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A generalized scalar pulse-width modulation for nine-switch inverters: An approach for non-sinusoidal modulating waveforms

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ABSTRACT

The nine-switch inverter has been proposed recently and, since then, a large number of applications have been investigated, specially as a substitute to the dual-bridge (back-to-back) converter. The main advantage of the nine-switch inverter is its lesser number of switches (nine instead of twelve of the back-to-back converter), which has as a tradeoff some restrictions in the total attainable amplitude at its outputs, dependent on the phase shift between its two terminal sets. Thus, when migrating modulation techniques from the conventional three-phase inverter to the nine-switch inverter, more concerns have to be addressed. This paper deals with pulse-width modulation strategies that can be easily implemented by using the concept of generalized scalar modulation in this type of inverter. In fact, such concept leads to a systematic and straight approach to the generation of any continuous or discontinuous pulse-width modulation strategy. Aiming the reduction of switching losses, the generalized modulation is applied with a specific distribution parameter that reduces the number of switchings of the three-phase nine-switch inverter. Experimental results confirm the validity of the proposed method.

1. Introduction

In the last decades, the increasing reliability of power semiconductor devices allowed the development of the field of power electronics in a wide variety of applications for renewable energy sources and power quality solutions [1]. This growth has boosted the development of pulse-width modulation (PWM) techniques providing a wide linear modulation range to the converters, a reduced computational burden in its implementation, fewer losses and a lower total harmonic distortion (THD) of the switching waveforms.

The modulation techniques for three-phase inverters can be classified in three types: indirect, such as space-vector modulation (SVM) [2] and scalar modulation; direct, such as selective harmonic elimination PWM [3]; and based on switching tables, where the switches' states are defined directly from control strategies, such as sliding mode control [4] and direct torque control [5].

Among the indirect modulation techniques, scalar modulation and SVM techniques have been largely used to command six-switch two-level voltage source inverters (VSI) [3,6] or multilevel inverters [7]. As comparison, in the SVM, the duty cycles of the switches in one inverter leg depend on the variables of other output phases, while, in scalar modulation, the duty cycles of the switches in one inverter leg do not depend on the other output phases. Moreover, the conventional SVM is based on the reference space vector, composed of a volt-second average of two active vectors and the zero vectors, while, in scalar modulation, the inverter switching states are identified by comparing a carrier signal (usually a triangle waveform) with a modulating signal. In particular, modified modulation techniques, that use non-sinusoidal modulating signals generated by adding zero axis components (homopolar components) to the three sinusoidal reference waveforms, could be applied in order to enhance a particular characteristic of the inverter, such as wider linear modulation range, efficiency or THD. Previous works [2] have shown that SVM produces switching sequences identical to those obtained with the modified scalar modulation when the appropriate zero axis components is used. Since the scalar approach uses simple equations only with scalar variables to determine the switches duty cycles, its implementation is more straightforward than the SVM, that uses lookup tables and trigonometric equations, specially if the modulation is applied to nonconventional converter topologies.

In the last decades, several authors proposed to generalize the PWM techniques of various three-phase converter topologies, such as the conventional six-switch two-level VSI [8], the multilevel inverter [9] and the matrix converter [10]. Based on a detailed

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analysis of these past efforts, it is observed that, unfortunately, the process of generalization is not straightforward and the derived PWM techniques of each topology bear little resemblance among them. On the other hand, most of the generalizations used the scalar approach, that is easier to understand and implement, instead of the two or three dimension vectorial approach.

One possible use of generalized scalar PWM is in the reduction of switching losses in high-efficiency power converters [10]. High switching losses are responsible for excessive thermal stress, reduction of the lifetime of semiconductor devices and additional cost associated with the heat sink and packaging. This issue becomes specially important in applications that require high switching frequencies such as power filters and variable frequency drives for high-speed motors. These same issues are equally applicable to the nine-switch inverter, which is composed of two three-phase inverter units, named top and bottom units, that share not only the dc-link voltage but also three switches, i.e. the three bottom switches of the top unit and the three upper switches of the bottom unit are the same [11]. The large number of applications already explored for this topology in a short amount of time only proves its feasibility as a possible substitute to the back-to-back converter, formed from two six-switch two-level VSIs sharing the same dc-link [12]. The main disadvantages of the nine-switch inverter when compared with the back-to-back converter are: larger voltage stress in the switches; more complex modulation techniques, switching patterns and dead-time algorithms; and uneven power loss distribution on the switches. Notwithstanding, the main advantage of the nine-switch inverter is its reduced number of switches (three fewer than the back-to-back converter), impacting on the cost, volume and weight of the system.

