Robust Voltage Regulation of A DC-AC Inverter with Load Variations via A HDOBC Approach

Zuo Wang, *Student Member, IEEE*, Yunda Yan, *Student Member, IEEE*, Jun Yang, *Senior Member, IEEE*, Shihua Li, *Senior Member, IEEE*, and Qi Li

***Abstract*—In this brief, a harmonic disturbance observer based control (HDOBC) approach is proposed for the robust voltage regulation design of a DC-AC inverter system. In distributed generation systems, wide range of load variations and effects of nonlinear loads result in significant degradations of control performance. Moreover, the loads, as the mismatched disturbances, impose adverse influences on the inverter system via a channel different from the control input. Toward that end, a harmonic disturbance observer (HDOB) is proposed to estimate the periodic load disturbances. By constructing new disturbance compensation gains, the effects of the mismatched periodic disturbances are removed from the output voltage channel. Rigorous stability analysis for the closed-loop system is presented. Experimental results are explored to illustrate the feasibility and capacity of the proposed control scheme.**

***Index Terms*—Periodic load disturbances, harmonic disturbance observer, DC-AC inverter systems, mismatched disturbance rejection.**

I. Introduction

ALONG with the development of smart grids and renewable energy systems, voltage source inverters have became one of the crucial elements in the process of power conversion. Moreover, higher-performance inverters are demanded in several practical industrial application areas, such as uninterrupted power supplies [1], motor drives [2], distributed generation (DG) systems [3], [4] and electric vehicle (EV) systems [5]. Prominent properties, including rapid dynamic response, offset-free tracking error, strong disturbance rejection ability and low total harmonic distortion should be guaranteed in the higher-performance DC-AC inverter systems.

For the control problems of such inverter devices, the PID and deadbeat schemes have been widely used due to the simplicity in implementation. It is well known that load variations are deemed as one of the main devastating factors which causes control performance degradation. For example, in DG and EV systems [3], there could be a wide range of load variations from zero to full load. The control performance is seriously affected by these disturbances. These simple control schemes are hard to achieve satisfying performance in dealing with these disturbances [6], [7].

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The advantage of more powerful computational ability of hardware devices facilitates practical implementation of advanced nonlinear control approaches in the area of voltage regulation of inverters. The available control schemes include, but not limited to, model predictive control [2], [8], sliding model control [9], [10], and repetitive control [7], [11], etc. These advantageous control algorithms focus on improving the DC-AC inverter performance from different aspects.

Due to the existence of various significant disturbances in the inverter, one major motivation for advanced algorithms is to reject disturbances [12]. One efficient way to improve system performance in the presence of disturbances is feedforward compensation of the disturbances. Disturbance estimation technique provides a feasible way to realize feedforward disturbance compensation. Recently, several effective approaches have been developed to estimate the disturbances in the inverter system, such as the disturbance observer [6], [13], [14], and the extended state observer (ESO) [15], [16]. In the DC-AC inverter systems, the load disturbances appear in a channel different from the control input, which does not satisfy the so-called matching condition [16], [17]. Moreover, the coupling between the output voltage and the load variation leads to the undesirable periodic disturbances. A generalized ESO based control approach is proposed in [16] for mismatched disturbance compensation, which only considers the case of slow-varying disturbances. However, in the presence of periodic disturbance, the approach in [16] is not available for higher control performance.

In this paper, a harmonic disturbance observer based control (HDOBC) approach is investigated to solve the mismatched periodic disturbances attenuation problem of DC-AC inverter systems. A novel harmonic disturbance observer (HDOB) is introduced to estimate the load disturbances. Thereafter, by properly constructing new disturbance compensation gains, the effects of the mismatched disturbances are removed from the output voltage channel. Finally, experimental results of a DC-AC inverter show much better robustness performance against mismatched load disturbances, as compared with conventional feedback control approaches.

