

Adaptive Synchronization of Grid-Connected Three-phase Inverters by Using Virtual Oscillator Control

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Abstract— This paper presents an adaptive synchronization for current-controlled grid-connected inverter based on a time-domain virtual oscillator controller (VOC). Inspired by the phenomenon of dynamics of adaptive oscillator under the perturbation effect. Firstly, the fast learning rule of the oscillator frequency is derived in order to make the oscillator evolve to the grid voltage. Thus realizing a phase-locking behavior, but without requiring the use of a dedicated phase-locked loop (PLL). Then, the unit orthogonal components are obtained to generate the current reference, and a current loop is designed by using a PR controller in the $\alpha\beta$ frame. Experimental results were obtained with comparison to PI current controller, showing the salient performances of the proposed method in front of grid frequency variations, voltage sags and swells.

Keywords—grid-connected inverter; dead-zone oscillator; adaptive synchronization; nonlinear control

I. INTRODUCTION

Since the penetration of renewable power generation such as photovoltaics, wind, fuel-cells etc. are growing, the inverters as an interface between the generation sources and utility grid, fulfill several roles in the coordination of highly distributed AC power systems. For example, owing to the flexibility of the grid-connected VSI control, it can achieve high power factor, DC voltage regulation harmonic current elimination and independent control of bidirectional active and reactive powers [1]-[3].

The conventional method for inverters control in Microgrid is droop control, which is based on modulating the inverter output such that the frequency and voltage amplitude are inversely proportional to the real and reactive power output, respectively [4][5]. The Microgrid of the future may need advanced inverters that don't simply follow what the grid is doing but actually help form the grid, by responding instantaneously to disturbances and working in concert to help keep the system stable. Departing from droop control, a nonlinear control strategy called virtual oscillator control was developed by an NREL team [6]-[8]. It is implemented by programming the dynamics of the oscillators onto the inverters' microcontrollers, and utilizing sinusoidal varying oscillator states to construct PWM control signals [9]. The VOC method has been proven to be independent of load and

the number of inverters, has emerged as the novel inverter control technique which requires no explicit communication. In [10], the average model has been built between the real and reactive-power outputs and terminal-voltage dynamics for parallel inverters systems, which has explained the global asymptotic synchronization of the coupled oscillators. Obviously, The VOC in his original version been extensively analyzed and implemented for islanded systems.

The control main objectives of grid-connected inverters are to be adjusted to synchronize and support the utility grid, such as inertia emulation, frequency regulation and voltage support [11]. The synchronization structures like phase-locked loop(PLL) have been broadly used in grid-connected inverter. However, the performance of conventional PLL control is deteriorated when the three-phase signals are unbalanced or distorted [12]. To overcome the drawbacks, an adaptive synchronization method based on limit cycle oscillator and a frequency-locked loop has been proposed in [13], and the method offers useful information to estimate the positive and negative components with a highly distorted grid voltage. However, the large computation will affect the transient response.

Inspired by the property of synchronization of the nonlinear dynamical oscillators, a VOC-based adaptive frequency synchronization method is proposed to extend this control technique for grid-connected applications in this paper. The learning rule of phase and frequency for dead-zone oscillator is derived in polar coordinates, which adapts its phase and frequency to the grid voltage. Through the independent current source and RLC oscillation, the current reference in $\alpha\beta$ -frame can be obtained, and then the output current error can be regulated by PR controller. The parameters of controller are discussed in details. Experimental results are provided to validate the effectiveness of the proposed method.

The paper is organized as follows. Section II explains the basic model of nonlinear dead-zone oscillator and adaptive synchronization method. In Section III, the control scheme of grid-tied inverter and parameters selection are presented. In Section IV, the experimental results are given to validate the proposed method under different abnormal grid conditions

with comparison to the conventional PI current controller. Finally, the conclusion are heighted in Section V.