The first PWM technique proposed for the nine-switch inverter was based on a sinusoidal modulation, which compares a high frequency triangular carrier with three sinusoidal reference signals, in order to create gating pulses for the switches [11]. The nine-switch inverter presents some restrictions in the total attainable amplitude at its outputs, dependent on the phase shift between its two terminal sets, which means that when migrating modulation techniques from the six-switch two-level VSI (Fig. 1(a)) to the nine-switch inverter (Fig. 1(b)), more concerns have to be addressed. These concerns were investigated in [13], using the concepts of continuous and discontinuous modulations. Moreover, a SVM has been proposed to extend the linear region of both top and bottom units of the nine-switch inverter [14]. The method increases the sum of modulation indexes up to 15% in contrast with the sinusoidal modulation. In order to reduce the number of semiconductor switchings, the authors presented a specific SVM switching pattern [14]. However, this conventional SVM can be used only in the different frequency (DF) operation mode. Recently, Dehghan et al. proposed a new SVM for the nine-switch inverter that supports both the common frequency (CF) and DF operation modes [15].

Although these papers explore specific modulation techniques, there is not any work that presents a generalized PWM strategy for nine-switch inverters. In this paper, a generalized PWM strategy for nine-switch inverters is proposed, in which the switching sequence is easily implemented by using the concept of scalar PWM. The scalar approach for the generalized PWM uses the non-sinusoidal modulating signals as reference voltages of the inverter legs to determine the switches duty cycles, making the implementation much simpler than the SVM. Based on this generalization, this paper presents specific PWM techniques that reduce the number of switchings in the nine-switch inverter, aiming the reduction of its power losses. Experimental results demonstrate the validity of the generalization concept and the feasibility of the specific PWM techniques.

2. Generalized scalar PWM technique for six-switch two-level inverters

The conventional three-phase six-switch two-level VSI is shown in Fig. 1(a). Due to the dc-link and the load characteristics, there are eight possible switch combinations, categorized in the SVM as active vectors (V_1, V_2, V_3, V_4, V_5 and V_6) and zero vectors (V_0 and V_7). Different PWM techniques are produced by simply changing the total zero time interval distribution between V_0 and V_7. This is the base for the generalized scalar PWM technique for the three-phase six-switch two-level VSI, proposed by Alves et al. [8]. The methodology to determine the general solution for the duty cycles is carried out as follows.

Consider the output voltage references defined by

$$v_{j0}^{*} = v_{j0}^{s} + v_h, \quad j = \{a, b \text{ or } c\}, \tag{1}$$

where v_h is the homopolar voltage component, known also as zero axis voltage component, and v_{j0}^{s} are the sinusoidal voltage components given by

$$v_{a0}^{s} = m\frac{v_{dc}}{\sqrt{3}}\cos(\omega t); \quad v_{b0}^{s} = m\frac{v_{dc}}{\sqrt{3}}\cos\left(\omega t - \frac{2\pi}{3}\right);$$
$$v_{c0}^{s} = m\frac{v_{dc}}{\sqrt{3}}\cos\left(\omega t + \frac{2\pi}{3}\right), \tag{2}$$

where m is the modulation index, v_{dc} is the dc-link voltage and ω is the desired angular frequency of the output voltages.

The general solution for the duty cycles, based on the digital implementation of the carrier-based modulation, is given by

$$D_j^G = \frac{1}{2} + \frac{v_{j0}^{*}}{v_{dc}}, \tag{3}$$

where D_j^G is the generalized duty cycle of the switch S_j and the carrier used henceforth is defined as a triangular waveform limited between 0 and 1 with frequency equal to f_{sw}.

Substituting (1) in (3), it is possible to find that

$$D_j^G = \underbrace{\frac{1}{2} + \frac{v_{j0}^{s}}{v_{dc}}}_{D_j} + \underbrace{\frac{v_h}{v_{dc}}}_{D_h}, \tag{4}$$

where D_j is the duty cycle associated with the sinusoidal voltage component and D_h is the duty cycle associated with the homopolar voltage component.

In order to carry out the generalization, it is necessary to define a parameter (μ) responsible for distributing the total zero vector duty cycle between V_0 and V_7 as follows:

$$D_{V0} = \mu D_{null}; \quad D_{V7} = (1-\mu)D_{null}, \tag{5}$$

where $0 \le \mu \le 1$ and D_{null} is the total zero vector duty cycle.

It is possible to determine the duty cycle of the generalized scalar PWM [8] as:

$$D_j^G = D_j \underbrace{-\mu D_{\min} + (1-\mu)(1-D_{\max})}_{D_h}, \tag{6}$$

where D_{min} and D_{max} are the minimum and maximum duty cycles of the upper switches of the six-switch two-level VSI, respectively.

The algorithm for the generalization process can be described as follows: first, compute the sinusoidal PWM solution for the duty cycles D_j in (4), using the reference voltages in (2); second, determine the minimum and maximum duty cycles among them; third, choose μ; fourth, the general solution for the duty cycles is determined using (6).