II. System modeling and problem analysis

A. Dynamic Model of Voltage Source Inverters

Fig. 1 gives an example of a typical voltage source DC-AC inverter control system, where V_{dc} and C_{dc} are the dc-link voltage and capacitor; L is the inductor of LC-filter; capacitor C in the filter is used to eliminate higher-order harmonic currents of switching frequencies; the main circuit consists of power switches S_{1-4}. The inverter output V_{inv} is denoted as uV_{dc} using the state space average technique, where $u \in [-1, 1]$ is the duty ratio function. Both linear resistance load and nonlinear diode rectifier load are considered. The dynamics of the inverter are presented as follows:

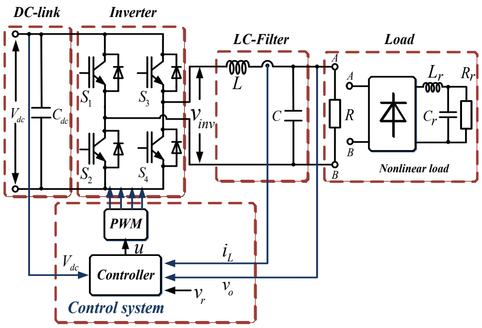


Fig. 1. Control structure of a typical voltage source DC-AC inverter.

$$\left\{ \begin{array}{l} \dot{v}_o = \frac{i_L}{C} - \frac{v_o}{ZC}, \\ \dot{i}_L = \frac{uV_{dc}}{L} - \frac{v_o}{L}, \end{array} \right. \tag{1}$$

where i_L is the current of inductor L, Z is the load, v_o is the output voltage of capacitor C and u is the duty ratio to generate the driving signals for switching devices.

B. Problem Formulation

Let v_r denote the reference. Voltage tracking error is defined as $x_1 = v_r - v_o$. Then (1) can be rewritten as follows:

$$\dot{x}_1 = \dot{v}_r - \frac{i_L}{C} + \frac{v_o}{Z_0 C} + d(t), \tag{2}$$

where Z_0 is nominal value of the load and $d(t) = \frac{v_o}{ZC} - \frac{v_o}{Z_0 C}$.

In order to separate the effects of load disturbance, the nominal part of the system is defined as a new state variable, x_2, for convenience of mathematic expression:

$$x_2 = \dot{v}_r - \frac{i_L}{C} + \frac{v_o}{Z_0 C}. \tag{3}$$

Differentiating the state variable x_2 and using (2), it yields:

$$\dot{x}_2 = f(v_r) - \frac{x_1}{LC} - \frac{x_2}{Z_0 C} - \frac{uV_{dc}}{LC} - \frac{1}{Z_0 C} d(t), \tag{4}$$

where $f(v_r) = \ddot{v}_r + \frac{\dot{v}_r}{Z_0 C} + \frac{v_r}{LC}$.

Denote state vector as $x = [x_1, x_2]^T$. Then, (1) can be written into a state space model, shown as:

$$\left\{ \begin{array}{l} \dot{x} = Ax + B_u u + B_d d + D, \\ y = C_m x, \end{array} \right. \tag{5}$$

where $A = \begin{bmatrix} 0 & 1 \\ -\frac{1}{LC} & -\frac{1}{Z_0 C} \end{bmatrix}$, $B_u = \begin{bmatrix} 0 \\ -\frac{V_{dc}}{LC} \end{bmatrix}$, $B_d = \begin{bmatrix} 1 \\ -\frac{1}{Z_0 C} \end{bmatrix}$, $D = \begin{bmatrix} 0 \\ f(v_r) \end{bmatrix}$ and $C_m = [1 \quad 0]$.

Notably, load disturbance $d(t)$ influences the DC-AC system via two different channels. In voltage channel, the disturbance is different from control input u, which is the so-called mismatched disturbance [16], [17]. In the state feedback controllers, they are hard to achieve satisfying performance because they can only suppress the disturbances in a relatively slow way [13], [16].

Remark 1: Main principal goals of the controller design for the inverter systems are to achieve stability, offset-free voltage tracking error, fast transmit behaviours, and higher-order harmonic elimination in the presence of load variations.

