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DC Current Harmonics Reduction in Multi-Inverter Topology

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***Abstract*— This letter presents a Space Vector Pulse Width Modulation (SVPWM) strategy for reducing the DC-link current harmonics in a multi– Voltage Source Inverter (VSI) topology with common DC-link bus. The DC current harmonic reduction is achieved by phase-shifting the PWM pattern of individual VSIs, with the inverters sharing the system total power. Simulation and experimental results are shown to validate the proposal.**

***Index Terms*—Pulse width modulated inverters, Space vector pulse width modulation, Harmonic analysis.**

I. Introduction

PARALLEL-CONNECTED inverters are typically used in systems where the total power needs to be shared among units to increase the modularity and the reliability. The parallel connection can be made in the inverter's DC-side, AC-side, or both [1]. Most of previously reported works on multiple inverter systems consider the parallel connection of both, the DC and AC sides of the inverters. The typical modulation technique used is interleaving, where the PWM carriers of the different inverters are phase-shifted. Ripple current reduction is obtained in the total AC current when adding all inverter currents [1]-[4]. However, almost no interest has been given to the current ripple reduction of total DC current that could be relevant if the inverters AC sides are not paralleled and are supplying independent loads. In [5][6] it has been shown that in systems with two three-phase inverters connected in parallel to the same DC source and supplying equal loads, it is possible to eliminate high-frequency harmonics of the total DC current if different switching sequences are used for the individual inverters. These switching sequences are called "asynchronous", and the main characteristic is that the zero vectors are applied at different instant in both inverters.

An approach considering three inverters connected to the same DC-link and again supplying equal loads has been presented in [7]. In this case, one VSI operates with the conventional SVPWM switching sequence and the other two with the "asynchronous" sequences. The asynchronous sequences allow the cancellation of the odd harmonics around the switching frequency and the overall harmonic content is lower than the case with two inverters in [7].

In this letter, the possibility of eliminating DC current harmonics, in a system with multiple inverters connected in parallel to a common DC source (Fig. 1) and supplying equal loads, is analyzed. A mathematical basis is provided and simulation and experimental results showing the effectiveness of the proposal are presented.

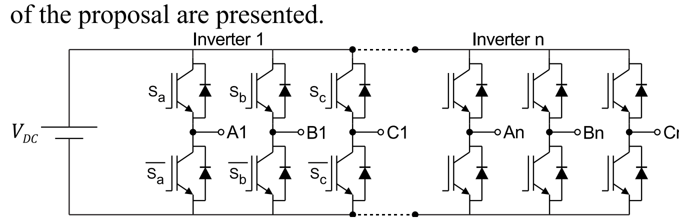

Fig. 1. Parallel-connected inverters with common DC-link.

II. DC current Fourier's Series

The DC-side current of a three-phase inverter can be expressed as function of the output currents (i_a, i_b and i_c) and the switching functions (S_a, S_b and S_c) per VSI leg.

$$i_{DC}(t) = S_a(t)i_a(t) + S_b(t)i_b(t) + S_c(t)i_c(t) \quad (1)$$

The switching functions are pulses applied during a certain period of time. In general, three pulses can be defined, a long pulse (P_1), a medium pulse (P_2) and a short pulse (P_3), as depicted in Fig. 2 for conventional SVPWM.

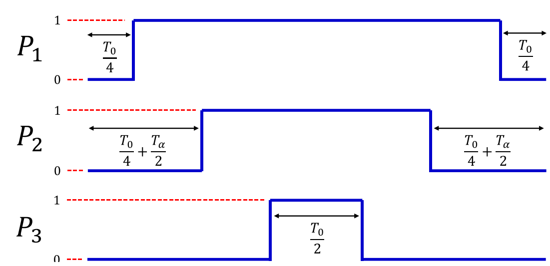

Fig. 2. Switching pulses in one period for conventional SVPWM.

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The switching functions expressed in terms of these pulses are presented in Table I. Therefore, the DC current can be determined as a function of these pulses and the phase output currents, as it is shown in Table II. Therefore, to analyze the DC current only these three pulses are required.