II. CONTROL SYSTEM DESCRIPTION

A. Nonlinear Dead-zone Oscillator

In this section, the basic model of VOC are reviewed. Fig.1 illustrates the electrical circuit of nonlinear dead-zone oscillator, which includes three parts component: (i) a passive RLC circuit (ii) an independent current source (iii) external perturbation.

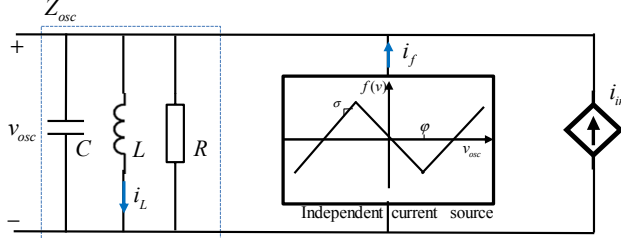


Fig.1 Electrical circuit of virtual oscillator

According to the RLC circuit, the storage elements L and C will lead to circuit oscillation, and its angular frequency ω_0 is:

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad (1)$$

The impedance of passive RLC circuit is:

$$Z_{osc} = \frac{RLs}{RLCs^2 + Ls + R} \quad (2)$$

If the initial voltage of capacitor is U_{c0} , the steady output voltage can be expressed as:

$$u_o(t) = U_{c0} \cos(\omega_0 t) \quad (3)$$

Regarding the independent current source, it composes of output i_f and feedback input voltage v_{osc} , the function between the two components should be designed to make the amplitude of output voltage v_{osc} stable, correspondingly, the frequency of output voltage is decided by the RLC circuit. The independent current source is able to defined as a static non-linear function as follows:

$$f(v_{osc}) = \begin{cases} \sigma v_{osc} - 2\sigma\phi & v_{osc} > \phi \\ -\sigma v_{osc} & |v_{osc}| = \phi \\ \sigma v_{osc} + 2\sigma\phi & v_{osc} < -\phi \end{cases} \quad (4)$$

Where σ is the slope of the dead-zone function, and ϕ is a parameter that defines the input range. When $|v_{osc}| = \phi$, it turns a current source to support the RLC circuit. Otherwise, it is a virtual resistor to absorb power.

According to Fig.1, by using Kirchoff's voltage and current laws, the dynamics of oscillator can be derived as:

$$\begin{cases} L \frac{di_L}{dt} = v_{osc} \\ C \frac{dv_{osc}}{dt} = -f(v_{osc}) - i_{in} - \frac{v_{osc}}{R} - i_L \end{cases} \quad (5)$$

Assuming the external perturbation i_{in} is zero, (5) can be expressed as:

$$\ddot{v}_{osc} + \sqrt{\frac{L}{C}} \left(\frac{df(v_{osc})}{dv_{osc}} + \frac{1}{R} \right) \dot{v}_{osc} + v_{osc} = 0 \quad (6)$$

It is clear that (6) is a second-order differential equation that named as dead-zone oscillator equation [14]. An important parameter for oscillator is p , which can be defined as:

$$p = \sqrt{\frac{L}{C}} \left(\sigma - \frac{1}{R} \right) \quad (7)$$

Based on the Liénard's theorem, when $p \ll 1$, the dead-zone oscillator emerges a stable and unique limit cycle, and its output approximates an ideal sinusoid in the time domain. Fig.2 shows the phase-plot of steady-state limit cycles and oscillator output when p varies.

