Selective Harmonic Mitigation Technique for High-Power Converters

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***Abstract*—In high-power applications, the maximum switching frequency is limited due to thermal losses. This leads to highly distorted output waveforms. In such applications, it is necessary to filter the output waveforms using bulky passive filtering systems. The recently presented selective harmonic mitigation pulsewidth modulation (SHMPWM) technique produces output waveforms where the harmonic distortion is limited, fulfilling specific grid codes when the number of switching angles is high enough. The related technique has been previously presented using a switching frequency that is equal to 750 Hz. In this paper, a special implementation of the SHMPWM technique optimized for very low switching frequency is studied. Experimental results obtained applying SHMPWM to a three-level neutral-point-clamped converter using a switching frequency that is equal to 350 Hz are presented. The obtained results show that the SHMPWM technique improves the results of previous selective harmonic elimination pulsewidth modulation techniques for very low switching frequencies. This fact highlights that the SHMPWM technique is very useful in high-power applications, leading its use to an important reduction of the bulky and expensive filtering elements.**

***Index Terms*—Filters, harmonic distortion, multilevel systems.**

I. Introduction

IN HIGH-POWER applications, the harmonic content of the output waveforms has to be reduced as much as possible in order to avoid distortion in the grid and to reach the maximum energy efficiency. On such applications, the thermal losses in power semiconductors limit the maximum switching frequency to a few hundreds of hertz, and multilevel converters are the most suitable power systems to be used. Many recent works with different multilevel converter topologies have been recently presented, showing their good performance for high-power applications [1]–[3].

In addition, it is necessary to use special modulation techniques and filtering systems in order to fulfill the grid codes in the point of common coupling. Usually, grid codes establish specific limits for harmonics up to 50th and for the total harmonic distortion (THD). The passive filters used to reduce harmonic distortion into the grid are very bulky and expensive.

On the other hand, the use of an efficient modulation method is very convenient to obtain output waveforms with acceptable harmonic content. One of the most interesting modulation techniques for high-power applications is the well-known selective harmonic elimination pulsewidth modulation (SHEPWM) technique originally presented in [4]. This technique is able to obtain output signals with lower harmonic content than other techniques because it makes a limited number of low-order harmonics zero. On the other hand, the recently presented selective harmonic mitigation pulsewidth modulation (SHMPWM) technique [5] is able to relax the constraints used in the SHEPWM technique to obtain output waveforms with better harmonic performance, taking into account actual grid regulations. In [5], it was shown that, using the SHMPWM technique with a switching frequency that is equal to 750 Hz, it is possible to fulfill both the CIGRE WG 36–05 and the EN 50160 grid code requirements without using any additional filtering system. In this paper, a very low switching frequency that is equal to 350 Hz is considered using only seven switching angles, which leads to new designs of the objective function (OF) of the SHMPWM technique. This is a big difference with [5], where the high number of switching angles achieved the fulfillment of the grid code without using filtering systems. In this paper, it is shown that, using seven switching angles, some harmonics are above the maximum limits of the grid code even using the SHMPWM technique. An analytical way to define the OF has been introduced in this paper, defining factors such as the safety margin ρ and the penalty factor λ_p. Depending on the specific application of the high-power converter, two possible solutions to define the OF have been introduced. The different solutions (strategies S1 and S2) are focused on the improvement of different harmonics, as is explained in Section IV. A comparison with the SHEPWM technique in the same low switching frequency conditions is included. A three-phase three-level diode-clamped converter is used as an experimental setup to illustrate the benefits obtained by the SHMPWM technique.

Using SHEPWM, it is possible to make zero a limited number of harmonics, but the noncanceled harmonics are not considered in the algorithm and could reach very high amplitudes. This leads to the fact that it is not possible to keep them below a desired value, having a great impact on the size and the cost of the filtering system. However, the flexibility of SHMPWM can be used to apply different criteria for low- and high-order harmonics considered in the grid code. Low-order harmonics can be reduced to values that are below the limits specified in the grid code. High-order harmonics, where there is not any control using SHEPWM, can be reduced using SHMPWM. In this paper, the computing effort of the SHMPWM technique is focused on reducing as much as possible the harmonic content which has to be filtered to fulfill the grid code. The main goal

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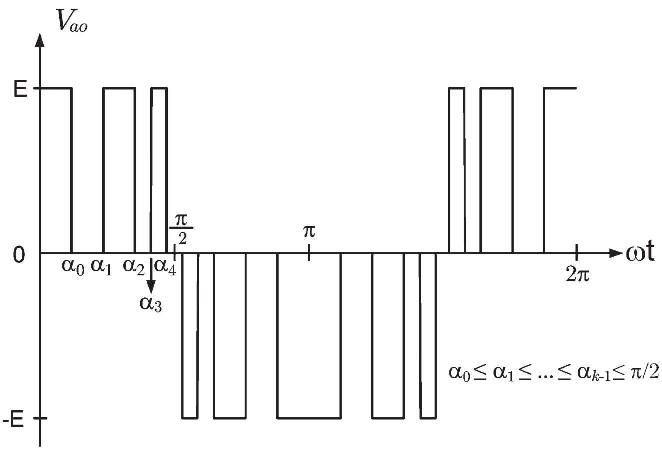

Fig. 1. Three-level preprogrammed PWM switching pattern with five switching angles (α_0, α_1, α_2, α_3, and α_4).

is to reduce the filtering requirements in order to decrease the size, weight, and cost of the filtering elements.