TABLE I
SWITCHING FUNCTIONS IN TERMS OF THE DEFINED PULSES

Sector	S_a	S_b	S_c	Sector	S_a	S_b	S_c
I	P_1	P_2	P_3	IV	P_3	P_2	P_1
II	P_2	P_1	P_3	V	P_2	P_3	P_1
III	P_3	P_1	P_2	VI	P_1	P_3	P_2

TABLE II
DC CURRENT AS FUNCTION OF THE DEFINED PULSES

Sector	Active vectors		Output current i_α/i_β	DC current $i_{DC}=f(S_{abc},i_{abc})$	DC current $i_{DC}=f(P_{123},i_{\alpha\beta})$
I	α	100	i_a	$(S_a-S_b)i_a$	$(P_1-P_2)i_\alpha$
	β	110	$-i_c$	$+(S_b-S_c)(-i_c)$	$+(P_2-P_3)i_\beta$
II	α	110	$-i_c$	$(S_b-S_a)i_b$	$(P_1-P_2)i_\beta$
	β	010	i_b	$+(S_a-S_c)(-i_c)$	$+(P_2-P_3)i_\alpha$
III	α	010	i_b	$(S_b-S_c)i_b$	$(P_1-P_2)i_\alpha$
	β	011	$-i_a$	$+(S_c-S_a)(-i_a)$	$+(P_2-P_3)i_\beta$
IV	α	011	$-i_a$	$(S_c-S_b)i_c$	$(P_1-P_2)i_\beta$
	β	001	i_c	$+(S_b-S_a)(-i_a)$	$+(P_2-P_3)i_\alpha$
V	α	001	i_c	$(S_c-S_a)i_c$	$(P_1-P_2)i_\alpha$
	β	101	$-i_b$	$+(S_a-S_b)(-i_b)$	$+(P_2-P_3)i_\beta$
VI	α	101	$-i_b$	$(S_a-S_c)i_a$	$(P_1-P_2)i_\beta$
	β	100	i_a	$+(S_c-S_b)(-i_b)$	$+(P_2-P_3)i_\alpha$

Each pulse is symmetrical respect to the middle of the period (Fig. 3) and has a Fourier series given by (2)-(5), with $x \in \{1,2,3\}$.

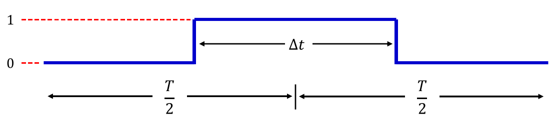


Fig. 3. Symmetric pulse.

$$P_x(t) = a_{0x}(t) + \sum_{n=1}^{\infty} a_{nx}(n,t)\cos(2\pi n f_s t) + \sum_{n=1}^{\infty} b_{nx}(n,t)\sin(2\pi n f_s t) \tag{2}$$

$$a_{nx}(n,t) = 2f_s \int_0^{1/f_s} P_x(t)\cos(2\pi n f_s t)\,dt \tag{3}$$

$$b_{nx}(n,t) = 2f_s \int_0^{1/f_s} P_x(t)\sin(2\pi n f_s t)\,dt \tag{4}$$

$$a_{0x}(t) = f_s \int_0^{1/f_s} P_x(t)dt \tag{5}$$

For the pulse in Fig. 3, the b_n Fourier's coefficients are null, whereas the other coefficients are given by:

$$a_n = (-1)^n\left(\frac{2}{n\pi}\right)\sin\left(n\pi\frac{\Delta t}{T}\right) \quad ; \quad a_0 = \frac{\Delta t}{T} \tag{6}$$

