Space Vector Analysis of Dead-Time Voltage Distortion in Multiphase Inverters

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Abstract—**Inverter dead-time effects have been widely investigated in past for three-phase voltage source inverters (VSIs). Recently, a great deal of research has concentrated on PWM methods suitable for multi-phase VSIs (with more than three phases). All PWM methods theoretically produce sinusoidal output voltages without low-order harmonics. This paper analyzes the dead-time effects on output variables of multi-phase VSIs in the case of carrier-based PWM techniques if no any compensation technique is applied. In particular, a generalized analysis for *n*-phase inverters is introduced first, and numerical verification for three-, five- and seven-phase inverters are performed to verify the analytical developments. The dead-time effect on load voltage is also represented in terms of multiple space vectors, and analysis of harmonics content for each α-β plane is given.**

Keywords— **Voltage distortion, multi-phase inverter, harmonic analysis, inverter nonlinearity, multiple space vectors**

I. Introduction

Pulse-width modulation inverters have widely been used in motor drives. However, these inverters produce voltage distortion due to nonlinear characteristics of switching devices such as turn-on/turn-off times, voltage drops on switches and diodes. A further important nonlinearity is caused by necessary dead-time introduced to avoid the so-called shoot-through of the dc link. In fact, to guarantee that both switches never conduct simultaneously, a small time delay is added to the gate signal of the turning on device. This small time, in order of μs, introduces magnitude and phase errors in the output voltage. The voltage distortion increases with switching frequency, introducing harmonic components that may cause instabilities and additional losses in the machine being driven. Relative voltage deviation effect is more significant for smaller inverter output voltages [1]-[5].

The dead-time problem has already been investigated by the industry [2], [3] and various solutions have been proposed. In most cases the compensation techniques are based on an average value theory, the lost volt-seconds are averaged over an entire period and added to the commanded value. A pulse-based compensation method has been proposed in [2], where the compensation is realized for each pulse. The compensation voltages in [3] are calculated by using dead-time, switching period, current command and dc-link voltage. Regardless of the method used, all dead-time compensation techniques are based on polarity of the current. This is especially true around the zero-crossing where an accurate measurement is needed to correctly compensate for the dead-time. In [4] an on-line dead-time compensation technique is presented, acquiring the additional computation burden to determine the phase angle of currents.

The area of multiphase variable-speed motor drives, in general, and multiphase induction motor drives, in particular, has experienced a substantial growth since the beginning of this century. Detailed overview of the current state-of-the-art in this area is given by [6]. The inverter dead-time effect on the steady-state and dynamic performances of a multi-phase induction machine with current control is analyzed in [7]. The paper suggests a modified current control scheme that is able to compensate inverter dead-time and provides sinusoidal currents. Although in this case it is possible to have perfect compensation of dead-times, the problem remains for the drives that are based on machine flux estimation, since dead-time introduces errors if input dc voltage and switch patterns are used for calculations instead of actual ac output voltages. Analysis and compensation method for a five-leg inverter driving two three-phase ac motors independently has been done in [8]. Practically, this analysis can be simplified as for three-phase inverters, since the motors are independent.

Even though the compensation of dead-times can be done on the basis of current measurement, never it is perfect since the turn-on/turn-off times are not known exactly and are depending on many factors [9], leading to either an over- or under-compensation.

An analysis of the effect of dead-time introduced for multi-phase inverters is given in [10], with a general extension to *n* phases and a specific investigation on five- and seven-phase inverters, with reference to carrier-based PWM techniques. In this paper the analysis is further developed by applying the multiple space vector representation of load voltages [11], leading to the definition of specific harmonic components in the different α-β planes. Examples are given for 5 and 7 phases [12], [13].

II. Dead-Time Effects in N-Phase Inverters

It is convenient to analyze the dead-time effects starting from a single inverter leg, and then to extend the results to the whole converter, having one leg for each one of the *n* output phases. Assuming a continuous carrier-based PWM technique to be applied, every switch turns on and turns off once in each switching period, always providing a pole voltage pulse.

As known, during the dead-time t_d, both the switching devices in inverter leg cease to conduct, and one of the two diodes conducts. If the current polarity is positive, the lower diode will conduct, otherwise the upper diode will conduct. It is assumed in further analysis that the system is balanced with sinusoidal phase currents i_k

$$i_k = I_M \sin\left[\omega_o t - (k-1)2\pi / n\right],\ k = 1, 2, \ldots, n \tag{1}$$

where $\omega_o = 2\pi f = 2\pi/T$ is the fundamental frequency.

The actual pole voltage of *k*-th leg, e_k, can be evaluated on the basis of the reference pole voltage, e_k^*, according to the sign of the phase current i_k as:

$$e_k = e_k^* - sign(i_k)\,\Delta V_d\,, \quad k = 1, 2, \ldots, n \tag{2}$$

where ΔV_d is the averaged voltage contribution due to the dead-time t_d over the switching period T_c

$$\Delta V_d = \frac{t_d}{T_c} V_{dc}\,. \tag{3}$$

The effects on n-phase inverters can be emphasized on the basis of the actual load voltage v_k expressed by pole voltages

$$v_k = e_k - \frac{1}{n}\sum_{j=1}^{n} e_j\,, \tag{4}$$

where v_k and e_k are load and pole voltages, and the number of phases $n \geq 3$ is odd integer.

