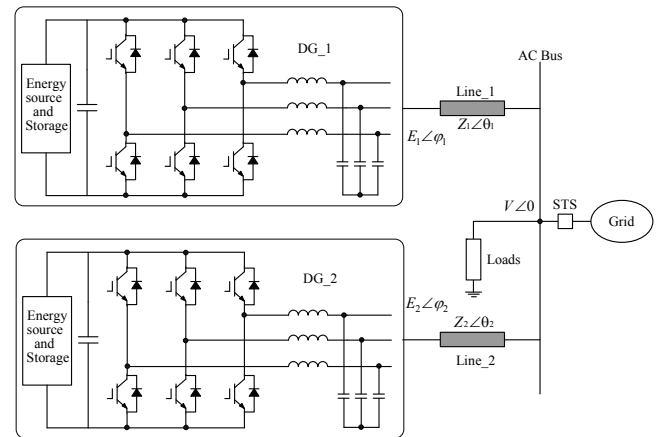


Fig.1 Schematic diagram of inverter-based microgrid

For simplicity, only one microgrid inverter is considered, as shown in Fig.2. Following will present the inherent reason for the current harmonic and power oscillation of the microgrid inverter, and then provide a new flexible control

structure for improving the current quality and power fluctuation without a PLL.

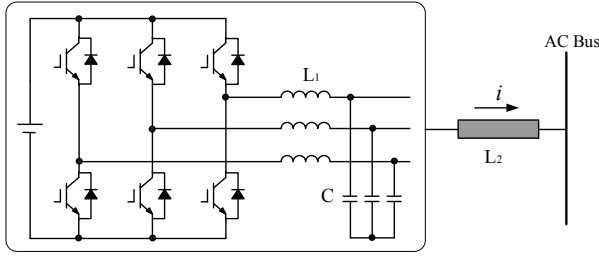


Fig.2 Schematic diagram of microgrid inverter

A. Inherent reason for current harmonics

As shown in Fig.2, three-phase ac bus voltage can be expressed as follows.

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

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

With the Clarke transformation, equation (1) can be rewritten as

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

where U_α^+ , U_α^- , U_β^+ , U_β^- are the positive and negative sequence components of U_α and U_β in stationary frame, respectively.

According to the instantaneous power theory, the active and reactive power of the inverter can be expressed as [18]

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

The microgrid inverter output currents can be derived from (3) as

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} u_\alpha & u_\beta \\ u_\beta & -u_\alpha \end{bmatrix}^{-1} \begin{bmatrix} P^* \\ Q^* \end{bmatrix} \quad (4)$$

where P^* and Q^* are the inverter output active/reactive power reference respectively.

The active and reactive current can be decomposed as

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_{\alpha(p)} \\ i_{\beta(p)} \end{bmatrix} + \begin{bmatrix} i_{\alpha(q)} \\ i_{\beta(q)} \end{bmatrix} = \frac{2}{3} \frac{P^*}{u_\alpha^2 + u_\beta^2} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} + \frac{2}{3} \frac{Q^*}{u_\alpha^2 + u_\beta^2} \begin{bmatrix} u_\beta \\ -u_\alpha \end{bmatrix} \quad (5)$$

Substituting (2) in to (5), the current components can be obtained as follows.

$$\begin{bmatrix} i_{\alpha(p)} \\ i_{\beta(p)} \end{bmatrix} = \frac{2}{3} \frac{P^*}{(u_\alpha^+ + u_\alpha^-)^2 + (u_\beta^+ + u_\beta^-)^2} \begin{bmatrix} u_\alpha^+ + u_\alpha^- \\ u_\beta^+ + u_\beta^- \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} i_{\alpha(q)} \\ i_{\beta(q)} \end{bmatrix} = \frac{2}{3} \frac{Q^*}{(u_\alpha^+ + u_\alpha^-)^2 + (u_\beta^+ + u_\beta^-)^2} \begin{bmatrix} u_\beta^+ + u_\beta^- \\ -u_\alpha^+ - u_\alpha^- \end{bmatrix} \quad (7)$$