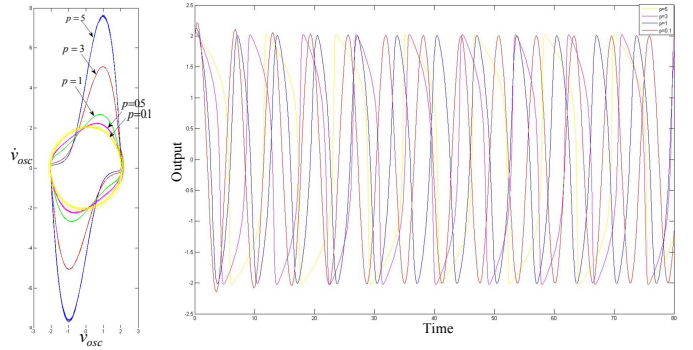


Fig.2 Phase-plot of limit cycles and output of oscillator when p varies

B. Adaptive synchronization with grid voltage

In nonlinear system, the oscillator models are interesting owing to its synchronization characteristic. The recent research has proven global asymptotic synchronization of coupled oscillator, which is used to formulate a control technique for decentralized power system. Similarly, regarding the grid-connected inverter, the first objective is that the oscillator should synchronize with the utility grid. Compared with the phase-locked loop control, the oscillator has intrinsic frequencies and cannot dynamically adapt its parameters. In order to apply the oscillator's synchronization property, the adaptive frequency control is employed in the dead-zone oscillator, which implies that the oscillator is able to adapt its frequency and phase to the input signal (grid voltage). By using the plasticity of oscillator, the system can change its own parameters to adapt the frequency and phase of input signal. Meanwhile, the amplitude of output is uninfluenced by the adaptive method. Thus, regarding the phase dynamics, we can

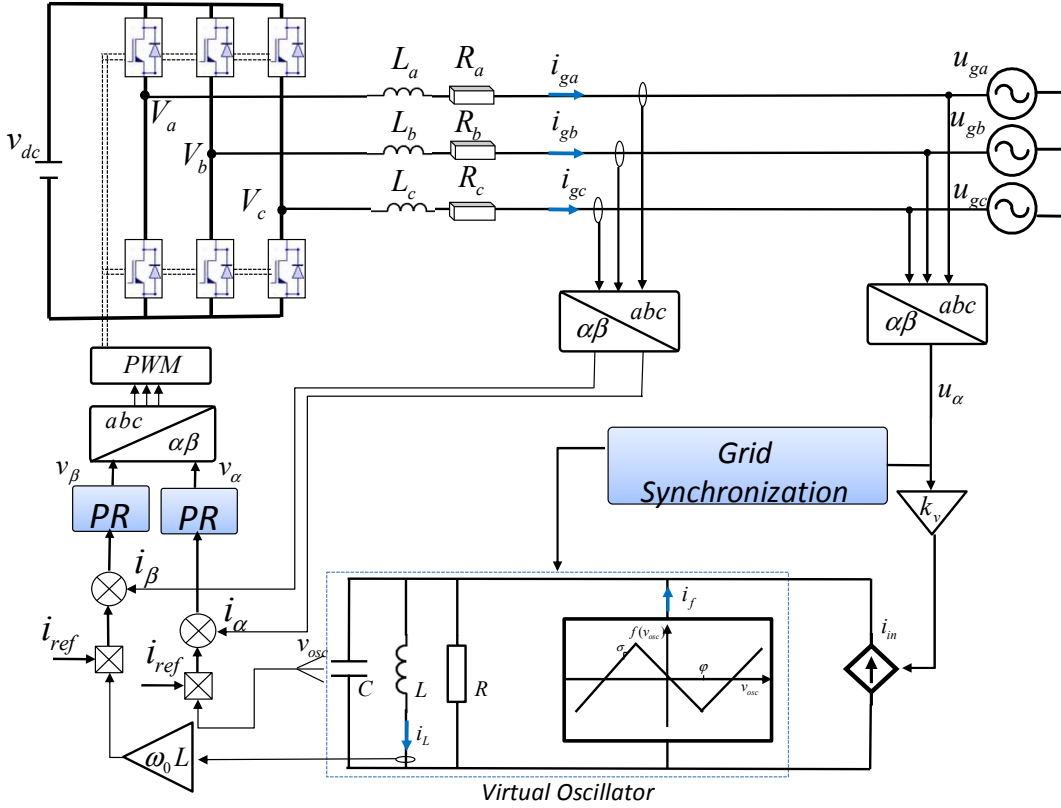


Fig.4 The proposed VOC control block diagram

rewrite (5) in the polar coordinates, and set $v_{osc} = r \cos \phi$ and $i_L = r \sin \phi$ as follows:

$$\begin{cases} \dot{r} = -\frac{r \sin \phi}{C} g(r \cos \phi) + \frac{r^2 \sin^2 \phi}{RC} - \frac{r^2 \sin \phi \cos \phi}{C} + (\sin \phi - \sin^3 \phi) \omega^2 C \\ \dot{\phi} = -\frac{g(r \cos \phi)}{C} - \frac{r \sin \phi}{RC} - \frac{r \cos \phi}{C} - \sin^2 \phi \omega^2 C + \frac{\varepsilon U \cos \phi}{r} \end{cases} \quad (8)$$

Where $r = \sqrt{v_{osc}^2 + i_L^2}$, ω is the intrinsic frequency of the oscillator, and U is the external perturbation. Notably, U is the α component in $\alpha\beta$ -frame which contains the frequency and phase information of grid. When the external perturbation U is zero, the oscillator system has an asymptotically stable unique circle. When the external perturbation U is small, the limit cycle will not change its performance, but only its form and time scale vary which leads to accelerate or decelerate the phase points.

Fig.3 shows a limit cycle of oscillator, and the coordinate system with \vec{v} and \vec{i}_L rotates with the phase point along the cycle. If the frequency of grid voltage and oscillator are closed, the oscillator frequency has to be the same as the effect of the grid voltage on the phase [15], [16]. Therefore, through the phase plot, the intrinsic frequency of the oscillator can be driven toward the frequency of the grid voltage, consequently, ω has to be equal with the effect of the grid voltage.

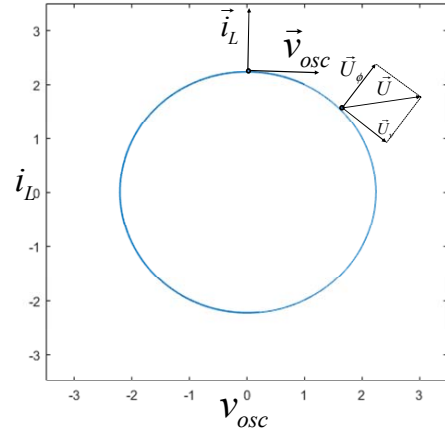


Fig.3 Phase plot of limit-cycle oscillator

According to the factor $\frac{\varepsilon U \cos \phi}{r}$ item in (8), the synchronization equation can be chosen as:

$$\dot{\omega} = -\varepsilon U \frac{v_{osc}}{\sqrt{v_{osc}^2 + i_L^2}} \quad (9)$$

Where ε is a coefficient controlling the adaptation speed. Note that the higher ε is, the faster the synchronization. The proof of convergence with oscillators has been discussed in

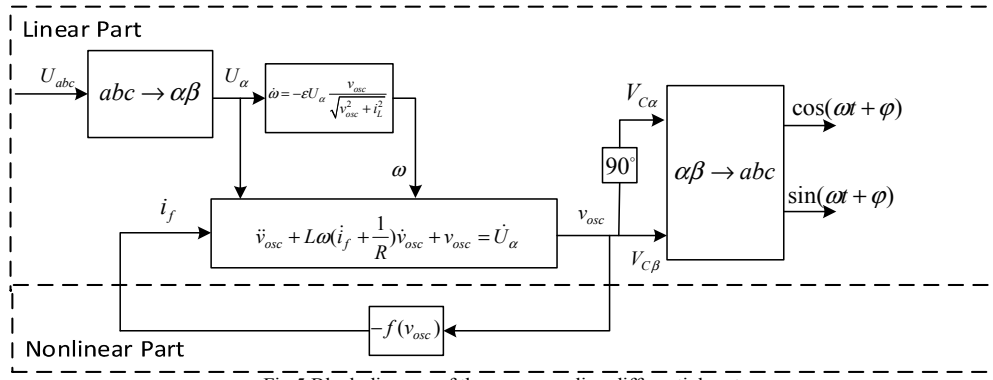


Fig.5 Block diagram of the corresponding differential system

[15]. Therefore, C can be fixed, the selection of L will influence the intrinsic frequency of the oscillator. Thus, the second order differential equation (6) can be rewritten as:

$$\ddot{v}_{osc} + L\omega\left(\frac{df(v_{osc})}{dv_{osc}} + \frac{1}{R}\right)\dot{v}_{osc} + v_{osc} = \dot{U} \quad (10)$$

III. SYSTEM DESCRIPTION

A. Control system Implementation

The control structure of VOC based grid-connected three-phase L-filter inverter is depicted in Fig.4. The current closed-loop includes two parts: i) Adaptive grid synchronization based on VOC to generate steady-stable orthogonal components; ii) Current loop controller.

The dynamic Since the virtual oscillator control is only implied for one phase, α phase that contains frequency and phase information of grid voltage is selected to be external signal. In this control scheme, the voltage is regarded as virtual current i_m . Then, the *grid synchronization* block is implemented from (9). Through the dead-zone oscillator control, the real and imaginary components of unit current reference are generated by orthogonal output v_{osc} and $\omega L i_L$. That means the independent current source could regulate the amplitude of orthogonal output to be one. Multiply by the current reference, the current references of current-loop are obtained in $\alpha\beta$ -frame. Next, since a PI controller is unable to track a sinusoidal reference without steady-state errors, the PR controller is employed to track the actual current reference. Finally, after $\alpha\beta-abc$ transformation, a conventional sine-triangle PWM scheme is used to generate a switching signal.

B. Paramter Selection

In order to ensure oscillation output can be unit sinusoidal component following the phase and frequency of grid voltage, firstly, the R and C should be selected to ensure a steady limit-cycle generated. The initial frequency of oscillator can be selected as the rated frequency 50Hz. According to (1) and (7), the constraints of initial state of oscillation can be written as:

$$\begin{cases} \sqrt{\frac{L}{C}}\left(\sigma - \frac{1}{R}\right) \ll 1 \\ R > \frac{1}{\sigma} \\ \frac{1}{\sqrt{LC}} = 100\pi \end{cases} \quad (11)$$

At the initial state, in order to observe the influence of parameter σ on the system performance we select the other parameters as follows:

$$R = 10, L = 250\mu H, C = 40.5mF, \phi = 0.47, k_v = 0.001$$

It can be seen that the limit cycle is approximately a circle if σ is less than 1 in Fig.6 (a), which means that the output of oscillator is approximately an ideal sinusoidal under other parameters fixed.

When vary ϕ as selected values in Fig.6 (b), the other parameters are fixed as:

$$R = 10, L = 250\mu H, C = 40.5mF, \sigma = 1, k_v = 0.001$$

Fig.6 (b) illustrates that varying ϕ will not affect the performance of oscillation in the current-voltage space. However, ϕ can be tuned to make the amplitude of output to be one, then we select $\phi=0.1$.

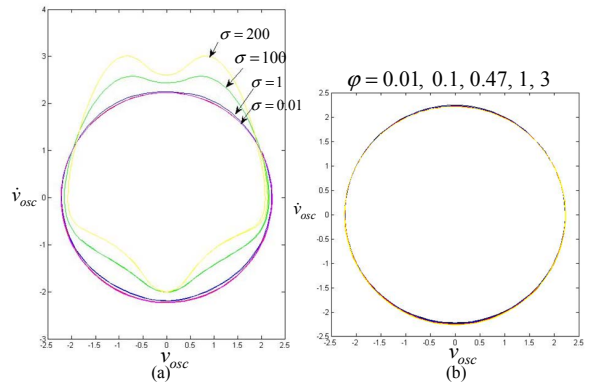


Fig.6 Phase plot of steady-state limit cycles for varying σ and ϕ

Considering the external perturbation parameter k_v , the current-voltage plot can be drawn when k_v varies in Fig.7. The controlled variables are selected as:

$$R = 10, L = 250\mu H, C = 40.5mF, \sigma = 1, \varphi = 0.1$$

Fig.7 illustrate that the limit cycle is approximately a circle if k_v is less than 0.01 under the controlled variables. Assuming the RMS grid voltage is 311V, the amplitude of external perturbation has influence on the performance of the oscillation. In particular, the amplitude of oscillator output is also subject to k_v . Considering the two constraints we select k_v equals to 0.001.

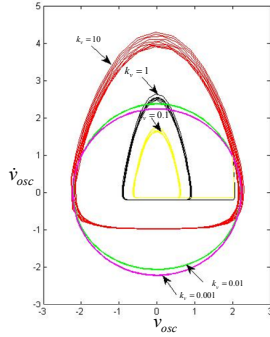


Fig.7 Phase plot of steady-state limit cycles for varying k_v

As mentioned earlier, the grid synchronization coefficient \mathcal{E} is selected as 0.2 with the purpose of the adaptation speed. Therefore, the parameters design of VOC have been discussed. Meanwhile, the PR controller of current loop designing can be designed by conventional method, then the paper will not go into details here.

IV. EXPERIMENTAL VALIDATION

In order to validate the effectiveness of the proposed control method, the system platform has been built in Fig. 8. The setup consists of a 2.2kW three-phase inverter, a dc power source, and grid simulator. The control algorithm is implemented by dSPACE 1006 platform for real-time control. The system parameters are described in Table I, and the waveforms are captured by an oscilloscope.

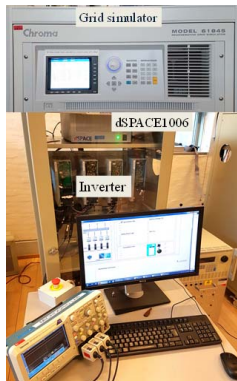


Fig.8 Configuration of the experimental platform

TABLE I. EXPERIMENTAL HARDWARE AND CONTROLLER PARAMETERS

System Parameters	
Filter Inductor	1.8mH
DC link Voltage	500V
Rated frequency	50Hz
Sampling frequency	10kHz
RMS grid voltage	311V
VOC Controller parameters	
R	10Ω
C	40.5mF
φ	0.1V
σ	1
k_v	0.01
\mathcal{E}	0.2
Current reference	10A
k_p, k_R	10, 200
Conventional Current Controller parameters	
k_p, k_i	0.08, 200

In order to ensure the initial oscillation is satisfied, the initial voltage of virtual capacitor is set as 1, and L is set as 25mH. Therefore, the initial frequency of oscillator output can stay in 50Hz in initial condition.

The steady output current based on proposed method is shown in Fig.8. The output current is sinusoidal with low THD, which donates that selected parameters of oscillator satisfied the external perturbation synchronization.

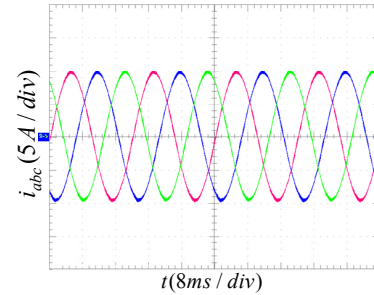


Fig.8 The steady output current of VOC-inverter

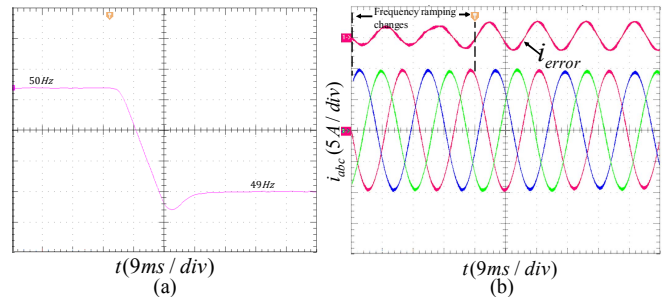


Fig.9 The experiment responses of two methods when the frequency varies from 50Hz to 49Hz