Finally, the Fourier series for the DC-link current will be:

$$i_{DC}(t) = A_0(t) + \sum_{n=1}^{\infty} A_n(n,t)\cos(2\pi n f_s t) \tag{7}$$

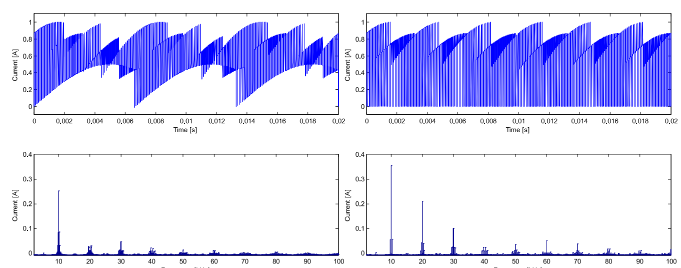
The expressions for A_0 and A_n are presented in (8)-(9), where the subindex α/β and β/α refers to the odd/even and even/odd sector, respectively:

$$A_0 = d_\alpha i_\alpha + d_\beta i_\beta \tag{8}$$

$$A_n = \left(\frac{4}{n\pi}\right)\left\{\cos\left[n\pi\frac{(d_0+d_{\alpha/\beta})}{2}\right]\sin\left(n\pi\frac{d_{\alpha/\beta}}{2}\right)i_{\alpha/\beta} + (-1)^n\cos\left[n\pi\frac{(d_0+d_{\beta/\alpha})}{2}\right]\sin\left(n\pi\frac{d_{\beta/\alpha}}{2}\right)i_{\alpha/\beta}\right\} \tag{9}$$

III. MULTIPLE-INVERTER SYSTEM

For a system with two inverters, the asynchronous sequences 0-α-β-β-α-0 and β-α-0-0-α-β are used [5], where only the zero-vector [000] is applied. This represents a difference respect to the conventional SVPWM sequence 0-α-β-0-0-β-α-0, where both zero-vectors, [000] and [111], are used. Fig. 4 shows the DC-link current and its harmonic frequency spectrum for a two-inverter system considering asynchronous and conventional sequence. An important reduction in the harmonic content is appreciated when the asynchronous sequences are used.



(a) (b)

Fig. 4. DC-link current (top) and its harmonic spectrum (bottom) for a) asynchronous sequences and b) conventional sequence.

On the other hand, as can be noted in Fig. 5, the two asynchronous sequences are not really different, but the same phase-shifted 180°. This characteristic can be generalized considering the conventional sequence as shown in Fig. 6.

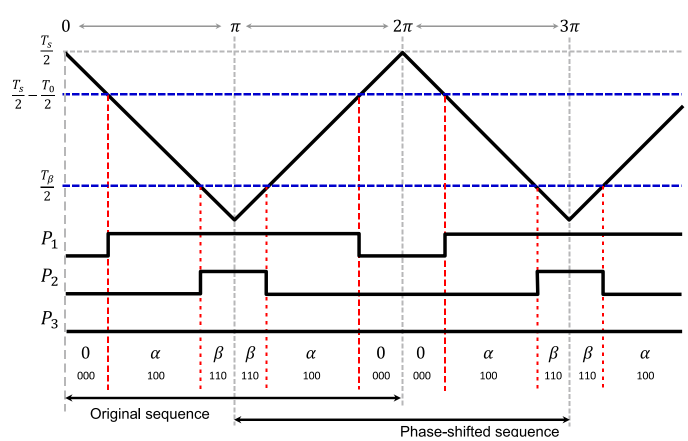


Fig. 5. Asynchronous switching sequence diagram.

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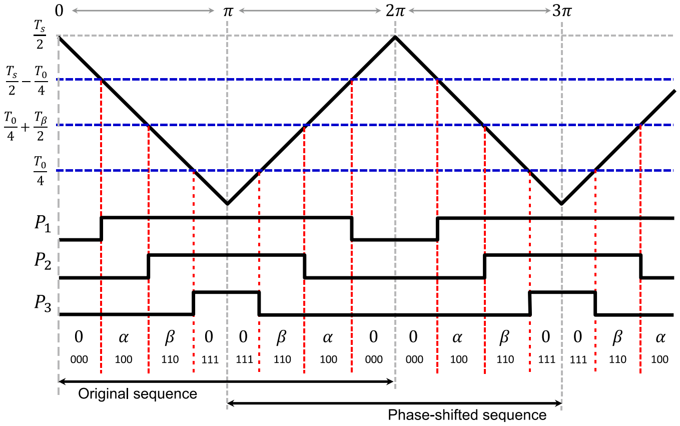


Fig. 6. Conventional switching sequence diagram.

