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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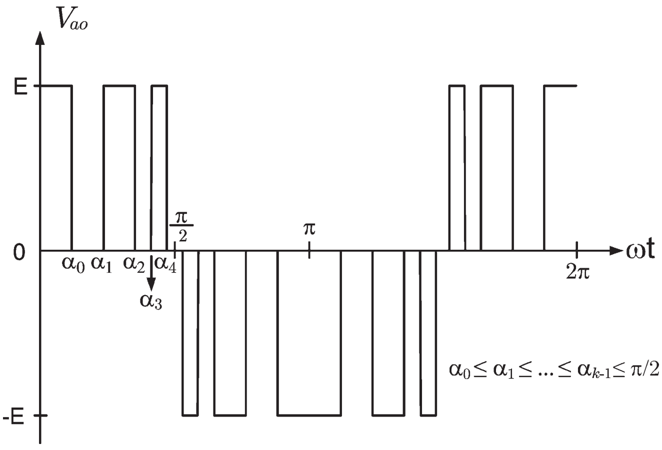


Fig. 1. Three-level preprogrammed PWM switching pattern with five switching angles (α_0, α_1, α_2, α_3, and α_4).

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

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

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:

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

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,

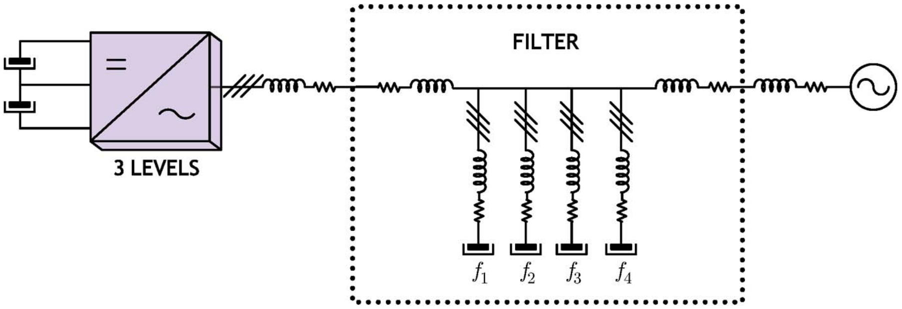


Fig. 2. Typical passive filter topology for high-power applications. This structure is known as LCL filter with harmonic traps.

different particularizations of (5) have been applied in order to achieve several optimization criteria.

It must be noticed that the definition of the c_i functions is the base of the SHMPWM technique because they must be adapted to the concrete conditions of the application. In this paper, two different strategies have been studied, and the details of each implementation will be discussed in Section IV.

The whole system described by (3) and (4) can be solved using an optimization method. Different algorithms have been tested, but the well-known simulated annealing optimization method [6], [9] has been finally used in this paper because it easily allows new formulations of the problem. Other methods such as particle swarm, tabu search, genetic algorithms, ant colony systems, stochastic evolution, etc., would obtain similar results [7], [8], [10].

III. FILTER DESIGN

High-power converters have to work at very low switching frequency, leading to output signals with undesired harmonic distortion. These harmonics have to be filtered in order to maintain the quality in the power supply. The obtained experimental results presented in this paper show that the SHMPWM technique is a powerful tool to be applied in order to relax the final filtering requirements. Any other element which reduces the harmonic content as the coupling transformer can also be considered in order to relax the requirements of the filter. There are different possible filtering strategies to reduce the harmonic content generated by power converters. The most commonly used are passive filters, active filters, and hybrid filters mixing both passive and active modules [11]–[13]. In high-power applications, passive filters are normally the most suitable solution. The filter topology most commonly used in high-power applications is the LCL filter with harmonic traps (Fig. 2). Filter design is a very important topic because, in high-power applications, the reactive elements are very bulky and expensive. Some important design guides can be found in [14] and [15]. The most important problem related to passive filters is the existence of possible resonances with the grid [16]. Different techniques have been reported in order to avoid this phenomenon when passive filters are used [17].

