International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 13, No. 3, September 2022, pp. 1843∼1853
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v13.i3.pp1843-1853 ❒ 1843

Fixed-time control of voltage dynamics of three-phase voltage source inverters with LC output filter

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Article Info

Article history:

Received Jan 12, 2022
Revised Jun 11, 2022
Accepted Jun 30, 2022

Keywords:

Cascade control
Fixed-time control
Voltage control
Voltage source inverter

ABSTRACT

This paper puts forward a fixed-time cascade voltage control system for three-phase voltage source inverters (VSIs) with LC output filter.First, a feedforward decoupling mechanism is used to elminate the dependency between the d-q parts of the control system. Then, proportional-integral (PI) regulators are used for current control in the inner loop. The current reference is provided by a novel VSI control technique developed for fixed-time voltage regulation and reference tracking. The approach suggested in this work tracks and maintains the voltage magnitude at its normalized value in a finite-time and before a maximum settling-time fixed in advance and independent of the system's initial state. The voltage controller also maintains current stability by providing a smoother and smaller current reference. A comparative study with VSI conventional PI control for linear, nonlinear and unbalanced loads confirms the theoretical results.

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1. INTRODUCTION

Power converters are among the main building blocks of electrical generation systems due to their numerous applications [1]-[11]. Voltage source inverters (VSIs), in particular, are commonly used for interfacing renewable energy sources and energy storage systems with the primary grid [12], [13]. VSIs have many applications including output voltage and current control [10], [13]-[17], active power filtering [3], [7], [18]-[20], and power factor compensation [21], [22], among other applications [4], [5].

VSIs are mainly used in power networks as DC-AC converters. Thus, their main control objectives is to provide and maintain the three-phase output voltage in the desired magnitude and frequency despite external disturbances and load variations while maintaining current stability. Achieving this objective requires a cascaded control structure where the outer/main control loop is for voltage while the inner one is for current. Many techniques has been developed in literature for this purpose. Proportional-resonant (PR) controllers designed in the $\alpha - \beta$ reference frame were suggested in [13] for voltage voltage, current and harmonic compensation. However, only the targeted frequencies are controlled because of the sinusoidal nature of the variables in the stationary reference frame $\alpha - \beta$. This adds limitations to the control performance as not all the undesired signals can be eliminated from the VSI's voltage/current output. Pogaku *et al.* [17] developed the conventional PI-based control structure for VSIs voltage and current control. This control system has the advantage of being easily tuned because of the small number of control parameters, and it is developed in the synchronous

$d-q$ reference frame so that the manipulated variables are not sinusoidal which facilitates the control. The conventional approach uses several feedforward and cross-terms though, that complicates the controller implementation and requires the online measures of other variables beside the output voltage and current and thus the use of several measurement equipments. Several advanced approaches of VSI control were studied in literature including model predictive control in [14], [23], fuzzy-logic [24], [25], sliding-mode [26], feedback control [27], and internal model control in [15]. However, the proposed control laws only achieves asymptotic convergence to the reference which means that the references can't be reached in a finite-time. Also, some of these works only address current control.

Fixed-time control is a novel approach in control systems design and has been applied in engineering fields such as robotics [28]-[31] and renewable energies [32]-[35]. Fixed-time control has the advantage of ensuring reference tracking and regulation before the desired pre-fixed time regardless of the unknown disturbances and the system nonlinearties. Fixed-time control can also involve other methods as sliding-mode control, feedback control and feedforward control among others to enhance further the control performance. These features make fixed-time control suitable for applications where the system is nonlinear and where the external disturbances are common.

In this paper, a novel voltage fixed-time control technique is developed for three-phase VSIs with LC output filter. The overall control system is designed in the $d-q$ reference frame with a cascade structure where the outer/main control loop is for voltage while the inner is for current. Compared to the proportional-integral (PI)-based conventional control, the suggested approach has the following advantages: i) Voltage regulation and reference tracking in a finite-time and before a maximum settling-time fixed in advance and that doesn't depend of the system initial conditions; ii) Enhancing current stability by minimizing the current reference; and iii) Fully decoupled control of voltage and current direct and quadratic components.