To determine how to reduce/eliminate DC current harmonics in a system with N inverters, first, it is necessary to define the Fourier's series of a generic pulse $P(t)$ that is phase-shifted a δ angle with respect to the mid-point (180°), as shown in Fig. 7. The coefficients of the series are:

$$a_n = (-1)^n \left(\frac{2}{n\pi}\right) \cos(n\delta) \sin\left(n\pi \frac{\Delta t}{T}\right) \quad , \quad a_0 = \frac{\Delta t}{T} \tag{10}$$

$$b_n = (-1)^n \left(\frac{2}{n\pi}\right) \sin(n\delta) \sin\left(n\pi \frac{\Delta t}{T}\right) \tag{11}$$

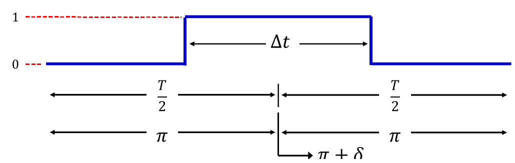


Fig. 7. Generic pulse.

Then, the Fourier series of the pulse is given by:

$$P(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos(2\pi n f_s t) + \sum_{n=1}^{\infty} b_n \sin(2\pi n f_s t) \tag{12}$$

$$P(t) = a_0 + \sum_{n=1}^{\infty} c_n \cos(2\pi n f_s t - n\delta) \tag{13}$$

where

$$c_n = (-1)^n \left(\frac{2}{n\pi}\right) \sin\left(n\pi \frac{\Delta t}{T}\right) \tag{14}$$

It can be noted that c_n equals the coefficient a_n for a symmetric pulse (see (6)). Considering (7) and the phase-shift angle δ, the Fourier series for the DC current is:

$$i_{DC}(t) = A_0(t) + \sum_{n=1}^{\infty} A_n(n,t) \cos(2\pi n f_s t - n\delta) \tag{15}$$

From the previous analysis, it is observed that phase-shifting the switching sequences impacts only the phase of the DC current harmonics (not the magnitude). Assuming a system with N inverters, where every inverter applies the conventional switching sequence but with a different phase-shift, the DC currents of the individual inverters will be given by (16), whereas the total DC current is calculated with (17).

$$i_{DC(k)} = A_{0(k)} + \sum_{n=1}^{\infty} A_{n(k)} \cos(2\pi n f_s t - n\delta_k) \tag{16}$$

$$i_{DC(total)} = \sum_{n=1}^{N} \left\{ A_{0(k)} + \sum_{n=1}^{\infty} A_{n(k)} \cos(2\pi n f_s t - n\delta_k) \right\} \tag{17}$$

Considering that all the inverters are supplying equal loads:

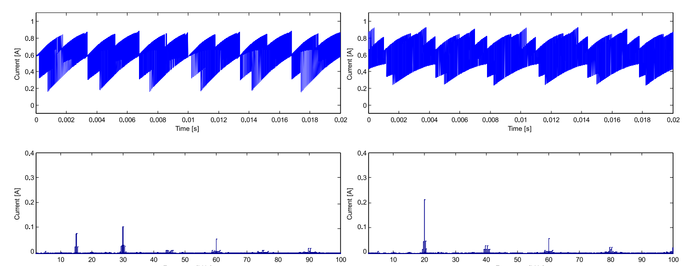
$$i_{DC(total)} = N A_0 + \sum_{n=1}^{\infty} \left\{ A_n \sum_{n=1}^{N} \cos(2\pi n f_s t - n\delta_k) \right\} \tag{18}$$