IV. SHMPWM VERSUS SHEPWM

As it has been commented previously, the SHEPWM technique has been widely used for high-power applications [18]–[21]. With this technique, it is possible to directly eliminate a limited number of harmonics (being this limitation related to the used switching frequency), reducing the tuned filters needed to meet the grid codes. The main drawback of the SHEPWM technique is that the value of the nonzeroed harmonics cannot be managed to get any optimization objective. The SHMPWM technique improves the SHEPWM results because it is able to reduce the filtering requirements, generating output signals with a higher number of harmonics under the values specified in the grid codes using the same switching frequency. This fact makes the SHMPWM technique specially useful for high-power applications. In addition, the SHMPWM technique can be used in a larger range of M_a, improving other previous techniques [22]–[24]. In this paper, the grid codes EN 50160 [25] and CIGRE WG 36–05 [26] have been considered in the computing process, but any other grid code could be chosen. These grid codes detail the specific limits up to harmonic order 50th. The THD is also limited by these specific grid codes to 8% but considering only the harmonics up to 40th. Table I summarizes the limits specified by the applied grid codes.

In order to compare the SHEPWM and the SHMPWM techniques, it is assumed that the control strategy of the converter avoids any possible resonance. The number of switching angles α_i is equal to seven per quarter of a 50-Hz cycle which corresponds to a switching frequency of 350 Hz using a three-level converter. With seven switching angles, the SHEPWM can fix the M_a and eliminate six nondesired harmonics, usually the nontriplen lower order harmonics, i.e., 5th, 7th, 11th, 13th, 17th, and 19th. A M_a range from 0.60 to 1.16 in steps of 0.01 is applied considering both the SHEPWM and the SHMPWM techniques.

The flexibility of the SHMPWM can be used in the computing process in order to determine the switching angles α_i which generate the most appropriate harmonic spectrum depending on the application. In this paper, two different strategies have been studied:

1) Strategy 1 (S1): A limited number of low-order harmonics must meet the grid code without any filtering system. The number of these harmonics must be at least the same than using SHEPWM. The rest of the harmonics specified in the grid code, which exceed the maximum limits, are reduced as much as possible independently whether they are low- or high-order harmonics. This idea can be translated to the OF using a particularized version

TABLE I
GRID CODE EN 50160 REQUIREMENTS + QUALITY GRID CODE CIGRE WG 36–05

Odd non-triplen harmonics		Odd triplen harmonics		Even Harmonics	
Harmonic order (n)	Relative Voltage (L_i)	Harmonic order (n)	Relative Voltage (L_i)	Harmonic order (n)	Relative Voltage (L_i)
5	6%	3	5%	2	2%
7	5%	9	1.5%	4	1%
11	3.5%	15	0.5%	6...10	0.5%
13	3%	21	0.5%	>10	0.2%
17	2%	>21	0.2%		
19	1.5%				
23	1.5%				
25	1.5%				
>25	0.2+32.5/n				

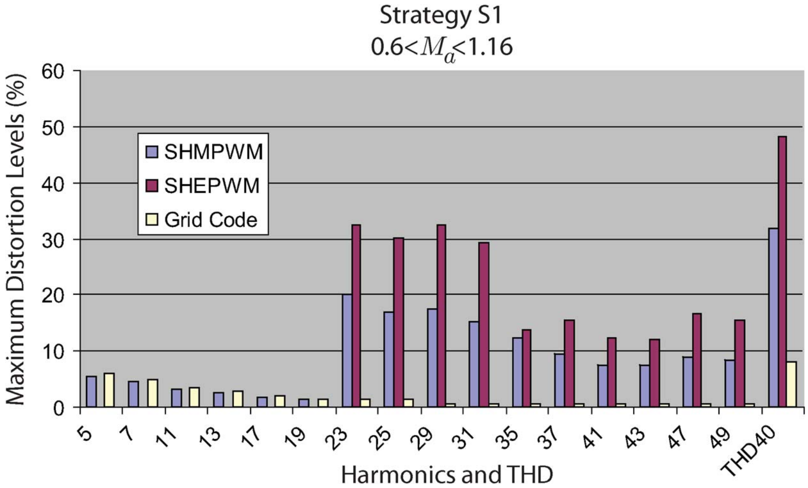


Fig. 3. Simulation results comparing SHEPWM and SHMPWM techniques considering S1 with a switching frequency that is equal to 350 Hz. Worst case in the interval $0.6 < M_a < 1.16$.