Equation (4) together with (2) leads to

$$v_k = v_k^* + u_k\,, \tag{5}$$

being v_k^* the reference load voltage

$$v_k^* = e_k^* - \frac{1}{n}\sum_{j=1}^{n} e_j^*\,, \tag{6}$$

and u_k the average load voltage error introduced by dead-time

$$u_k = \Delta V_d\left[-sign(i_k) + \frac{1}{n}\sum_{j=1}^{n} sign(i_j)\right]. \tag{7}$$

The voltage error expressed by (7) can be seen as the sum of two square-wave signals [10]: the first with unity amplitude and period T, whereas the second with amplitude $1/n$ and period T/n, as shown in Fig. 1 (a) and (b), respectively.

The Fourier development of the load voltage error can be easily obtained as a combination based on these two signals, leading to

$$\begin{aligned} u_k = \Delta V_d \frac{4}{\pi}\Big\{ &-sin\left[\omega_o t-(k-1)\frac{2\pi}{n}\right] - \frac{1}{3}sin\left[3\left(\omega_o t-(k-1)\frac{2\pi}{n}\right)\right] \\ &-\frac{1}{5}sin\left[5\left(\omega_o t-(k-1)\frac{2\pi}{n}\right)\right] - \ldots + \frac{1}{n}sin\left[n\left(\omega_o t-(k-1)\frac{2\pi}{n}\right)\right] + \\ &\frac{1}{3n}sin\left[3n\left(\omega_o t-(k-1)\frac{2\pi}{n}\right)\right] + \frac{1}{5n}sin\left[5n\left(\omega_o t-(k-1)\frac{2\pi}{n}\right)\right] + \ldots \Big\} \end{aligned}. \tag{8}$$

It can be noted that all harmonic components of the second signal completely erase with corresponding harmonics of the first signal, leading to the following simplified expression

$$u_k = -\Delta V_d \frac{4}{\pi}\sum_{h=1}^{\infty}\frac{1}{h} sin\left[h\left(\omega_o t-(k-1)\frac{2\pi}{n}\right)\right], \tag{9}$$

where h is odd integer not multiple of n. Equation (9) states that the harmonic spectrum of the voltage error introduced by dead-time t_d almost coincides with the one of a square wave signal having period T and amplitude ΔV_d, just the harmonics with order h multiple of the phase number n are missing, being this a property of balanced multi-phase systems [11].

The amplitude of harmonics can be calculated by (9) as

$$U_h = \frac{4}{\pi}\frac{1}{h}\Delta V_d \quad (h \text{ is odd integer not multiple of } n). \tag{10}$$

Note that harmonics amplitude is independent of both output voltage amplitude and load power factor ($PF = cos\,\phi$), but it depends on the dead-time duration t_d only.

III. Multiple Space Vector Representation

In the following of the paper, multiple space vectors are used to represent voltage and current phase quantities:

$$x_0 = \frac{1}{n}\sum_{k=1}^{n} x_k\,, \tag{11}$$

$$\bar{x}_h = \frac{2}{n}\sum_{k=1}^{n} x_k\,\alpha^{h(k-1)}\,, \; h = 1, 3, \ldots, n-2 \tag{12}$$

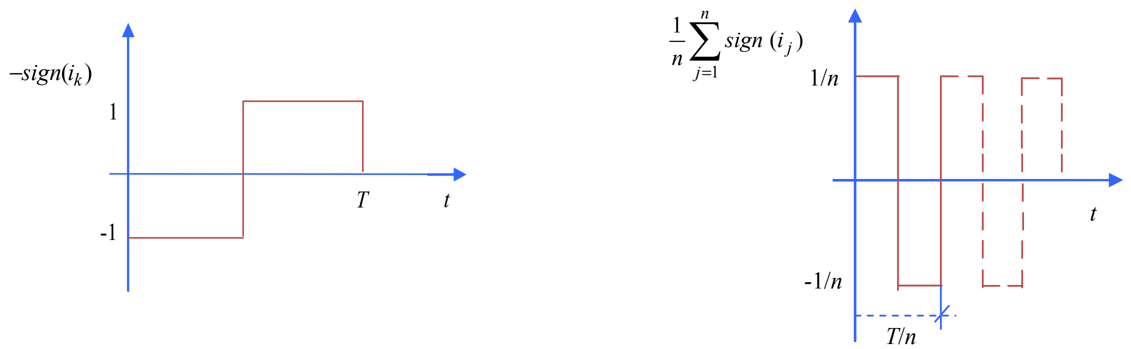
where x_0 is zero-sequence (homopolar) component, equal to zero in balanced systems, and $\bar{x}_h$ is the h-th component of multiple space vectors [11], being $\alpha = exp\,(j2\pi/n)$.