The rest of the paper is organized as follows. In section 1 the proposed control system is designed and its efficiency is verified through a simulation study. Section 2 is devoted to the discussion and the analysis of the results of the design procedure and the comparative simulation. Finally, the study is summarized and concluded in section 3.

2. METHOD

To design the proposed controller, some mathematical preliminaries are required:

Lemma 1: Consider the simple-integrator system given by (1) [36], [37].

$$\dot{x} = g(t,x),\ x(0) = 0 \tag{1}$$

Where $g : R_+ \times R^n \rightarrow R^n$ is a nonlinear function. If there exists a continuous radially unbounded and positive definite function $V(x)$ such that (2).

$$\dot{V}(x) \leq -\alpha V^p - \beta V^q \tag{2}$$

Where $\alpha, \beta > 0$, $p > 1$ and $0 < q < 1$, then the origin of system (1) is globally fixed-time stable with the settling-time T verifying as (3).

$$T \leq T_{max} := \frac{\pi\mu}{2\sqrt{\alpha\beta}} \tag{3}$$

To design the proposed control system, a linear model of the three-phase voltage source converters (VSC) with LC output filter (see Figure 1) is required. To obtain such a model, two steps will be taken :

- First, the model will be designed in the abc/dq reference frame so that the manipulated variables are direct and not sinusoidal and they also have two components (direct and quadratic) instead of three, which facilitates significantly the model and control system design process.
- Second, during the sampling period T_s of the pulse width modulation (PWM), a linear average model of the three-phase VSC with LC output filter can be established, where the PWM dynamics are modeled as a first order transfer function [38] .

Thus, the three-phase VSC with LC output filter can be modeled in the abc/dq reference frame in two single-phase systems [38], [39] as depicted in Figure 2.

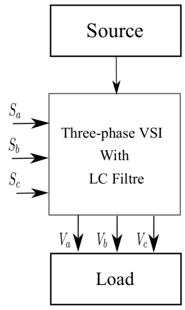


Figure 1. Three-phase VSI with LC output filter

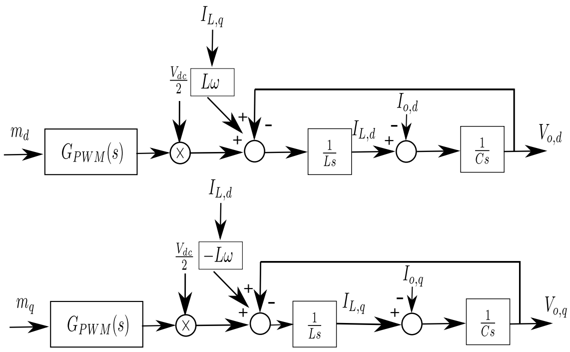


Figure 2. Three-phase VSI with LC output filter model in the d-q synchronous reference frame

The model contains the following elements:
– The voltage V_{dc} of DC voltage source.
– The PWM transfer function $G_{PWM}(s)$ given as [38], expressed as (4).

$$G_{PWM}(s) = \frac{1}{1 + 1.5T_s s} \tag{4}$$

Where T_s is the sampling period. L and C are repectively the filter inductance and capacity. V_o is the output voltage and $V_{o,d}$ and $V_{o,q}$ are its d-q components. I_o is the output current and $I_{o,d}$ and $I_{o,q}$ are its d-q components. ω is the rotation pulsation of the reference frame. V_{ind} is the VSC control input and $V_{inv,d}$ and $V_{inv,q}$ are its d-q components. I_L is the inductance current and $I_{L,d}$ and $I_{L,q}$ are its d-q components.