of (5). In this case, the penalty factor λ_p is equal to 1000. Moreover, the L_i levels have been divided in two groups. For harmonics up to 19th, the L_i values are the limits specified by the grid code, as in [5]. For higher harmonics up to 49th, the maximum harmonic distortion obtained using the SHEPWM technique in the whole range of M_a has been used as the L_i values. In this case, $\rho = 0.9$;

2) Strategy 2 (S2): A limited number of low-order harmonics must meet the grid code without any filtering system. The number of these harmonics must be at least the same than using SHEPWM, as in S1. For the rest of the harmonics considered in the grid code, S2 is focused on reducing as much as possible the harmonic content from order 23rd to 29th. In addition, S2 is designed to keep, if possible, the higher order harmonics up to 49th below the maximum values obtained using the SHEPWM technique. In this case, the particularized version of (5) is defined using a penalty factor λ_p that is equal to 5000 for all the harmonics up to 29th and equal to 1000 for higher harmonics. The L_i levels are those defined for strategy S1 except for the harmonics 23rd, 25th, and 29th, where a constant value that is equal to 15% has been used. Again, $\rho = 0.9$ has been chosen.

S1 represents the most immediate way to apply SHMPWM with a reduced number of switching angles. On the other hand, S2 is focused on reducing the grid connection filter, taking into account that the reactive elements to filter the low-order harmonics are specially bulky and expensive. S2 pays special attention on lower order harmonics at the expense of relaxing the allowed distortion of the high-order harmonics.

It must be noticed that both S1 and S2 are obtained, defining the c_i cost functions mentioned in Section II in a suitable way. The working conditions are completely different compared with those in [5], and a heuristic search is needed to translate the descriptions of the strategies presented previously to the group of c_i functions. This search is an important novelty presented in this paper.

V. SIMULATION RESULTS

The SHEPWM and the SHMPWM techniques applying S1 and S2 have been tested first by simulations. A three-level converter has been considered to compare the techniques. Figs. 3 and 4 show a comparison between the obtained simulation results using the SHEPWM and the SHMPWM techniques considering S1 and S2, respectively. In both figures are represented the worst THD and the worst value of distortion of

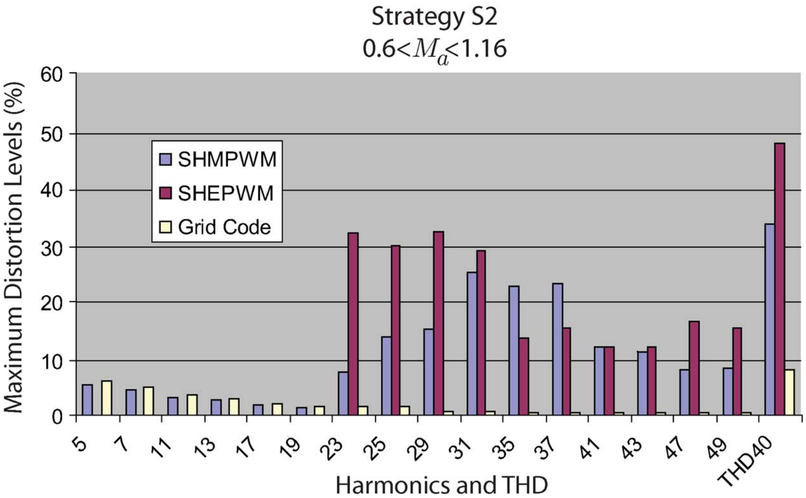


Fig. 4. Simulation results comparing SHEPWM and SHMPWM techniques considering S2 with a switching frequency that is equal to 350 Hz. Worst case in the interval $0.6 < M_a < 1.16$.

each harmonic obtained for a specific range of the modulation index M_a (from 0.60 to 1.16). In Fig. 3, it is clear that, using the SHMPWM technique with S1, the maximum distortion levels for the noneliminated harmonics are under the maximum values obtained using the SHEPWM technique. This fact is particularly relevant for harmonics 23rd–31st, where the results obtained using the SHEPWM technique nearly double those obtained using the SHMPWM method.