The inverse multiple space vector transformations are [11]:

$$x_k = x_0 + \sum_{h=1}^{n} \bar{x}_h \cdot \alpha^{h(k-1)}\,, \quad h = 1, 3, \ldots, n-2. \tag{13}$$

For each space vector $\bar{x}_h$, a corresponding phase quantity $x_k^{(h)}$ can be introduced, leading to

$$x_k = x_0 + \sum_{h=1}^{n} x_k^{(h)}\,, \quad x_k^{(h)} = \bar{x}_h \cdot \alpha^{h(k-1)}\,. \tag{14}$$



(a) (b)

Fig. 1. Waveforms of the two contributions to the voltage error u_k normalized with respect to ΔV_d.

IV. Numerical Verification

In order to verify the theoretical developments shown in previous sections, circuit simulations are carried out by Sim-PowerSystems of Matlab considering three-, five- and seven-phase inverters supplying sinusoidal balanced current sources as in (1), with f = 50 Hz, I_M = 20 A. The dead-time duration is t_d = 20 µs, the switching frequency is $1/T_c$ = 2 kHz, and the dc voltage supply is V_{dc} = 200 V. A continuous symmetrical carrier-based PWM technique is considered, leading to $2n+1$ steps modulation .

A couple of relevant cases are considered in relation with different load power factors: load current in phase with voltage ($\phi = 0°$, $PF = 1$) and load current in opposite phase with voltage ($\phi = 180°$, $PF = -1$). Furthermore, different values of modulation index $m = V^*/V_{dc}$ are investigated (0.1, 0.2, 0.45), being $m_{\max} = [2\cos(\pi/2n)]^{-1}$ according to [14]. The harmonic spectrum of the voltage error is shown in all cases up to 19th harmonic component.

A. Three-phase inverters

The case of three-phase inverters is almost well known in literature and it is just briefly treated here.

The load voltage error introduced by dead-time in three-phase inverters is considered by setting $n = 3$ in (7)

$$u_k = \Delta V_d\{-sign(i_k)+[sign(i_1)+sign(i_2)+sign(i_3)]/3\}. \quad (15)$$

The corresponding time diagram $u_k(t)$ is depicted in Fig. 2 for the first phase (k=1). The multiple space vector representation (12) for the load voltage error of the three-phase inverter leads to the following single vector

$$\bar{u}_1 = \frac{2}{3}\left[u_1 + u_2\alpha + u_3\alpha^2\right]. \quad (16)$$

The locus of space vector u_1 is represented in Fig. 3, with real (α) and imaginary (β) components depicted on x- and y-axis, respectively.

The harmonics amplitude of load voltage error can be expressed by (10), leading to the harmonic spectrum depicted in Fig. 4 (black column at left side). In the same figure are shown the corresponding values obtained by circuit simulation with different modulation indexes (m = 0.1, 0.2, 0.45, columns from left to right side). Note that the amplitude of fundamental U_1 is calculated according to [10]. In Fig. 4 (a) is considered the case of load power factor $PF = 1$, whereas in Fig. 4 (b) is considered the case of load power factor $PF = -1$. As expected, only odd-order harmonics appear in simulation results, and harmonics with order multiple of three are missing (3th, 9th, and 15th) according to (8) by setting $n = 3$. Furthermore, amplitudes of harmonic components are practically the same in all cases, resulting to be independent of both modulation index and load power factor.

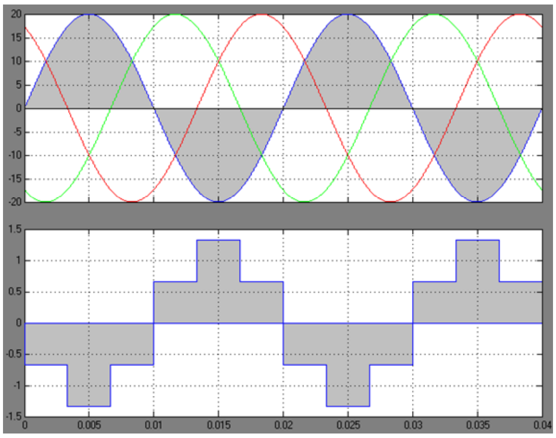


Fig. 2. Currents i_k (top) and load voltage error u_1 (bottom, normalized with respect to ΔV_d) for three-phase inverters