From (6) and (7), it can be observed that the inverter current is not sinusoidal if the power reference of P^* and Q^* are constant. The inherent reason is that the denominators of (6) and (7) are not constant, as shown in (8)

$$\begin{aligned} (u_\alpha^+ + u_\alpha^-)^2 + (u_\beta^+ + u_\beta^-)^2 &= (U^+)^2 + (U^-)^2 + 2u_\alpha^+ u_\alpha^- + 2u_\beta^+ u_\beta^- \\ &= (U^+)^2 + (U^-)^2 - 2U^+ U^- \cos(2\omega t + \theta_p + \theta_n) \end{aligned} \quad (8)$$

With the Fourier analysis theory, it can be concluded that the inverter current will be distorted with higher THD if the inverter power is constant. Note that IEEE Std.1547 specifies that the current THD should be less than 5%. Therefore, following will present a solution to the inverter current harmonic elimination.

B. Current harmonic elimination and power fluctuation analysis

As discussed in the previous section, the inherent reason for the inverter current harmonics comes from $2U^+ U^- \cos(2\omega t)$ in (8). Therefore, the current harmonics can be eliminated on condition that $2U^+ U^- \cos(2\omega t)$ is cancelled, which can be easily achieved with a notch filter. Then (6) and (7) can be rewritten as

$$\begin{aligned} \begin{bmatrix} i_{\alpha(p)} \\ i_{\beta(p)} \end{bmatrix} &= \frac{2}{3} \frac{P^*}{[(u_\alpha^+ + u_\alpha^-)^2 + (u_\beta^+ + u_\beta^-)^2]F(s)} \begin{bmatrix} u_\alpha^+ + u_\alpha^- \\ u_\beta^+ + u_\beta^- \end{bmatrix} = \\ &\frac{2}{3} \frac{P^*}{(U^+)^2 + (U^-)^2} \begin{bmatrix} u_\alpha^+ + u_\alpha^- \\ u_\beta^+ + u_\beta^- \end{bmatrix} \end{aligned} \quad (9)$$

$$\begin{aligned} \begin{bmatrix} i_{\alpha(q)} \\ i_{\beta(q)} \end{bmatrix} &= \frac{2}{3} \frac{Q^*}{[(u_\alpha^+ + u_\alpha^-)^2 + (u_\beta^+ + u_\beta^-)^2]F(s)} \begin{bmatrix} u_\beta^+ + u_\beta^- \\ -u_\alpha^+ - u_\alpha^- \end{bmatrix} = \\ &\frac{2}{3} \frac{Q^*}{(U^+)^2 + (U^-)^2} \begin{bmatrix} u_\beta^+ + u_\beta^- \\ -u_\alpha^+ - u_\alpha^- \end{bmatrix} \end{aligned} \quad (10)$$

$$\text{And } F(s) = (s^2 + \omega_n^2) / (s^2 + k\omega_n s + \omega_n^2)$$

In this way, the inverter current only consists of the fundamental positive and negative components, excluding the harmonic components. However, the power fluctuation will

appear in this case, and the active and reactive power fluctuations can be expressed as follows.

$$\tilde{p} = \frac{3}{2} (u_{\alpha}^{-} i_{\alpha}^{+} + u_{\beta}^{-} i_{\beta}^{+} + u_{\alpha}^{+} i_{\alpha}^{-} + u_{\beta}^{+} i_{\beta}^{-}) \quad (11)$$

$$\tilde{q} = \frac{3}{2} (u_{\beta}^{+} i_{\alpha}^{-} - u_{\alpha}^{+} i_{\beta}^{-} - u_{\alpha}^{-} i_{\beta}^{+} + u_{\beta}^{-} i_{\alpha}^{+}) \quad (12)$$