Fig. 4 shows a comparison between the simulation results obtained using the SHEPWM technique and the SHMPWM method with S2. In this case, the maximum distortion levels in the range 23rd–29th have been reduced as much as possible compared with the SHEPWM results and with SHMPWM using S1. This is very interesting because the filtering elements needed in the tuned filters are more bulky, heavy, and expensive in low-order harmonics. This advantage is achieved at the expense of the fact that harmonics 35th and 37th are higher than the maximum values obtained using SHEPWM. S2 could be a very interesting strategy in those cases where it is better to reduce the maximum power supported by the reactive elements of low-order harmonics than in high-order harmonics because the cost, weight, and size grow more than linearly. These results demonstrate that the flexibility of the SHMPWM method can be very useful and lets the designer to choose the most appropriate filtering shape according to each application. In S2, the main goal is to reduce as much as possible the harmonics 23rd–29th, but any other strategy could be chosen.

Using the SHMPWM technique with S1 or S2, it can be noticed that the very low order harmonic (up to harmonic 19th) distortion levels are under the limits specified by the grid codes. Using the SHEPWM and the SHMPWM techniques, any tuned filter in the low-order harmonics is not necessary. In the higher order harmonics, if S1 is applied, the obtained distortion is much higher using the SHEPWM method than using the SHMPWM technique. This means that the tuned filters have to support higher powers which deal with more bulky and expensive filtering elements. On the other hand, if S2 is applied, the most important advantage of SHMPWM compared with SHEPWM is focused on the reduction of the tuned filters dedicated to the lower order harmonics. It must be noticed that this is a very important advantage because the cost in both, inductors and capacitors, grows more than linearly when the maximum current (or voltage) is increased, keeping the inductance or reactance value.

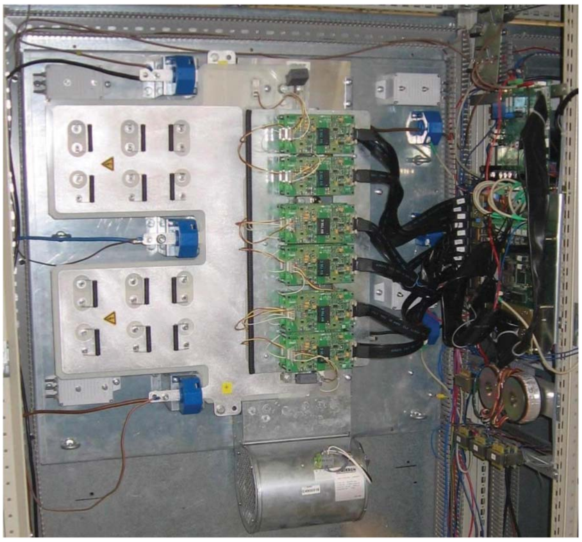


Fig. 5. 150-kVA IGBT-based back-to-back three-level diode-clamped inverter. The dc-link voltage is 800 V.

VI. EXPERIMENTAL RESULTS

All the results presented in the previous sections have been experimentally tested using the 150-kVA insulated-gate-bipolar-transistor (IGBT)-based back-to-back three-level three-phase diode-clamped converter shown in Fig. 5. This prototype is a scale-down model of high-power converters, and both the modulation techniques and the experimental results obtained with it can be extended to any three-level higher power converter. The chosen semiconductors are the IGBT modules SKM 300 GB 123 D of 300 A and 1200 V from Semikron. A hardware platform based on a TMS320VC33 digital signal processor is used to control the rectifier and the inverter sides of the converter. The rectifier side is controlled to establish a dc-link voltage that is equal to 800 V. The inverter side is used

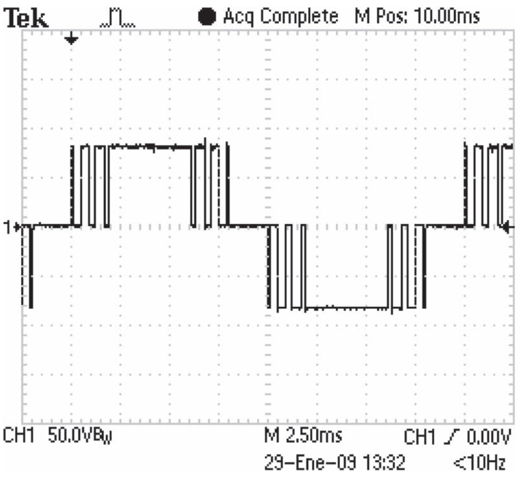


Fig. 6. Experimental phase to middle point voltage using seven switching angles for a three-level converter obtained using a 1:5-voltage-ratio oscilloscope probe.