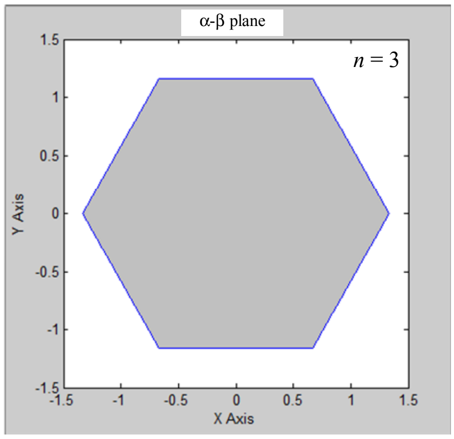
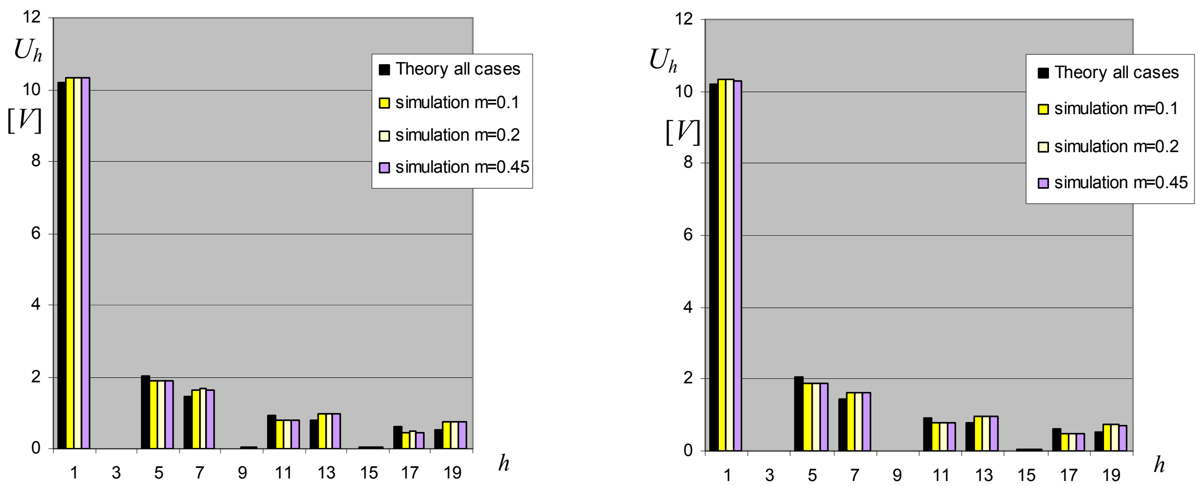


Fig. 3. Locus of space vector of load voltage error on first plane, $\bar{u}_1$, (normalized to ΔV_d) introduced by dead-time for three-phase inverters.



(a) $PF = 1$

(b) $PF = -1$

Fig. 4. Harmonic spectrum of load voltage error obtained by theory (calculated) and by circuit simulation for three-phase inverter with different modulation indexes and load power factors.

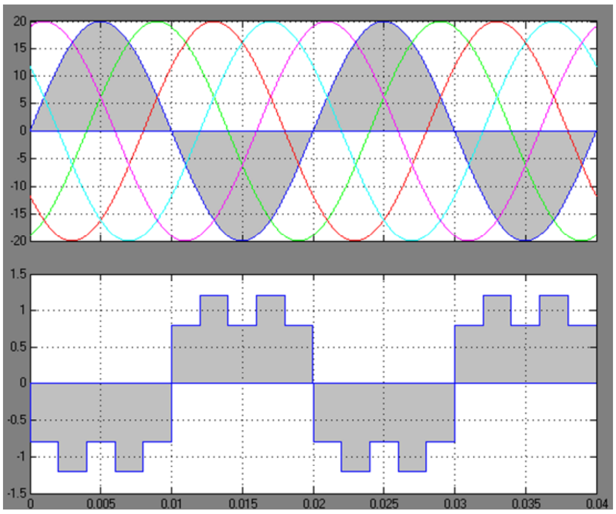


Fig. 5. Currents i_k (top) and load voltage error u_1 (bottom, normalized with respect to ΔV_d) for five-phase inverters.

B. Five-phase inverters

The load voltage error introduced by dead-time in five-phase inverters is evaluated by setting $n = 5$ in (7)

$$u_k = \Delta V_d \{-sign(i_k) + [sign(i_1) + sign(i_2) + sign(i_3) + sign(i_4) + sin(i_5)]/5\} . \quad (17)$$

The time diagram $u_k(t)$ is depicted in Fig. 5 for the first phase (k=1), considering five-phase sinusoidal balanced load currents, $i_k = I_M \, sin[\omega_o t - (k-1)2\pi/5]$.

The harmonics amplitude of load voltage error can be expressed by (10), leading to the harmonic spectrum depicted in Fig. 6 (black column at left side). In the same figure are shown the corresponding values obtained by circuit simulation with different modulation indexes (m = 0.1, 0.2, 0.45, columns from left to right side). Note that the amplitude of fundamental U_1 is calculated according to [10]. In Fig. 6 (a) is considered the case of load power factor $PF = 1$, whereas in Fig. 6 (b) is considered the case of load power factor $PF = -1$.

TABLE I
HARMONIC MAPPING FOR THE FIVE-PHASE SYSTEM $r = 0, 1, 2, \ldots$

Plane	Five-phase system
first (α_1-β_1)	$10r \pm 1$ (1, 9, 11, 19, 21…)
third (α_3-β_3)	$10r \pm 3$ (3, 7, 13, 17, 23…)

As expected, only odd-order harmonics appear in simulation results, and harmonics with order multiple of five are missing (5th and 15th), according to (8) by setting n=5. Furthermore, amplitudes of harmonic components are practically the same in all cases, resulting to be independent of both modulation index and power factor.