Equation (9) and (10) can be rewritten as

$$\begin{cases} i_{\alpha}^{+} = \frac{2}{3} \frac{u_{\alpha}^{+} P^{*}}{(U^{+})^2 + (U^{-})^2} + \frac{2}{3} \frac{u_{\beta}^{+} Q^{*}}{(U^{+})^2 + (U^{-})^2} \\ i_{\beta}^{+} = \frac{2}{3} \frac{u_{\beta}^{+} P^{*}}{(U^{+})^2 + (U^{-})^2} + \frac{2}{3} \frac{-u_{\alpha}^{+} Q^{*}}{(U^{+})^2 + (U^{-})^2} \\ i_{\alpha}^{-} = \frac{2}{3} \frac{u_{\alpha}^{-} P^{*}}{(U^{+})^2 + (U^{-})^2} + \frac{2}{3} \frac{u_{\beta}^{-} Q^{*}}{(U^{+})^2 + (U^{-})^2} \\ i_{\beta}^{-} = \frac{2}{3} \frac{u_{\beta}^{-} P^{*}}{(U^{+})^2 + (U^{-})^2} + \frac{2}{3} \frac{-u_{\alpha}^{-} Q^{*}}{(U^{+})^2 + (U^{-})^2} \end{cases} \quad (13)$$

Substituting (13) and (2) into (11) and (12), the power fluctuations can be obtained as follows.

$$\tilde{p} = \frac{2P^{*}}{(U^{+})^2 + (U^{-})^2} (u_{\alpha}^{+} u_{\alpha}^{-} + u_{\beta}^{+} u_{\beta}^{-}) = \frac{-2P^{*}U^{+}U^{-}}{(U^{+})^2 + (U^{-})^2} \cos(2\omega t + \theta_p + \theta_n) \quad (14)$$

$$\tilde{q} = \frac{2Q^{*}}{(U^{+})^2 + (U^{-})^2} (u_{\alpha}^{-} u_{\alpha}^{+} + u_{\beta}^{+} u_{\beta}^{-}) = \frac{-2Q^{*}U^{+}U^{-}}{(U^{+})^2 + (U^{-})^2} \cos(2\omega t + \theta_p + \theta_n) \quad (15)$$

Form the above analysis, it can be observed when the current harmonics are eliminated, the power oscillation occurs, which is twice the fundamental frequency.

C. Flexible control of current harmonics and power fluctuations

In order to achieve the flexible control of current harmonics and power fluctuations, a new solution is proposed by combing both abovementioned methods with an adjustable coefficient as follows.

$$i_{\alpha p}^{*} = \frac{2}{3} P^{*} \left\{ \frac{k u_{\alpha}}{(u_{\alpha})^2 + (u_{\beta})^2} + \frac{(1-k)u_{\alpha}}{[(u_{\alpha})^2 + (u_{\beta})^2]F(s)} \right\} \quad (16)$$

$$i_{\beta p}^{*} = \frac{2}{3} P^{*} \left\{ \frac{k u_{\beta}}{(u_{\alpha})^2 + (u_{\beta})^2} + \frac{(1-k)u_{\beta}}{[(u_{\alpha})^2 + (u_{\beta})^2]F(s)} \right\} \quad (17)$$

$$i_{\alpha q}^{*} = \frac{2}{3} Q^{*} \left\{ \frac{k u_{\beta}}{(u_{\alpha})^2 + (u_{\beta})^2} + \frac{(1-k)u_{\beta}}{[(u_{\alpha})^2 + (u_{\beta})^2]F(s)} \right\} \quad (18)$$

$$i_{\beta q}^{*} = \frac{2}{3} Q^{*} \left\{ \frac{-k u_{\alpha}}{(u_{\alpha})^2 + (u_{\beta})^2} + \frac{-(1-k)u_{\alpha}}{[(u_{\alpha})^2 + (u_{\beta})^2]F(s)} \right\} \quad (19)$$

where k represents the adjust coefficient, and $0 \leq k \leq 1$.

The control structure of the proposed method is shown in Fig.3, where the PR control is used for the inverter current regulation [19-21]. Considering that the current harmonic amplitudes reduce as their frequency increase, only low-order current harmonics are regulated with PR controller. Following will provide the experimental verification.