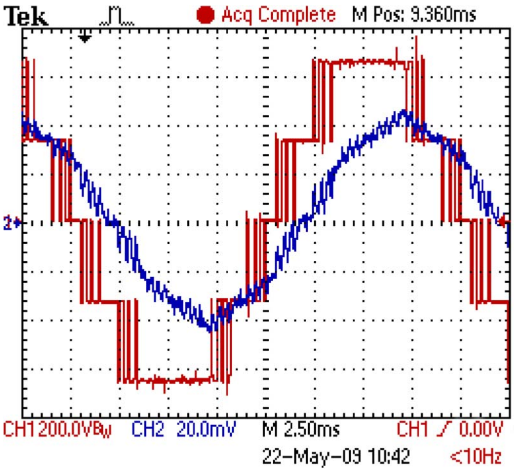
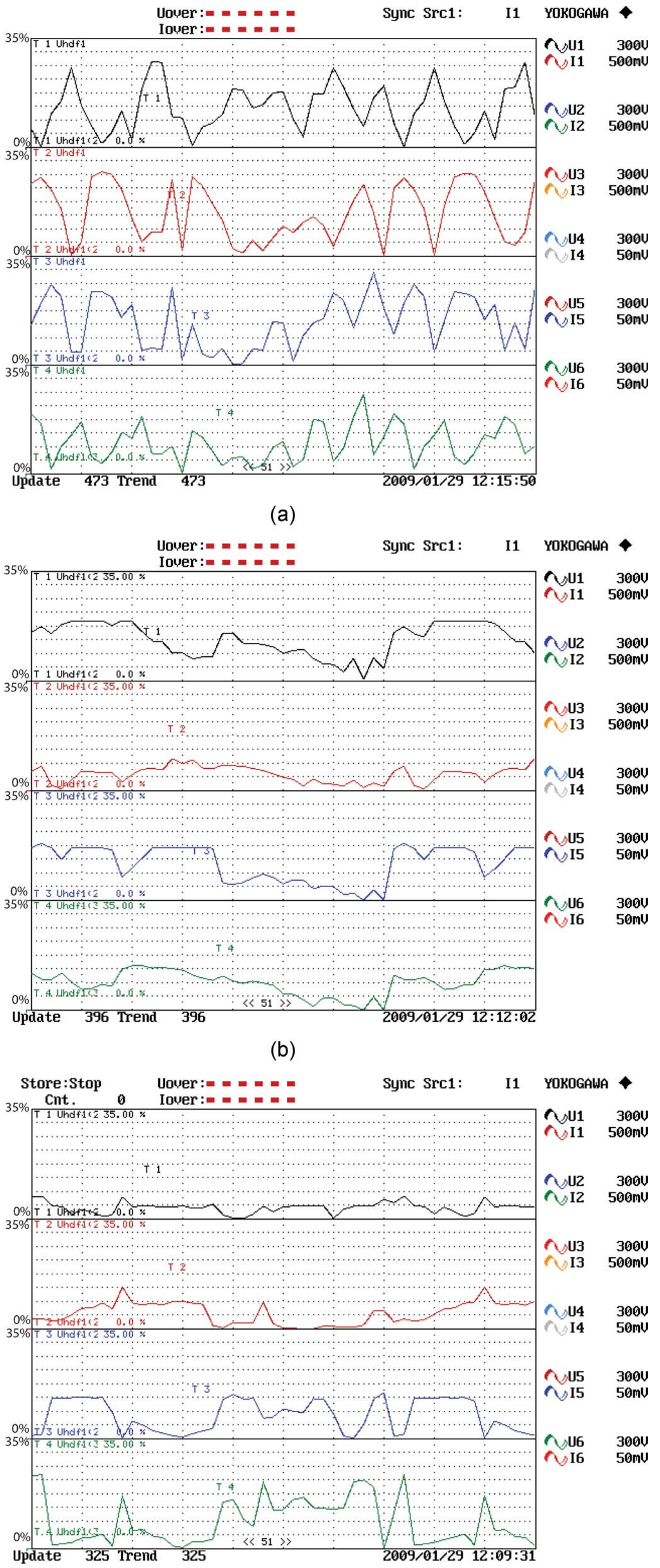