The multiple space vector representation (12) for the load voltage error of the five-phase inverter leads to the following two vectors:

$$\bar{u}_1 = \frac{2}{5}\left[u_1 + u_2\alpha + u_3\alpha^2 + u_4\alpha^3 + u_5\alpha^4\right], \quad (18)$$

$$\bar{u}_3 = \frac{2}{5}\left[u_1 + u_2\alpha^3 + u_3\alpha + u_4\alpha^4 + u_5\alpha^2\right]. \quad (19)$$

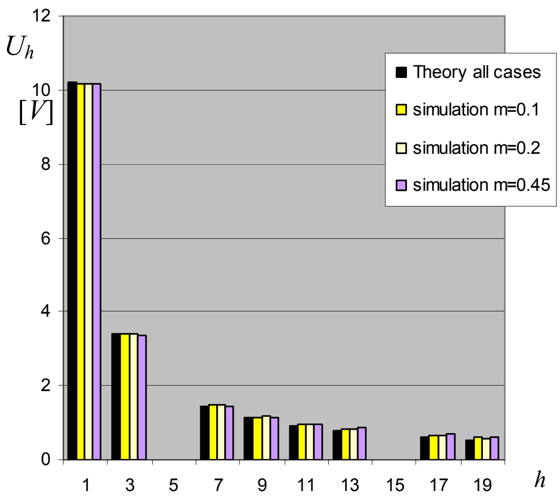
The loci of these space vectors are depicted in Figs. 7 and 8, considering planes α_1-β_1 and α_3-β_3, respectively.

With reference to the inverse multiple space vector transformation (14), the load voltage error can now be expressed as the sum of two components, one for each space vector [12] as

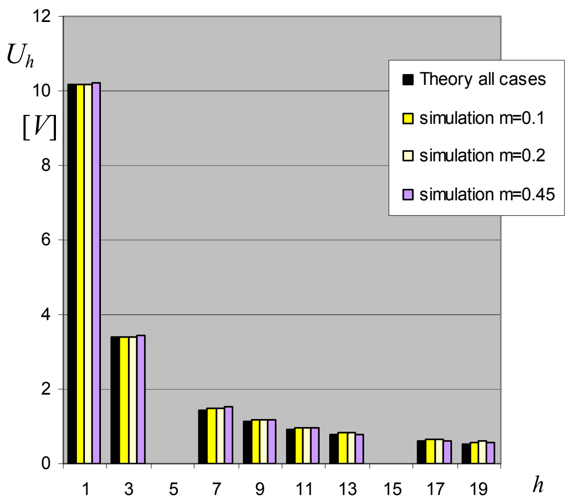
$$u_k = u_k^{(1)} + u_k^{(3)}, \qquad k = 1, 2, \ldots, 5 \quad (20)$$

$$x_k^{(1)} = \bar{x}_1 \cdot \alpha^{(k-1)}, \; x_k^{(3)} = \bar{x}_3 \cdot \alpha^{3(k-1)} . \quad (21)$$

In Figs. 9 and 10 are depicted these two components for the first load phase, $u_1^{(1)}$ and $u_1^{(3)}$, respectively. Note that harmonics are mapped on the two components (21) according to Table I. This is a property of multi-phase systems [7], [14] and it can be applied to the analysis of multi-phase motors to determine the effects of dead-times on currents.



(a) $PF = 1$



(b) $PF = -1$

Fig. 6. Harmonic spectrum of load voltage error obtained by theory (calculated) and by circuit simulation for five-phase inverter with different modulation indexes and load power factors.

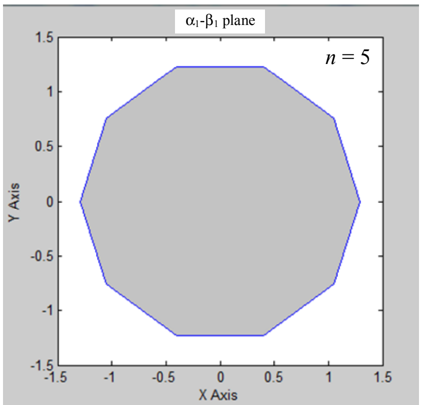


Fig. 7. Locus of space vector of load voltage error on first plane, $\bar{u}_1$ (normalized to ΔV_d), introduced by dead-time for five-phase inverters.

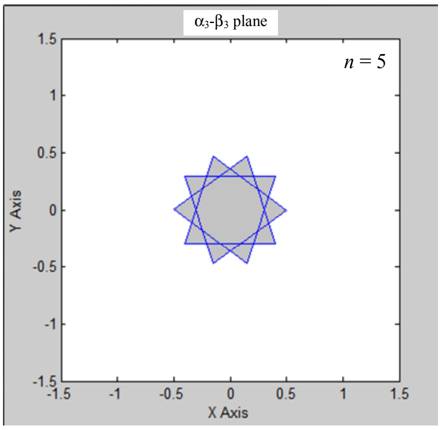


Fig. 8. Locus of space vector of load voltage error on third plane, $\bar{u}_3$ (normalized to ΔV_d), introduced by dead-time for five-phase inverters.

C. Seven-phase inverters

Also the load voltage error introduced by dead-time in seven-phase inverters is evaluated by setting n = 7 in (7)

$$u_k = \Delta V_d \{-sign(i_k) + [sign(i_1) + sign(i_2) + sign(i_3) + sign(i_4) + sin(i_5) + sign(i_6) + sign(i_7)]/7\} . \quad (22)$$

The time diagram $u_k(t)$ is depicted in Fig. 11 for the first phase (k=1), considering seven-phase sinusoidal balanced load currents, $i_k = I_M \, sin[\omega_o t - (k-1)2\pi/7]$.