III. Development of the HDOBC approach

In this brief, the harmonic disturbance observer based controller is proposed by the following three steps. Firstly, a baseline state feedback controller is provided for output voltage tracking in the absence of disturbances. Then, a harmonic disturbance observer is designed to estimate the mismatched load disturbances. Finally, a composite controller is designed by integrating the baseline controller and harmonic disturbance observer together.

A. Baseline Controller

A composite PD controller is provided in absence of disturbances, given by:

$$u_b = \frac{LC}{V_{dc}} f(v_r) + K_x x, \tag{6}$$

where $f(v_r) = \ddot{v}_r + \frac{\dot{v}_r}{Z_0 C} + \frac{v_r}{LC}$, $K_x = [K_{x_1}, \ K_{x_2}]$ are the feedback control gains and chosen as $K_{x_i} > 0, \ i = 1, 2$. Note that the first term $\frac{LC}{V_{dc}} f(v_r)$ designed here is based on the philosophy of feedback linearization, which is used to generate the desired steady-state of control input. It can be verified that the tracking error dynamics is exponentially stable in the absence of load disturbances as long as the control gains $K_{x_i}, \ i = 1, 2$ are properly selected.

Remark 2: It is well known that the effects of mismatched disturbances are usually addressed by employing integral terms into the control law, then the modified control law can be obtained as:

$$u_{bI} = \frac{LC}{V_{dc}} f(v_r) + K_x x + K_I \int_0^t x_1 d\tau, \tag{7}$$

where $K_I > 0$ is the integral gain to be designed.

Submitting the modified control law (7) into system model (5) and combining with (2), the dynamics of output voltage tracking error x_1 is depicted as follows:

$$\begin{array}{l} \ddot{x}_1 + \left(\frac{V_{dc}}{LC} K_{x_2} + \frac{1}{Z_0 C} \right) \dot{x}_1 + \left(\frac{V_{dc}}{LC} K_{x_1} + \frac{1}{LC} \right) x_1 \\ + \frac{V_{dc}}{LC} K_I \int_0^t x_1 d\tau = \dot{d} - \frac{V_{dc}}{LC} K_{x_2} d. \end{array} \tag{8}$$

Taking derivative of voltage tracking error $x_1(t)$ in (8), one obtains that $x_1(t)$ will converge to zero asymptotically as long as the disturbance $d(t)$ and its derivative are uniformly bounded and $d(t)$ has a constant steady-state value. However, the load disturbances $d(t)$ here are periodic disturbances. Integral action is not able to thoroughly compensate the effects of periodic disturbances in this case.

Remark 3: Resonant control, based on the internal model principle, is also widely applied to remove harmonic disturbances in power electronics via a feedback approach. For the inverter system, a resonant control law can be shown as:

$$u_{bR} = \frac{LC}{V_{dc}} f(v_r) + K_x x + K_R x_1 cos(\omega_n t + \theta), \tag{9}$$

where $K_R > 0$ is resonant gain to be designed, ω_n is the angular frequency, and θ is the phase-lead angle for the delay compensation at resonant frequency. The resonant control part works as a patch to the baseline controller in (6) to deal with the considered periodic disturbances. A parallel combination of multiple resonant controllers can be used to eliminate significant harmonic distortion with heavy computational burden [11].

B. Construction of the Harmonic Disturbance Observer

As mentioned above, load disturbance is expressed as $d(t) = \left(\frac{1}{ZC} - \frac{1}{Z_0 C}\right) v_o$, in which the output voltage v_o is in sinusoidal form. Denote $A = \left(\frac{1}{ZC} - \frac{1}{Z_0 C}\right)$. The load disturbance $d(t)$ can be coordinated into the product formula of a numerical value A with a periodic signal v_o. Therefore, the load disturbance can be rewritten as $d(t) = A\sin(\omega t + \varphi)$, where A is the amplitude, ω is the angular frequency and φ is the initial phase of disturbance $d(t)$. The main idea of the harmonic disturbance observer is to embed the internal model of the periodic disturbance $d(t)$ into the design process. Owning to the second-order model characteristic of periodic disturbance $d(t)$, a new state variable is defined as $x_3 = A\cos(\omega t + \varphi)$ to facilitate the expression.