Fig. 7. Experimental current and line voltage for $M_a = 1.20$ obtained using a $1:5$-voltage-ratio oscilloscope probe and $10\ \mathrm{mV/A}$ for the current probe.

to feed a passive RL load with $R = 120\ \Omega$ and $L = 15$ mH. Both SHMPWM and SHEPWM techniques have been applied to the inverter in order to compare their performances. In the computing process, real power semiconductors have been considered to keep a safety margin of 32 μs between two consecutive switching angles, as in [2].

The SHMPWM technique in a closed-loop control scheme was presented in [27], where the switching frequency was equal to 750 Hz. However, in this case, the reference waveforms to be generated by the inverter side are determined in open loop, corresponding to a 50-Hz purely sinusoidal signal. In addition, in this paper, the same grid codes are applied, but only seven switching angles are considered, leading to a low switching frequency that is equal to 350 Hz as can be observed in Fig. 6. Fig. 7 shows the current of one phase in the load and the line voltage for $M_a = 1.20$ using the SHMPWM technique with S2. An oscilloscope voltage probe with an attenuation ratio of $1:5$ and a 10-mV/A current probe were used to obtain both captures. The SHMPWM technique allows obtaining solutions with good performance with M_a up to 1.20. However, a modulation index range from 0.6 to 1.16 is chosen in order to make a fair comparison with the well-known SHEPWM technique.



(a)

(b)

(c)

Fig. 8. Experimental values in the whole M_a range obtained using (a) SHEPWM, (b) SHMPWM-S1, and (c) SHMPWM-S2. (From top to bottom) Harmonics 23rd, 25th, 29th, and 31st. The scales have been adjusted from 0% to 35% of the fundamental harmonic amplitude.

In Fig. 8, the trends of the magnitudes of the harmonics (23rd, 25th, 29th, and 31st) using the different techniques studied in this paper have been represented. Fig. 8(a)–(c)

TABLE II
SIMULATION AND EXPERIMENTAL RESULTS USING THE SHEPWM AND THE SHMPWM TECHNIQUES CONSIDERING S1 AND S2

Harmonic order (n)	Maximum Limit (L_i)	SHEPWM(%)		SHMPWM-S1(%)		SHMPWM-S2(%)	
		simulations	experiments	simulations	experiments	simulations	experiments
5	6	0.00	0.26	5.40	5.54	5.40	5.50
7	5	0.00	0.26	4.50	4.48	4.50	4.47
11	3.5	0.00	0.22	3.15	3.21	3.15	3.19
13	3	0.00	0.18	2.70	2.74	2.68	2.73
17	2	0.00	0.20	1.80	1.93	1.80	1.82
19	1.5	0.00	0.33	1.35	1.45	1.35	1.37
23	1.5	34.52	32.03	20.16	20.48	7.60	7.75
25	1.5	30.08	28.07	16.80	16.71	13.93	12.02
29	1.32	32.49	33.05	17.64	17.93	15.20	15.06
31	1.25	29.30	27.02	15.12	15.05	25.32	25.14
35	1.13	13.76	13.09	12.45	12.57	22.82	22.40
37	1.08	15.45	15.15	9.45	9.95	23.26	22.85
41	0.99	12.22	12.09	7.56	7.68	12.06	12.21
43	0.96	12.12	12.07	7.56	7.32	11.14	10.97
47	0.89	16.72	17.02	8.82	8.88	8.18	8.02
49	0.86	15.77	15.23	8.32	8.03	8.24	7.84
THD_{40}	8	48.21	49.84	32.31	34.03	34.87	34.12

corresponds to the results obtained using the SHEPWM technique, using the SHMPWM with S1, and using the SHMPWM with S2, respectively. In all cases, the vertical scale has been adjusted from 0% to 35% of the fundamental harmonic amplitude. The horizontal scale is the simulation time. In the experiment, the modulation index M_a is changing continuously from 0.60 to 1.16 using steps that are equal to 0.01. Each specific modulation index value is applied for 1 s, and the experimental results have been taken for 1 min in order to show the results for all the modulation index range.