The harmonics amplitude of load voltage error can be expressed by (10), leading to the harmonic spectrum depicted in Fig. 12 (black column at left side). In the same figure are shown the corresponding values obtained by circuit simulation with different modulation indexes (m = 0.1, 0.2, 0.45, columns from left to right side). Note that the amplitude of fundamental U_1 is calculated according to [10]. In Fig. 12 (a) is considered the case of load power factor PF = 1, whereas in Fig. 12 (b) is considered the case of load power factor PF = –1.

As expected, only odd-order harmonics appear in simulation results, and harmonics with order multiple of seven are missing (here just 7th), according to (8) by setting n=7. Furthermore, amplitudes of harmonic components are practically the same in all cases, resulting to be independent of both modulation index and power factor.

The multiple space vector representation (12) for the load voltage error of the seven-phase inverter leads to the following three vectors

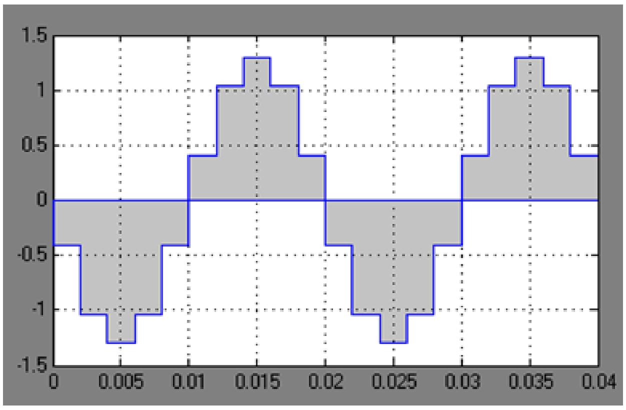


Fig. 9. Load voltage error component on first phase $u_1^{(1)}$ (normalized to ΔV_d) associated to space vector on first plane (α_1-β_1) , n = 5.

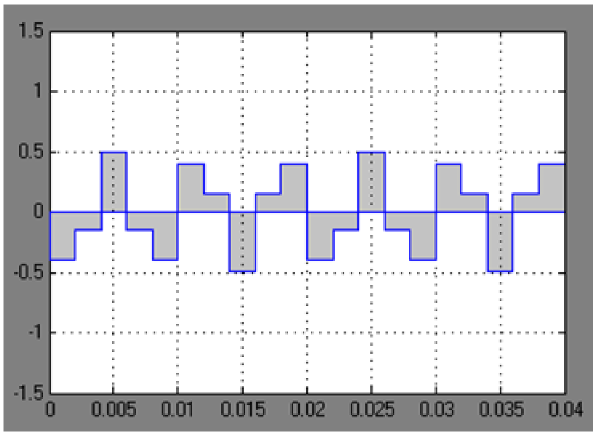


Fig. 10. Load voltage error component on first phase $u_3^{(1)}$ (normalized to ΔV_d) associated to space vector on third plane (α_3-β_3), n = 5.

$$\bar{u}_1 = \frac{2}{7}\left[u_1 + u_2\alpha + u_3\alpha^2 + u_4\alpha^3 + u_5\alpha^4 + u_6\alpha^5 + u_7\alpha^6\right], \quad (23)$$

$$\bar{u}_3 = \frac{2}{7}\left[u_1 + u_2\alpha^3 + u_3\alpha^6 + u_4\alpha^2 + u_5\alpha^5 + u_6\alpha + u_7\alpha^4\right], \quad (24)$$

$$\bar{u}_5 = \frac{2}{7}\left[u_1 + u_2\alpha^5 + u_3\alpha^3 + u_4\alpha + u_5\alpha^6 + u_6\alpha^4 + u_7\alpha^2\right]. \quad (25)$$

The loci of these space vectors are depicted in Figs. 13, 14, and 15, considering planes α_1-β_1, α_3-β_3, and α_5-β_5 respectively.

With reference to the inverse multiple space vector transformation (14), the load voltage error can now be expressed as the sum of three components, one for each space vector [13], as

$$u_k = u_k^{(1)} + u_k^{(3)} + u_k^{(5)}, \qquad k = 1, 2, \dots, 7 \quad (26)$$

$$x_k^{(1)} = \bar{x}_1 \cdot \alpha^{(k-1)}, \; x_k^{(3)} = \bar{x}_3 \cdot \alpha^{3(k-1)}, \; x_k^{(5)} = \bar{x}_5 \cdot \alpha^{5(k-1)}. \quad (27)$$

In Figs. 16, 17, and 18 are depicted these three components for the first load phase, $u_1^{(1)}$, $u_1^{(3)}$, and $u_1^{(5)}$, respectively. Note that harmonics are mapped on the three components (27) according to Table II. Also in this case, this property of multi-phase systems [7], [14] can be applied to the analysis of multi-phase motor to determine the effects of dead-times on currents.