This paper is organized as follows; in Section II, the SHMPWM principle is briefly summarized. Section III describes the filter design problem and the most commonly used solution. In Section IV, the differences between the SHEPWM and the SHMPWM techniques are detailed, and a comparison using the obtained simulation results is carried out in Section V. The experimental results validating the improvements obtained using the SHMPWM method are presented in Section VI. Finally, the conclusions of this paper are detailed in Section VII.

II. SHMPWM Principle

The Fourier analysis of the typical three-level preprogrammed PWM switching pattern (Fig. 1) considering k switching angles α_i $(i = 0, \ldots, k-1)$ generates the following equations, where H_j is the harmonic amplitude of jth order:

$$H_j = \frac{4}{j\pi} \sum_{i=0}^{k-1} \left[(-1)^i \sin(j\alpha_i)\right], \qquad \text{where } j = 1, 2, \ldots, n. \tag{1}$$

These equations can be solved in order to obtain the harmonic amplitude $H_1, H_2, \ldots, H_n$ desired values. The classic SHEPWM technique fixes the value of H_1 [which is normally called the modulation index (M_a)] to a certain value and also eliminates $k-1$ harmonics. Usually, the most interesting harmonic orders to be eliminated are the odd nontriplen ones because, using three-phase topologies without neutral connection, the triplen harmonics do not appear in the line-to-line voltages. Therefore, the application of the SHEPWM technique leads to solving the following expressions:

$$\begin{aligned} H_1 &= \frac{4}{\pi} \sum_{i=0}^{k-1} \left[(-1)^i \sin(\alpha_i)\right] \\ 0 &= \frac{4}{j\pi} \sum_{i=0}^{k-1} \left[(-1)^i \sin(j\alpha_i)\right], \quad \text{where } j = 5, 7, 11, \ldots, q. \end{aligned} \tag{2}$$

The SHMPWM technique is based on the idea that it is not necessary to reduce to zero the harmonics while they are kept below the acceptable levels. Those levels are defined by the grid codes which establish the maximum allowed limits for each harmonic order and THD in order to maintain the quality of the grid. The SHMPWM technique is based on solving the following inequality system, where L_i is the maximum allowed level imposed by the applied grid code

$$\begin{aligned} &|M_a - H_1| \leq L_1 \\ &\frac{1}{|H_1|} \frac{4}{j\pi} \sum_{i=0}^{k-1} \left[(-1)^i \sin(j\alpha_i)\right] \leq L_j, \\ &\qquad \text{where } j = 5, 7, 11, \ldots, 49. \end{aligned} \tag{3}$$

The SHMPWM method relaxes the restrictions of (2) and is able to generate output signals with low harmonic content applying (3). This fact allows considering more harmonic orders than the SHEPWM technique as can be observed from (2) and (3). This flexibility is very useful in high-power systems due to that the filtering system requirements will be relaxed, which leads to an important reduction in the cost, volume, and weight of the filtering components. Hence, it is possible to choose the most appropriate filtering shape for each application previously to the computing process.

The inequality system (3) can be synthesized in an OF which has to be minimized

$$OF(\alpha_0, \ldots, \alpha_{k-1}) = \sum_{i=1,5,\ldots,49} c_i E_i^2 + c_{\text{THD}} THD. \tag{4}$$

The c_i coefficients of the OF are modeled as nonlinear functions and, in general, have been implemented as follows:

$$\begin{aligned} &\text{if } (E_i < \rho L_i) \qquad c_i = 1 \\ &\text{else} \qquad\qquad\quad\; c_i = \lambda_p \end{aligned} \tag{5}$$

where $\rho \epsilon$ (0, 1] is the safety margin of the maximum allowed level L_i and λ_p is defined as the penalty factor $(\lambda_p \gg 1)$.

The L_i values correspond to the maximum allowed levels shown in (3). As can be observed from (5), if the obtained harmonic distortion of order ith (E_i) is below the 80% (assuming that $\rho = 0.8$) of its corresponding L_i value, the associated c_i is equal to one. In the other case, as the distortion is close to the maximum allowed value L_i, a penalty is imposed in the c_i coefficient in order to focus the optimization search, reducing the distortion in this specific harmonic order. This penalty is defined as the weight factor λ_p.

In [5], where the SHMPWM technique was introduced using 15 switching angles, a safety margin ρ that is equal to 0.8 and a constant ratio penalty factor λ_p that is equal to 1000 were used. The L_i values were equal to the maximum values defined by the applied grid code. As was shown in [5], using 15 switching angles per quarter of a period gives enough flexibility to completely fulfill the grid code. However, for very high power applications, a low number of switching angles have to be used. In this paper, seven switching angles have been applied (this corresponds to a switching frequency that is equal to 350 Hz), and this does not allow enough margin to meet the grid codes without any additional filtering system. In this way, as examples of the flexibility of the SHMPWM technique,