All the experimental results are summarized in Table II for experiments E1 and E2. The harmonic order, the maximum levels specified by the grid codes, and the results obtained with SHEPWM and SHMPWM techniques are shown from left to right. The shown results correspond with the maximum harmonic distortion obtained in the whole range of M_a. All the harmonic distortion values are specified as a percentage with respect to the fundamental harmonic value. All the studied harmonics of interest (odd nontriplen) are from top to bottom, and the detailed THD obtained, considering up to harmonic 40th, is in the final row.

The results from Table II show the advantages obtained using the SHMPWM technique in comparison with SHEPWM due to the flexibility of the method. As can be observed from Table II, the simulation results are in accordance with the obtained experimental results. From the experimental results, for harmonics up to 19th, using SHEPWM and SHMPWM, any filtering system is not necessary because the maximum output values are always under the limit specified in the grid codes. For the rest of the harmonics considered by the grid code, from 23rd to 49th, the results obtained using the SHMPWM technique depend on the selected strategy during the computation process (S1 or S2).

Considering E1, the maximum values obtained using SHMPWM are always below the maximum values obtained using SHEPWM in the whole M_a range. This result represents a great advantage of the SHMPWM with respect to the SHEPWM because the grid connection filter requirements will clearly be reduced. For instance, the harmonic distortions from 23rd to 31st are improved, reducing the maximum level nearly to the half value.

Considering E2, for harmonics from 23rd to 49th, from the data in Table II, it can be noticed that harmonics 23rd–29th are greatly reduced compared with those obtained using SHEPWM. This was the primary objective of S2, i.e., to determine the switching angles to be applied to the SHMPWM technique. In fact, the distortion of the harmonics from 23rd to 29th using S2 is also lower than that achieved by S1. This improvement is achieved at the expense of the fact that harmonics 35th and 37th have distortion above the level obtained using the SHEPWM technique. S2 was defined in this way because the filtering elements needed to meet the grid codes are bigger and more expensive while the harmonics considered have lower orders.

VII. CONCLUSION

In this paper, a comparison between SHEPWM and SHMPWM for very low switching frequency (350 Hz) for a three-level converter has been presented. In high-power applications, the thermal losses limit the maximum switching frequency to a few hundreds of hertz ($f_s < 500$ Hz). In this context, it is necessary to eliminate the undesired harmonics using filtering systems. The SHEPWM has been traditionally used in high-power applications because it is able to generate output waveforms with a limited number of eliminated harmonics. In this paper, it has been demonstrated that, using very low switching frequency, the SHMPWM technique is able to generate output signals with better harmonic performance compared with the SHEPWM technique in a wide range of the modulation index.

In this paper, the flexibility of the SHMPWM technique has been exploited considering different criteria to determine the switching angles to be applied to the three-level converter. One of the strategies (S1) was defined to improve the results of the SHEPWM for all the harmonics that are not zeroed. A second strategy (S2) has been also introduced in order to reduce as much as possible the filter requirements for low-order harmonics above the maximum limit imposed by the grid code.

The simulation and experimental results show that the maximum output values of the harmonics using the SHMPWM technique up to 19th are below the limits imposed by the applied grid codes. These harmonics are eliminated using SHEPWM. Therefore, these harmonics do not need to be filtered using both techniques. On the other hand, the noneliminated harmonics obtained using SHEPWM have much higher values compared with those obtained using the SHMPWM technique using S1. This fact leads to a reduction in the maximum power supported by the elements of the tuned filters to be used. The consequence is a significant reduction in cost, size, and weight of the filtering system required to fulfill the grid codes. Finally, the results obtained for S2 show that any filtering shape can be applied to determine the switching angles for the SHMPWM technique. The S2 objective was to achieve a great reduction in the noneliminated low-order harmonics, and this goal has been reached. The experimental results validating the proposed concepts are included.

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