Then the extended state equation for the inverter system is written as:

$$\begin{cases} \dot{x}_1 = x_2 + d, \\ \dot{x}_2 = f(v_r) - \frac{1}{LC}x_1 - \frac{1}{Z_0 C}x_2 - \frac{V_{dc}}{LC}u - \frac{d}{Z_0 C}, \\ \dot{d} = \omega x_3, \\ \dot{x}_3 = -\omega d. \end{cases} \tag{10}$$

Then, the harmonic disturbance observer can be designed as (11), which is applied to estimate the mismatched disturbances.

$$\begin{cases} \dot{\hat{x}}_1 = \hat{x}_2 + \hat{d} + \alpha_1(x_1 - \hat{x}_1), \\ \dot{\hat{x}}_2 = f(v_r) - \frac{1}{LC}\hat{x}_1 - \frac{1}{Z_0 C}\hat{x}_2 - \frac{V_{dc}}{LC}u \\ -\frac{1}{Z_0 C}\hat{d} + \alpha_2(x_1 - \hat{x}_1), \\ \dot{\hat{d}} = \omega\hat{x}_3 + \alpha_3(x_1 - \hat{x}_1), \\ \dot{\hat{x}}_3 = -\omega\hat{d} + \alpha_4(x_1 - \hat{x}_1), \end{cases} \tag{11}$$

where $\alpha_i > 0, \ i = 1, 2, 3, 4$ are the observer gains to be designed so as to obtain desired transient responses.

C. Harmonic Disturbance Observer Based Controller Design

In order to deal with the matched and mismatched load disturbances, the composite harmonic disturbance observer based control law is designed as follows:

$$u = u_b + K_d\hat{d} + K\omega\hat{x}_3, \tag{12}$$

where $K = \frac{LC}{V_{dc}}$ and $K_d = K_{x_2}$ are the new designed compensation gains. Both $\hat{d}$ and $\hat{x}_3$ are the estimations provided by the designed harmonic disturbance observer.

Remark 4: According to the output regulation theory in [12], [18], the disturbance effects are removed from the output channel with the steady states forced to the objectives, which is the guideline for choosing compensation gains in this brief.

In order to indicate the proposed HDOBC method more clearly, the control block diagram is illustrated in Fig. 2.

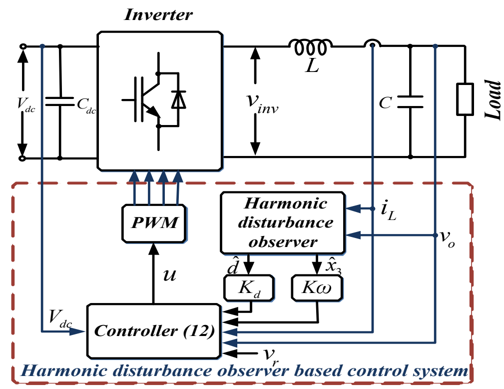


Fig. 2. Block diagram of the proposed control system.

IV. Stability analysis

Lemma 1 [16]: The following single-input linear system:

$$\dot{x} = Ax + Bu, \tag{13}$$

is asymptotically stable if A is is a Hurwitz matrix and u is bounded and satisfies $\lim_{t\to\infty} u(t) = 0$.

Theorem 1: For the inverter system (5), the mismatched periodic load disturbances can be attenuated from the output voltage channel in the steady-state in the presence of the proposed HDOBC law (12), on condition that the feedback control gains $K_{x_i}, \ i = 1, 2$ and observer parameters $\alpha_i, \ i = 1, 2, 3, 4$ in (11) are properly selected such that A_e in (14) and $A_c = A + B_u K_x$ in (17) are Hurwitz matrices, respectively.