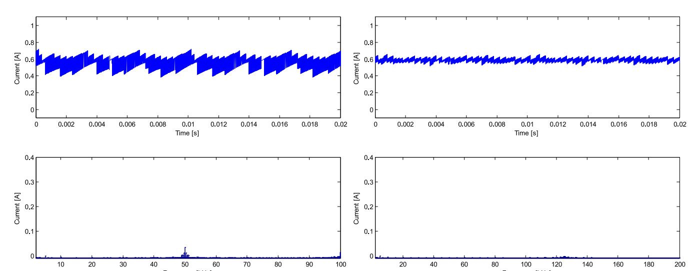
From (18) it is obtained that to eliminate harmonics it is required that the summation $\sum_{n=1}^{N} \cos(2\pi n f_s t - n\delta_k) = 0$. This can be achieved defining the phase-shift angle of the switching sequences as in (19), then the previous summation will be non-zero only when n is a multiple of N.

$$\delta_k = (k-1)\left(\frac{2\pi}{N}\right) \tag{19}$$

IV. Simulation Results

The total DC current and its harmonic frequency spectrum for different number of parallel-connected inverters are shown in Figs. 8-9. It is evident that as higher the number of inverters used, lower is the harmonic content of the DC current.


(a) (b)
Fig. 8. DC-link current for a) $N = 3$ and b) $N = 4$.


(a) (b)
Fig. 9. DC-link current for a) $N = 10$ and b) $N = 25$.

V. Experimental Results

An experimental rig with up to four three-phase inverters, based on IPA083N10N5XKSA1, has been built to validate the work. A Texas Instrument F28379 is used as control board. The GWINSTEK PSU 100-15 provides the DC volts for all

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inverters. Inductive-resistive loads are used, and waveforms data tables obtained with a RIGOL DS4014E oscilloscope are plotted in MATLAB software. The total DC current and its harmonic frequency spectrum for three and four parallel-connected inverter sets are shown in Figs. 10-11. The reduction of the DC current harmonic components is evident when the proposed phase-shifting of the PWM carriers is applied. As in the simulations, it can be noticed that as higher the number of parallel inverters, lower is the DC current ripple.

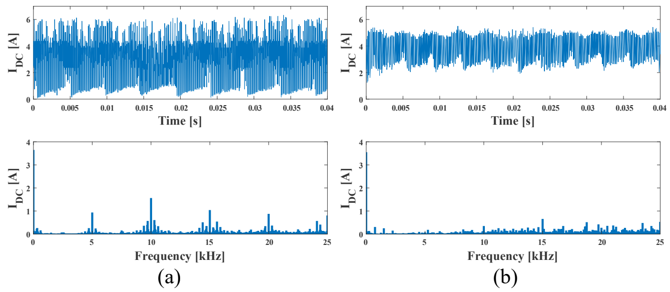

Fig. 10. DC-link current (top) and its frequency spectrum (bottom) with $N = 3$. a) Conventional switching sequence. b) Switching sequence with phase-shifted carriers.

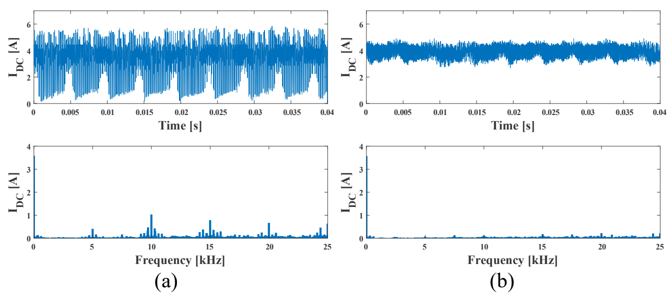

Fig. 11. DC-link current (top) and its frequency spectrum (bottom) with $N = 4$. a) Conventional switching sequence. b) Switching sequence with phase-shifted carriers.

VI. Conclusion

This paper has presented a mathematical analysis of the DC current in systems with multiple parallel-connected inverters. It has been shown that it is possible to reduce the harmonic content of this current by phase-shifting the switching sequence of the individual inverters. Simulation and experimental results validate the study.

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