This work proposes a novel three-phase VSI voltage control technique that ensures fixed-time regulation and reference tracking. Figure 3 shows a schematic of the proposed controller. The output voltage references $V_{ref,d}$ and $V_{ref,q}$ are set as follows $V_{ref,d} = V_{ref}$ and $V_{ref,q} = 0$ where V_{ref} is the desired voltage magnitude so that in the steady state the output voltage magnitude verifies $V_{o,magn} = \sqrt{V_{o,d}^2 + V_{o,q}^2} = V_{ref}$. Since voltage magnitude in power networks is standardized and fixed, V_{ref} will be supposed constant in this work. The direct and quadratic control loops are decoupled using current feedforward terms. In the inner loops, conventional PI controllers are used for current regulation. For the outer loops, the following fixed-time controller is proposed for voltage control given as (5).

$$\begin{aligned} f(V_{ref,d}, V_d) &= K \int sign(V_{ref,d} - V_d) \mid V_{ref,d} - V_d \mid^{1+\frac{2}{\mu}} \\ &\quad + sign(V_{ref,d} - V_d) \mid V_{ref,d} - V_d \mid^{1-\frac{2}{\mu}} dt \\ f(V_{ref,q}, V_q) &= K \int sign(V_{ref,q} - V_q) \mid V_{ref,q} - V_q \mid^{1+\frac{2}{\mu}} \\ &\quad + sign(V_{ref,q} - V_q) \mid V_{ref,q} - V_q \mid^{1-\frac{2}{\mu}} dt \end{aligned} \tag{5}$$

Where $K > 0$ and $\mu > 1$ are the control gains.

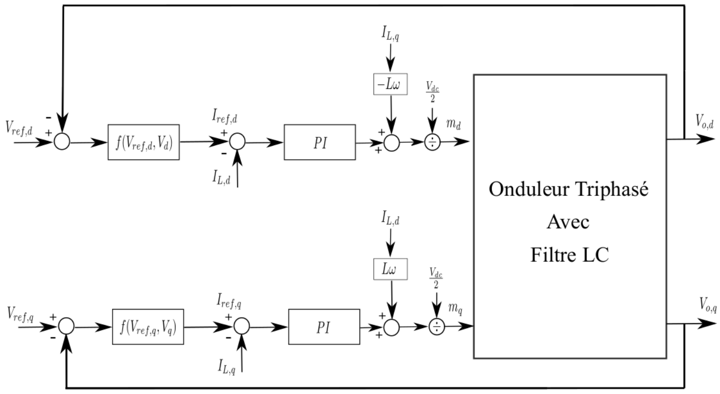


Figure 3. The proposed controller of three-phase VSI with LC output filter

The design procedure is identical for both V_d and V_q, so to avoid redundancy we will present the design for V_d only. Let's consider the following positive definite Lyapunov function given as (6). The derivative of the Lyapunov function (6) is given as (7).

$$V = (V_{ref,d} - V_d)^2 \tag{6}$$

$$\dot{V} = 2(V_{ref,d} - V_d)(\dot{V}_{ref,d} - \dot{V}_d) \tag{7}$$

$\dot{V}_{ref,d} = 0$ because $V_{ref,d}$ is supposed constant, expressed as (8).

$$\dot{V} = -2(V_{ref,d} - V_d)\dot{V}_d \tag{8}$$

Denote $I_{L,d,ref}$ inductance current direct component reference. One can write $I_{L,d,ref} = f(V_{ref,d}, V_d)$. In cascade control structure the inner loop is faster than the outer loop, therefore the current steady state is reached faster than voltage steady state. The controller is designed in the d-q frame and thus, the manipulated variables are static. Since PI control achieves asymptotic convergence, then by using PI for current control, two scenarios can be considered: Either the current tracking error converge asymptotically to zero in which case we have $I_{L,d} = I_{L,d,ref} + E$ with $\dot{E} \leq 0$ or the PI controller provides a constant steady state error in which case $I_{L,d} = I_{L,d,ref} + E$ with $E \neq 0$ and $\dot{E} = 0$. In both cases we have (9) and (10). One also has using VSI model given as (11).