Furthermore, the frequency deviation is taken into consideration, and the transient response are shown in Fig.9 with comparison between the conventional current controller and proposed method. Fig.9(a) illustrates the frequency waveform when the grid frequency abruptly changed from

50Hz to 49Hz. It is remarkable that a frequency undershoot appears during the frequency damping, the transient time is approximately 0.015s. With the proposed method, there is no frequency undershoot, and it takes less time to synchronize with the new phase and frequency than conventional PLL in Fig.9 (b).

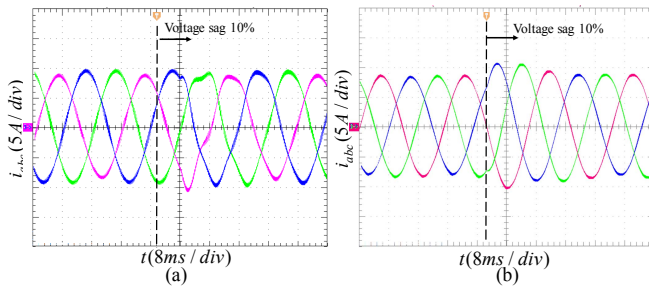


Fig.9 The experiment responses of two methods when the amplitude 10% sag

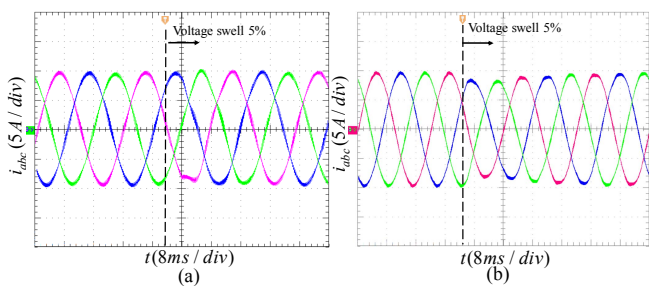


Fig.10 The experiment responses of two methods when the amplitude 5% swell

An amplitude variation test in grid voltage was made according to the IEEE 1547 Standard, which is $88\% \leq V \leq 110\%$. Firstly, considering 10% voltage sag, Fig.10 (a) illustrates the transient response with the PI current controller. Notice that output currents are highly distorted during the transient time 0.032s. However, with the proposed method in Fig.10 (b), the response time is faster and lower THD than previous method in the presence of 10% amplitude variations. Similarly, the comparison results are presented in Fig.11 under 5% voltage swell. In both cases, with the proposed method, notice that output current amplitude temporarily increases after the sag/swell, and then it takes less than one line-cycle to restore the current amplitude to the reference. It can be concluded that the proposed method has better robustness and faster performances than conventional PI current controller.

The three-phase inverter based on VOC current controller was experimentally validated, and it is clear that the proposed method is able to accurately synchronize with the grid voltage, in particular under frequency and amplitude variations scenarios. The adaptive method addresses the robustness and fast response performances compared with conventional current-loop control.

V. CONCLUSION

A novel adaptive grid synchronization scheme for grid-connected inverter is proposed based on virtual oscillator, which is able to produce synchronized signals with desired constant amplitude despite frequency and phase variations.

Based on the synchronization property of oscillator, the control scheme does not require the use of a dedicated phase-locked loop. The experimental results verified the merits of the proposed technique compared with the conventional current control, in particular its robust, rapidity and stable operation under grid variations.

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