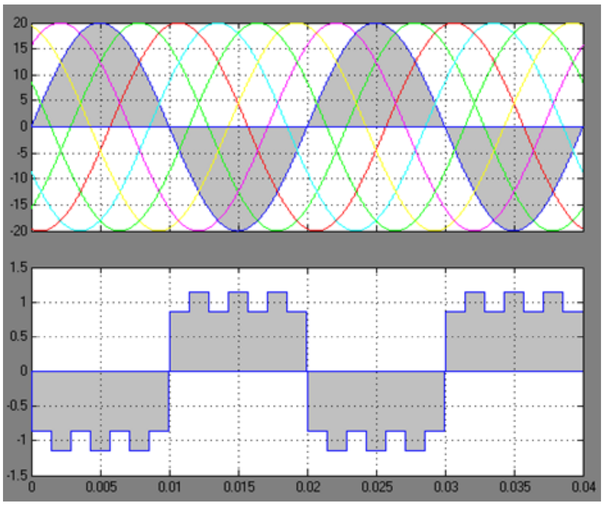


Fig. 11. Currents i_k (top) and load voltage error u_1 (bottom, normalized with respect to ΔV_d) for seven-phase inverters.

V. Conclusion

The dead-time introduced in voltage source inverters to prevent the shoot-through of the dc link has effects on inverter operation. It causes a decrease in the fundamental component of load voltages and introduces voltage distortions, despite PWM methods theoretically produce sinusoidal outputs, free from any lower order harmonics. This is important in all cases where the output voltage is set in open-loop or it is evaluated on the basis of dc voltage and switching pattern.

In this paper the analysis of dead-time effects on inverter output variables was generalized to multi-phase inverters, first by analytical developments, then by circuit simulations for three- five- and seven-phase inverters.

The analysis has been further developed by introducing the multiple space vectors representation of load voltage error. In this way, the harmonic voltage distortion was emphasized on each α-β plane of multiple space vectors, and well defined harmonic mapping has been pointed out.

Numerical simulations confirm all the analytical developments with a good approximation.

TABLE II
HARMONIC MAPPING FOR THE SEVEN-PHASE SYSTEM r = 0, 1, 2, ...

Plane	Seven-phase system
first (α_1-β_1)	$14r \pm 1$ (1, 13, 15, 27, 29…)
third (α_3-β_3)	$14r \pm 3$ (3, 11, 17, 25, 31…)
fifth (α_5-β_5)	$14r \pm 5$ (5, 9, 19, 23, 33…)

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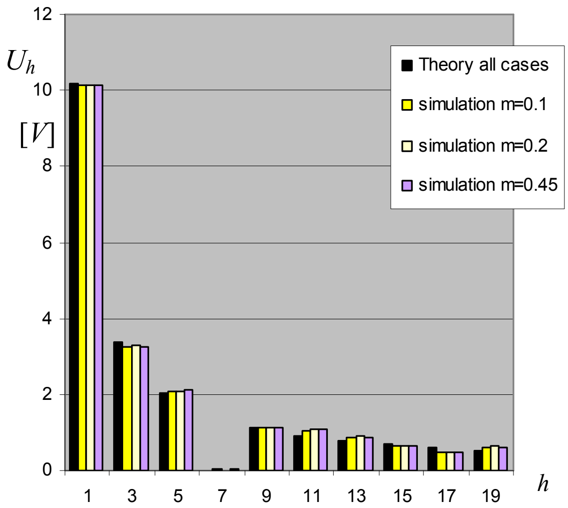
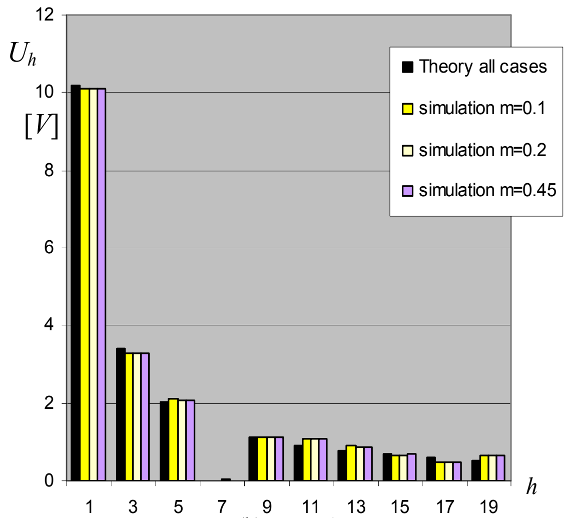


(a) $PF = 1$



(b) $PF = -1$

Fig. 12. Harmonic spectrum of load voltage error obtained by theory (calculated) and by circuit simulation for seven-phase inverter with different modulation indexes and load power factors.

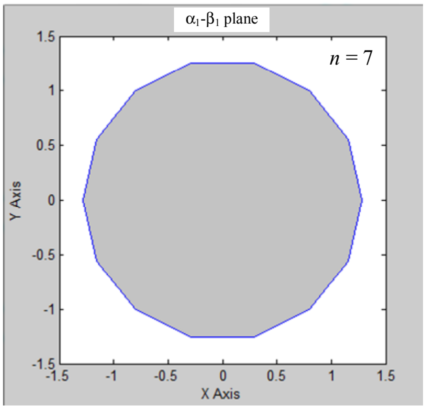


Fig. 13. Locus of space vector of load voltage error on first plane, $\bar{u}_1$ (normalized to ΔV_d), introduced by dead-time for seven-phase inverters.