Proof: For the DC-AC inverter system, the state disturbance estimation errors are defined as $e_1 = x_1 - \hat{x}_1, e_2 = x_2 - \hat{x}_2, e_3 = d - \hat{d}, e_4 = x_3 - \hat{x}_3$.

Taking the derivative of estimation errors and combining with (11) and (12), the error dynamics can be written as follows:

$$\dot{e} = A_e e, \tag{14}$$

where $e = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \end{bmatrix}$, $A_e = \begin{bmatrix} -\alpha_1 & 1 & 1 & 0 \\ -\alpha_2 - \frac{1}{LC} & \frac{-1}{Z_0 C} & \frac{-1}{Z_0 C} & 0 \\ -\alpha_3 & 0 & 0 & \omega \\ -\alpha_4 & 0 & -\omega & 0 \end{bmatrix}$.

The characteristic polynomial of the observer error dynamics is then derived and given by:

$$P(s) = |sI - A_e|. \tag{15}$$

The stability of the HDOB can be obtained by selecting all the parameters in $P(s)$ such that A_e is a Hurwitz matrix. The observer parameters $\alpha_i, i = 1, 2, 3, 4$ can be calculated out in this way. Then the observer estimation error e for the HDOB is asymptotically stable, which implies:

$$\begin{aligned} &\lim_{t\to\infty}[d(t) - \hat{d}(t)] = 0, \\ &\lim_{t\to\infty}[x_3(t) - \hat{x}_3(t)] = 0. \end{aligned} \tag{16}$$

Then the closed-loop system can be written as follows:

$$\begin{aligned} \begin{bmatrix} \dot{x} \\ \dot{e} \end{bmatrix} = &\begin{bmatrix} A_c & B_u K_{ce} \\ 0 & A_e \end{bmatrix} \begin{bmatrix} x \\ e \end{bmatrix} \\ &+ \begin{bmatrix} B_u K & B_u K_d + B_d \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{d} \\ d \end{bmatrix}, \end{aligned} \tag{17}$$

where $K_{ce} = [K\alpha_3,\ 0,\ K_d,\ K\omega]$ and $A_c = A + B_u K_x = \begin{bmatrix} 0 & 1 \\ -\frac{V_{dc}}{LC}K_{x_1} - \frac{1}{LC} & -\frac{V_{dc}}{LC}K_{x_2} - \frac{1}{Z_0 C} \end{bmatrix}$.

Denote $X = x - B_u K d$. By taking the derivative of X, the coordinate transformation can be written as:

$$\begin{bmatrix} \dot{X} \\ \dot{e} \end{bmatrix} = \begin{bmatrix} A_c & B_u K_{ce} \\ 0 & A_e \end{bmatrix} \begin{bmatrix} X \\ e \end{bmatrix} + \begin{bmatrix} B_u K_d + B_d + A_c B_u K \\ 0 \end{bmatrix} d. \quad (18)$$

Substituting compensation gains K_d and K into (18), it yields:

$$\begin{bmatrix} \dot{X} \\ \dot{e} \end{bmatrix} = \begin{bmatrix} A_c & B_u K_{ce} \\ 0 & A_e \end{bmatrix} \begin{bmatrix} X \\ e \end{bmatrix}. \quad (19)$$

Since both A_c and A_e are Hurwitz matrices, it is easy to get the conclusion that the system (19) is asymptotically stable. Under the given conditions of *Theorem 1*, by *Lemma 1*, the following results are obtained:

$$\lim_{t\to\infty} X(t) = \lim_{t\to\infty}(x - B_u K d) = 0, \quad (20)$$

which implies that

$$\lim_{t\to\infty} y(t) = 0. \quad (21)$$

It is obvious that the output of the system is not influenced by the mismatched disturbances in steady state, which means that disturbances are attenuated from the output voltage channel. This completes the proof. ■

V. Implementation and Validation

To evaluate the superiority of the proposed control scheme, detailed experimental studies based on dSPACE DS1103 real-time test setup are carried out. Proper gains are carefully chosen for the composite PD (6), composite PRD (9), and HDOBC (12) approach here. The experimental test setup is illustrated in Fig. 3, comprising an inverter main circuit, a real-time controller, DC power supplies, digital oscilloscope, voltage and current sensors, etc. The switching frequency generated by dSPACE is $10kHz$.