$$I_{L,d} = I_{L,d,ref} + E \tag{9}$$

$$\begin{aligned} \dot{I}_{L,d} &= \dot{I}_{L,d,ref} + \dot{E} \\ &\leq \dot{I}_{L,d,ref} \end{aligned} \tag{10}$$

$$(I_{L,d} - I_{o,d})\frac{1}{Cs} = V_{o,d} \tag{11}$$

Where $I_{o,d} = \frac{V_{o,d}}{Z_{load}}$ and the load impedance $Z_{load} = \sqrt{R_{load}^2 + (L_{load}\omega)^2}$. This yields expressed as (12). System (12) has a first order-system dynamics thus $V_{o,d}$ converge exponentially to its final value $Z_{load}I_{L,d}$ in the settling-time $T_{settling} \approx 3Z_{load}C$. Since $C \ll 1$ and $L_{load} \ll 1$, then $T_{settling} \approx 3Z_{load}C \ll 1$. Therefore system (12) has fast dynamics and $V_{o,d}$ converge exponentially in a negligible time to its final value $Z_{load}I_{L,d}$. Thus, the convergence time can be safely neglected and one can write $V_{o,d} = Z_{load}I_{L,d}$. This yield expressed as (13) and (14). In virtue of Lemma 1, the error $V_{ref,d} - V_d$ converge to zero, and thus V_d converge to $V_{ref,d}$, before the desired pre-fixed settling-time T verifying given as (15).

$$V_{o,d} = \frac{Z_{load}}{Z_{load}Cs + 1}I_{L,d} \tag{12}$$

$$\dot{V}_{o,d} = Z_{load}\dot{I}_{L,d} \leq Z_{load}\dot{I}_{L,d,ref} \quad (13)$$
$$\leq Z_{load}K\big[sign(V_{ref,d} - V_d) \mid V_{ref,d} - V_d \mid^{1+\frac{2}{\mu}}$$
$$+ sign(V_{ref,d} - V_d) \mid V_{ref,d} - V_d \mid^{1-\frac{2}{\mu}} \big]$$

$$\dot{V} \leq \, -2Z_{load}K(V_{ref,d} - V_d)\big[sign(V_{ref,d} - V_d) \mid V_{ref,d} - V_d \mid^{1+\frac{2}{\mu}} \quad (14)$$
$$+ sign(V_{ref,d} - V_d) \mid V_{ref,d} - V_d \mid^{1-\frac{2}{\mu}} \big]$$
$$\leq \, -2Z_{load}K\big[\mid V_{ref,d} - V_d \mid^{2+\frac{2}{\mu}} + \mid V_{ref,d} - V_d \mid^{2-\frac{2}{\mu}} \big]$$
$$\leq \, -2Z_{load}K\big[V^{1+\frac{1}{\mu}} + V^{1-\frac{1}{\mu}}\big]$$

$$T \leq \frac{\pi\mu}{4Z_{load}K} \quad (15)$$

Remark, the aforementioned analysis shows that fixed-time regulation and reference tracking of the VSI output voltage is mathematically ensured despite the asymptotic current control in the cascade control system of the VSI.

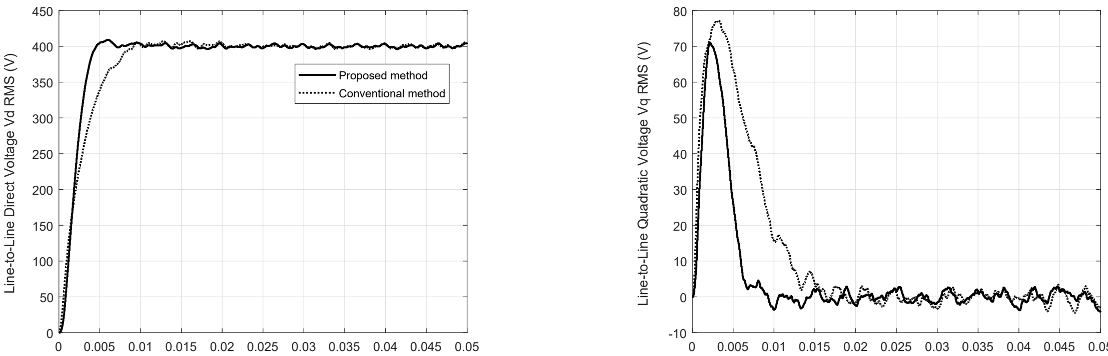
Three comparative studies will be conducted to highlight the effectiveness of the proposed control strategy compared to conventional cascade PI-based VSI control [17]. The simulations test system is a 400 V RMS electrical network containing a DC voltage source V_{dc} = 700 V, a VSI, an LC filter with L = 2 mH and C = 29.8 μF and a resistive charge in the first case study, a nonlinear charge in the second and a linear unbalanced resistive charge with impedance Z_{load} = 53 Ω in the third. The control gains used in the simulations are as follows $K = 10$, $\mu = 20$, $K_p = 15$ and $K_i = 1 \times 10^{-5}$ where K_p and K_i are the PI current controllers gains and they were chosen as such to highlight the ability of the proposed control system to provide better performance with smaller control signal. The pre-fixed settling-time thus verifies $T \leq 0.0296s$.