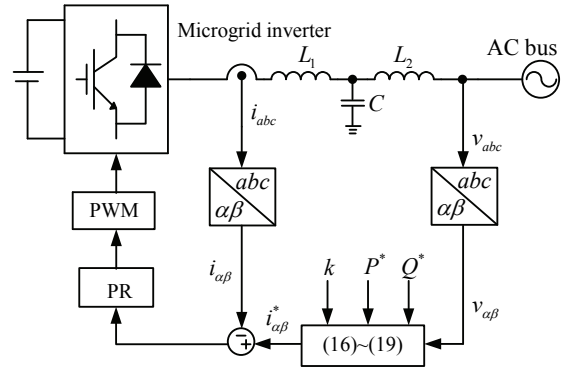


Fig.3 Single-line diagram of system control structure

III. PERFORMANCE EVALUATION

In order to verify the effectiveness of the proposed method, the performance evaluation tests are carried out and the system parameters are listed as follows.

TABLE I. SYSTEM PARAMETERS

Parameters	Value	Parameters	Value
DC bus/V	120	u_a /V	$50\angle 0^\circ$
u_b /V	$34.2\angle -137^\circ$	u_c /V	$34.2\angle 137^\circ$
P^* / W	250	Q^* / Var	200
L_1 / mH	5	L_2 / mH	1
C / uF	9.9	0.0 ~ 0.2s	$k = 0$
0.2 ~ 0.4s	$0 < k < 1$	0.4 ~ 0.6s	$k = 1$

Fig.4 shows the tests results. From 0s to 0.2s, $k=0$. It can be observed that the current is sinusoidal, but both the active and reactive powers fluctuate, which is in agreement with the theoretical analysis of (14) and (15). On the other hand, from 0.4s to 0.6s, $k=1$. It can be observed that the inverter currents are distorted with larger low-order harmonics, while both active and reactive powers of the inverter are almost constant, which is consistent with the above theoretical analysis in Section II.

From 0.2s to 0.4s, k is linearly increased. It can be observed that the current harmonics increase and power fluctuations reduce as the adjust coefficient of k rises. Note that the inverter current amplitude is affected by the adjust coefficient of k . An interesting observation is that the inverter current amplitude approaches the minimum value in case of $k=0.5$, while reaches the maximum value with $k=1$. Therefore, the current harmonics and power fluctuations, as well as the current amplitude, should be considered to improve the power quality and avoid the overcurrent of the inverter in practical applications.

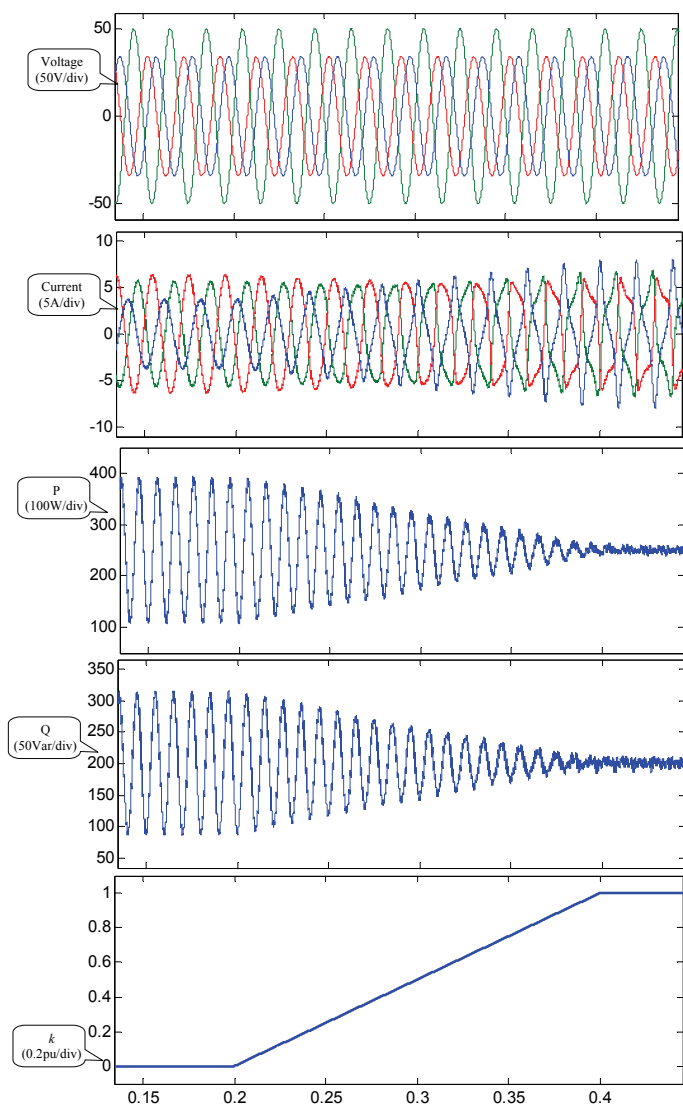


Fig.4 Simulation results of the proposed method under unbalanced grid voltage conditions. (a) ac bus voltage, (b) inverter current, (c) inverter active power, (d) inverter reactive power, (e) adjust coefficient of k