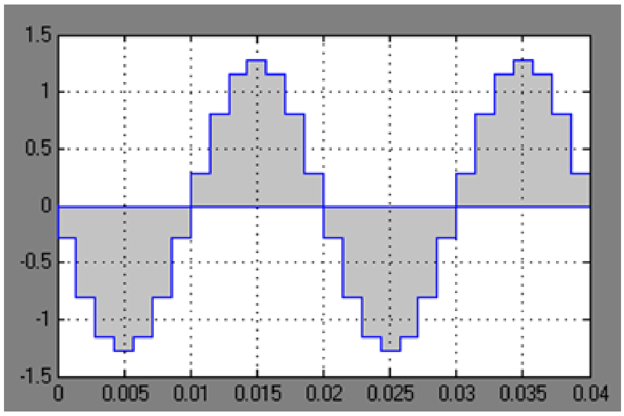


Fig. 16. Load voltage error component on first phase $u_1^{(1)}$ (normalized to ΔV_d) associated to space vector on first plane (α_1-β_1), $n = 7$.

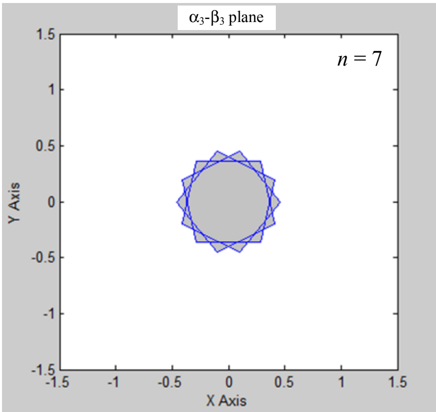


Fig. 14. Locus of space vector of load voltage error on third plane, $\bar{u}_3$ (normalized to ΔV_d), introduced by dead-time for seven-phase inverters.

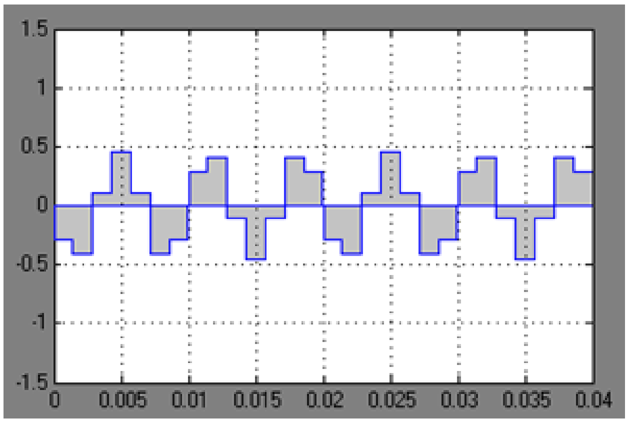


Fig. 17. Load voltage error component on first phase $u_1^{(3)}$ (normalized to ΔV_d) associated to space vector on third plane (α_3-β_3), $n = 7$.

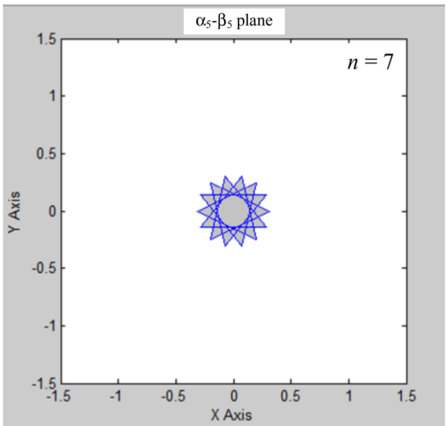


Fig. 15. Locus of space vector of load voltage error on fifth plane, $\bar{u}_5$ (normalized to ΔV_d), introduced by dead-time for seven-phase inverters.

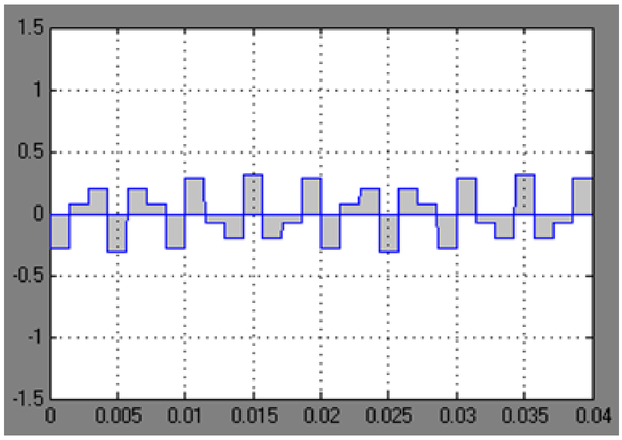


Fig. 18. Load voltage error component on first phase $u_1^{(5)}$ (normalized to ΔV_d) associated to space vector on fifth plane (α_5-β_5), $n = 7$.

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