– Case 1: Linear load

In this case study we consider a linear load purely resistive with impedance Z_{load} = 53 Ω. The results of the simulations are shown in Figure 4 and Figure 5. The output voltage direct and quadratic components are displayed in Figures 4(a) and 4(b) respectively while the control signals direct and quadratic components are displayed in Figures 5(a) and 5(b) respectively.

– Case 2: Nonlinear load

In this case study we consider a nonlinear load containing a diode-based rectifier with LC filter (L_{load} = 1 mH, C_{load} = 100 μF) and a resistive charge R = 80 Ω. The results of the simulations are shown in Figure 6, Figure 7, and Figure 8. The output voltage direct and quadratic components are displayed in Figures 6(a) and 6(b) respectively while the control signals direct and quadratic components are displayed in Figures 8(a) and 8(b) respectively. Figure 7 presents the voltage output magnitude variations.



(a) (b)

Figure 4. Output voltage RMS using the proposed and the conventional control methods for (a) direct component and (b) quadratic component

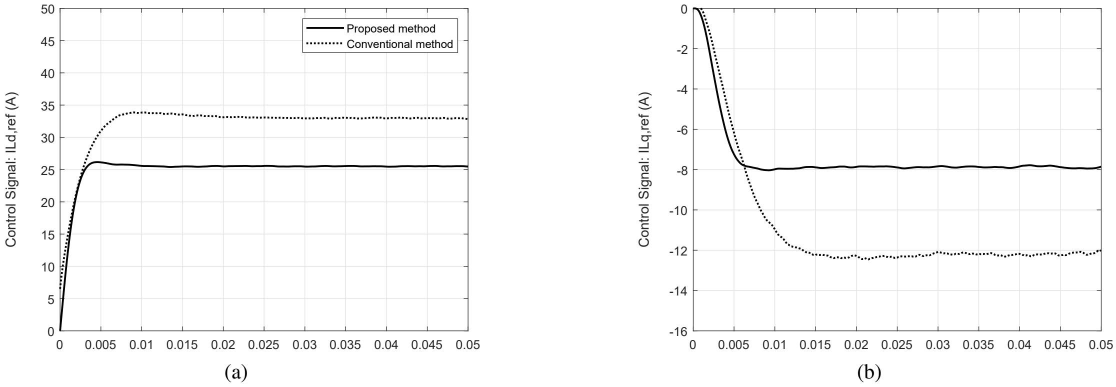


Figure 5. The control signals using the proposed and the conventional control methods for (a) direct component and (b) quadratic component