Further tests are carried out under unbalanced grid voltage conditions. As shown in Fig.5, it can be observed that the proposed work well under normal conditions. It should be noted that the abovementioned analysis and performance evaluation are carried out in grid-connected mode. For grid-forming mode with unbalanced loads, the proposed method is still valid, but a slight modification is needed to replace the current control with the droop control. Detailed analysis and experimental results would be reported in the future.

IV. CONCLUSION

This paper has presented a new control structure for operating the microgrid inverter under unbalanced grid voltage conditions. It can achieve the coordinate control of power and current quality by an adjustment coefficient and needn't any PLL. The performance evaluation results indicate that the proposed method is effective under both balanced and unbalanced grid voltage conditions. Detailed design guideline

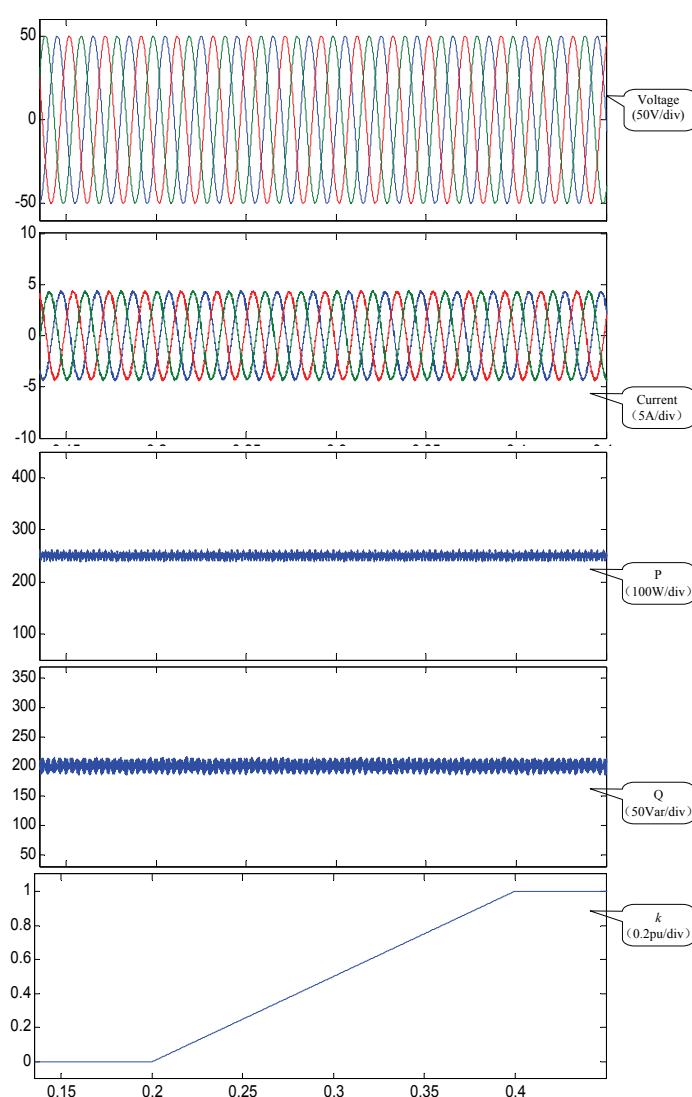


Fig.5 Simulation results of the proposed method under balanced grid voltage conditions. (a) ac bus voltage, (b) inverter current, (c) inverter active power, (d) inverter reactive power, (e) adjust coefficient of k

of the adjustment coefficient for different control objectives would be reported in the future paper.

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