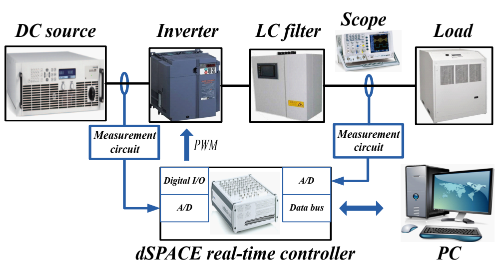


Fig. 3. Experimental test setup.

A. Robust Performance Against Linear Load Variations

Specifically, the load resistance is expected to have a step change from its nominal value $Z_0 = 100\ \Omega$ to $Z = 50\ \Omega$ at $t = 0.2$ second. The DC-link voltage and reference voltage are $V_{dc} = 150\ V$ and $v_r = 110\sin(100\pi t)\ V$, respectively. For simplicity in practical implementation, fourfold poles are adopted here for the designed observer (11), which are selected as $-p = -100$. The observer parameters are given as $\alpha_1 = -1.5 \times 10^3$, $\alpha_2 = -9.2 \times 10^7$, $\alpha_3 = 3.9 \times 10^6$, and $\alpha_4 = -1.3 \times 10^5$, respectively. The relevant curves in the presence of these controllers are shown in Fig. 4.

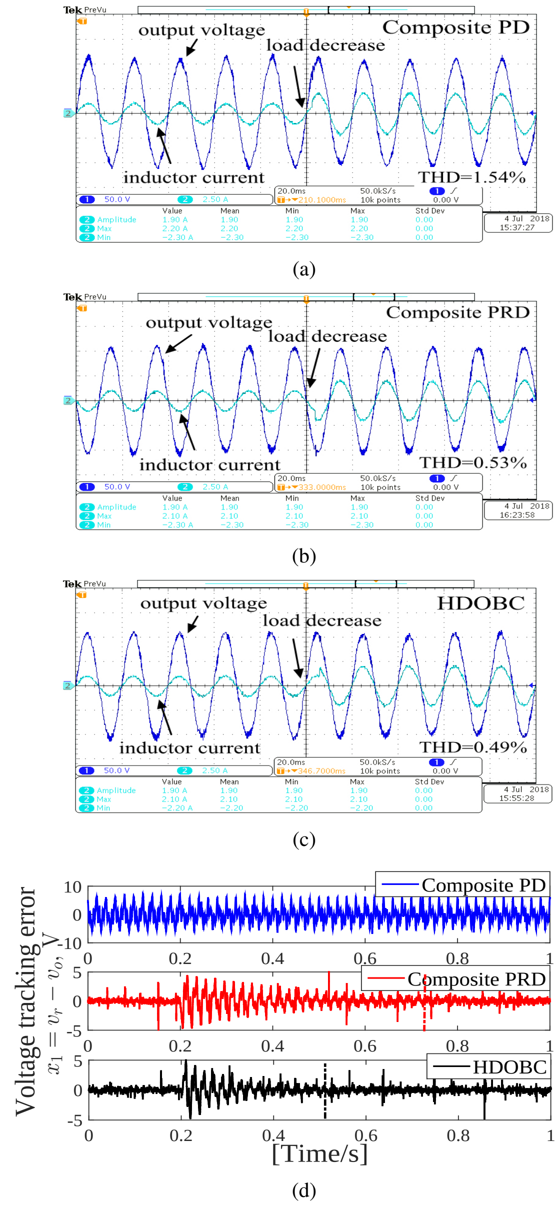
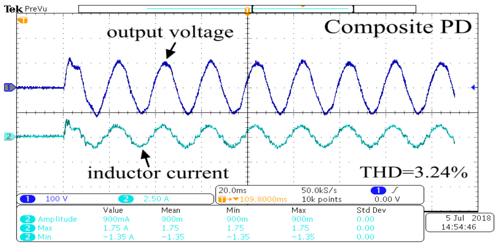


Fig. 4. Voltage and current curves with linear load. (a) Composite PD (6). (b) Composite PRD (9). (c) HDOBC (12). (d) Voltage tracking error $x_1(t)$.