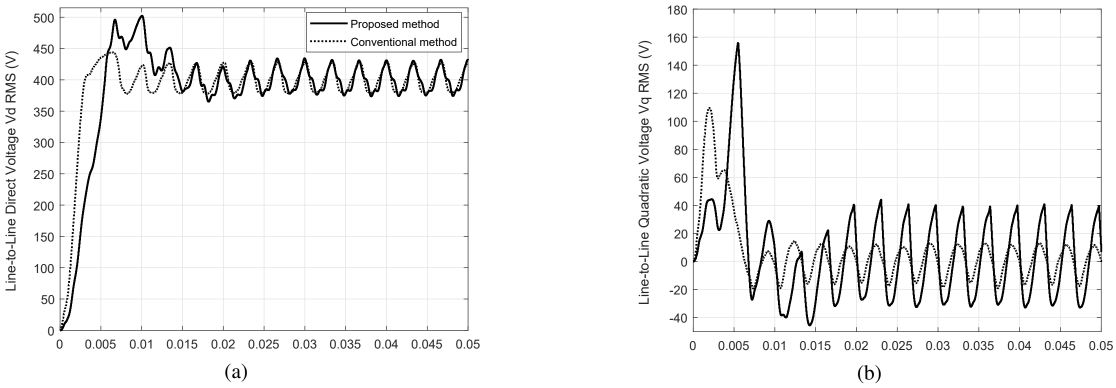


Figure 6. Output voltage RMS using the proposed and the conventional control methods for (a) direct component and (b) quadratic component

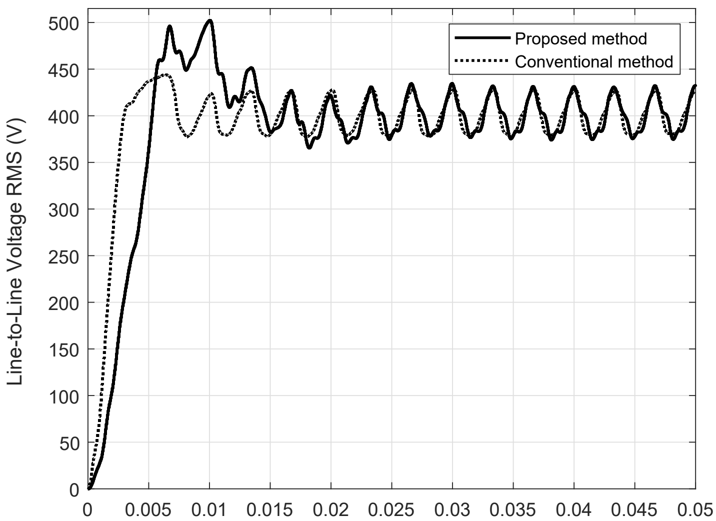
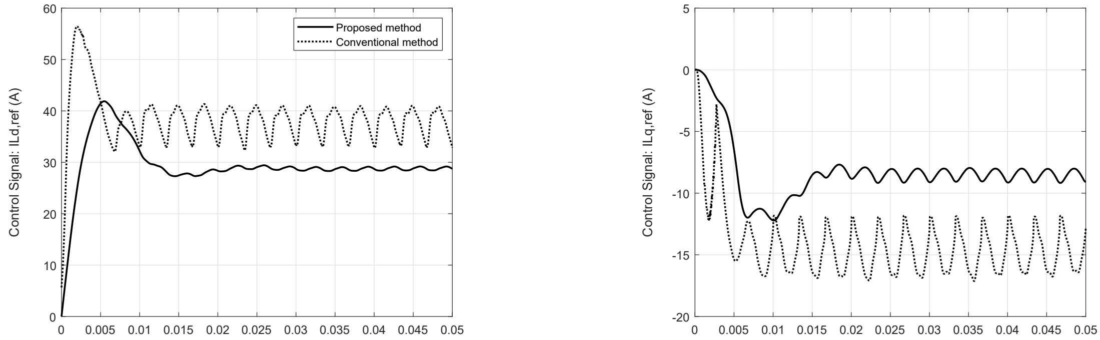


Figure 7. Output voltage RMS using the proposed and the conventional control methods

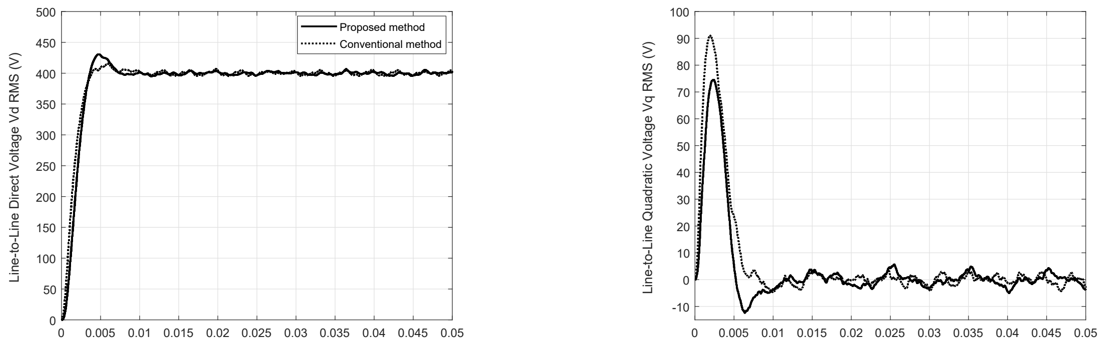


(a) (b)

Figure 8. The control signals using the proposed and the conventional control methods for (a) direct component and (b) quadratic component

– Case 3: Unbalanced load

In this case study we consider a linear unbalanced load with active and reactive powers per phase given as: P_1 = 1 kW, P_2 = 1.5 kW, P_3 = 0.5 kW, Q_1 = 100 VAR, Q_2 = 50 VAR, Q_3 = 150 VAR. The results of the simulations are shown in Figure 9, Figure 10, and Figure 11. The output voltage direct and quadratic components are displayed in Figures 9(a) and 9(b) respectively while the control signals direct and quadratic components are displayed in Figures 11(a) and 11(b) respectively. Figure 10 presents the voltage output magnitude variations.



(a) (b)

Figure 9. Output voltage RMS using the proposed and the conventional control methods for (a) direct component and (b) quadratic component

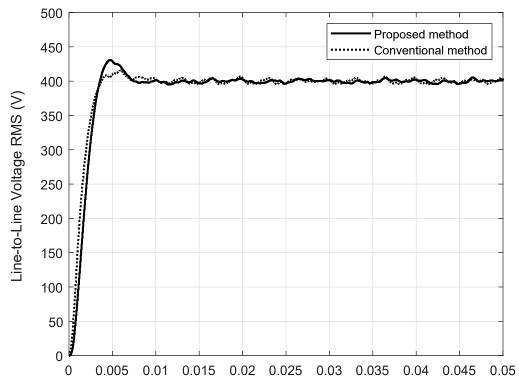


Figure 10. Output voltage RMS using the proposed and the conventional control methods

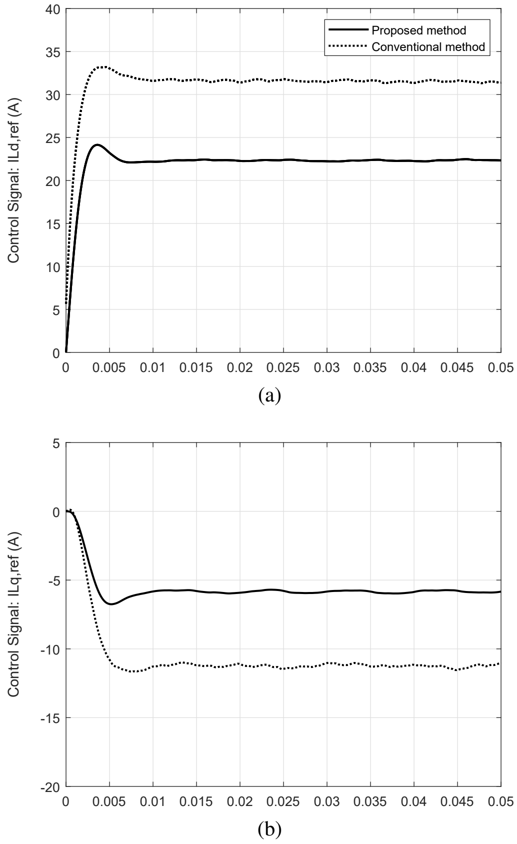


Figure 11. The control signals using the proposed and the conventional control methods for (a) direct component and (b) quadratic component