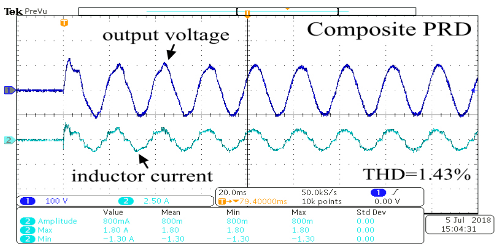
B. Robust Performance Against Nonlinear Load

To further investigate robustness against nonlinear load, a generic rectifier load is taken into consideration. The parameters of the nonlinear load is chosen as rectifier inductor $L_r = 5 \times 10^{-3}\ H$, capacitor $C_r = 50 \times 10^{-6}\ F$, and resistor $R_r = 100\ \Omega$. Response curves are shown in Fig. 5.

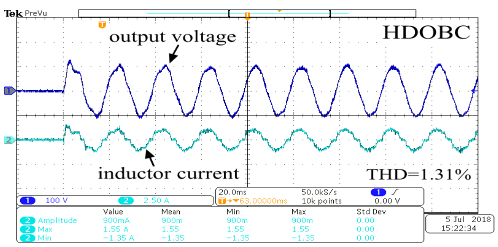
In order to clearly characterize transient and steady-state behaviours of the proposed approach, performance comparisons are listed in Table I. Since tracking errors always exist in the composite PD approach, the convergence time is not given. Compared with the other two approaches, the



(a)



(b)



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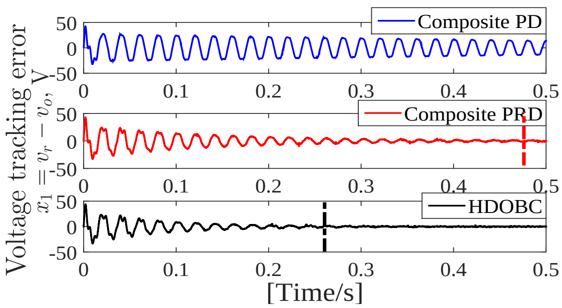

(d)

Fig. 5. Voltage and current curves with nonlinear load. (a) Composite PD (6). (b) Composite PRD (9). (c) HDOBC (12). (d) Voltage tracking error $x_1(t)$.

TABLE I
PERFORMANCE COMPARISONS.

Algorithms	**Linear (L) / Nonlinear (N) load**	
	Convergence time t_r (s)	**THD value** (%)
Composite PD (6)	– (L) / – (N)	1.54 (L) / 3.24 (N)
Composite PRD (9)	0.55 (L) / 0.48 (N)	0.53 (L) / 1.43 (N)
HDOBC (12)	0.30 (L) / 0.25 (N)	0.49 (L) / 1.31 (N)

proposed HDOBC approach is effective to obtain satisfying performances in all the given operating conditions. It offers the shortest convergence time and minimum THD values as shown in Table I, which illustrates the efficacy of the proposed solution.

VI. Conclusion

In this brief, a HDOBC approach has been investigated for the voltage source inverter system with the purpose of achieving robustness against load variations. By utilizing the technique of harmonic disturbance observer, the mismatched periodic disturbances have been estimated accurately. Simultaneously by adequately choosing feedforward compensation gains, a real-time remedy for the effects of load variations is available for the proposed HDOBC approach. Experimental results have been conducted to validate the feasibility and effectiveness. Some limitations still exist, our future research will focus on investigating extended HDOB to reject higher-order harmonics. The presented simple but effective control approach is also expected to extend to other types of converters and rectifiers.

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