3. RESULTS AND DISCUSSION

Based on the analysis provided in the previous section we can state the theorem:

Theorem: The control protocol (5) drives the voltage direct and quadratic components V_d and V_q to the desired references $V_{ref,d}$ and $V_{ref,q}$ before the pre-fixed settling-time given as (16).

$$T \leq \frac{\pi\mu}{4Z_{load}K} \tag{16}$$

Where Z_{load} the load impedance. The performance of the designed control system has been tested in the case of a linear, a nonlinear and an unbalanced load. As for the first case, Figure 4 shows that the RMS of both direct and quadratic components of the output voltage exhibit fast dynamics and reach their reference values 400 V and 0 V respectively before the pre-fixed time 0.0296 s. Furthermore, the suggested control technique provides a less fluctuating output voltage than its conventional PI counterpart. The voltage control also provides a smoother and less fluctuating control signal with lower values using the proposed control system as can be seen in Figure 5.

In the case of a nonlinear load, Figure 6 shows that the fixed-time approach drives the RMS of the output voltage direct component to its reference value 400 V before the pre-fixed time 0.0296 s, as designed, and with similar fluctuations afterwards to the output direct voltage fluctuations when using the conventional method. The proposed control system also causes a higher but short overshoot that lasts 5 ms. The quadratic component of the output voltage exhibits fluctuating dynamics using both the control systems with relatively high overshoot using the proposed approach, however this doesn't affect the output voltage dynamics that resembles those of the its direct component in term of convergence speed, overshoot and fluctuations magnitude as shown in Figure 7. In term of control signals, Figure 8, shows that proposed fixed-time voltage control requires a smaller and less fluctuating control signal compared to the conventional one in both the direct and quadratic components of the control signal.

In presence of an unbalanced load, Figure 9 shows that the fixed-time approach drives the RMS of the output voltage direct component to its reference value 400 V before the pre-fixed time 0.0296 s, as designed, with a slightly higher overshoot but with similar fluctuations afterwards to the output direct voltage fluctuations when using the conventional method. The quadratic component of the output voltage also exhibits fluctuating dynamics using both the control systems with lower overshoot however using the proposed approach. The output voltage dynamics resembles those of the its direct component in term of convergence speed, overshoot and fluctuations magnitude as shown in Figure 10. In term of control signals, Figure 11, shows that proposed fixed-time voltage control requires a smaller and less fluctuating control signal compared to the conventional one in both the direct and quadratic components of the control signal.

4. CONCLUSION

This article introduces a fixed-time voltage control system of three-phase voltage source inverters (VSIs) with LC output filter. A fixed-time voltage control technique is developed to ensure regulation and reference tracking before the desired pre-fixed time despite the unknown disturbances. This technique is implemented in the outer loop of the VSI control system while the inner loop uses PI controllers for current regulation and feedforward terms to decouple the control of direct and quadratic voltage and current components. Three comparative simulation case studies conducted with linear, nonlinear and unbalanced loads under the proposed and the conventional PI-based control confirmed the theoretical results regarding voltage regulation and reference tracking before the desired pre-fixed time for all types of loads with slightly higher overshoot in case of nonlinear and unbalanced ones. The simulations also showed that the control signal provided by the proposed approach is always less fluctuating and has smaller values compared to conventional control.

ACKNOWLEDGEMENTS

This work is supported by Morocco's National Center for Scientific and Technical Research within the Research Excellence Scholarships Program.

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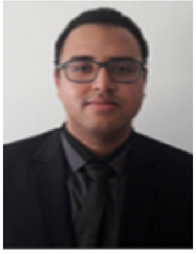

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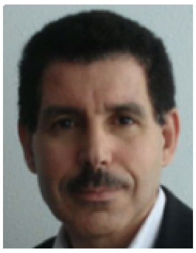

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