Selective Harmonic Mitigation Technique for Cascaded H-Bridge Converters with Equal DC Link Voltages

B. Subba Reddy, G. Surendra

Abstract—**Multilevel converters are very attractive for applications in medium-voltage high power range since they are capable of producing the high quality output waveform with low switching frequency. The multilevel topology is obtained by the cascaded H-bridge converter (CHB) which is formed from the series connection of H-bridge cells. A new method to generate switching three-level pulse width modulation (PWM) patterns to meet specific grid codes is presented. Studying of all harmonics and total harmonic distortion is the global problem in multilevel converters. The proposed method is the selective harmonic mitigation PWM is used to preprogramming the harmonic output waveform. This fact leads to the reduction of bulky and costly grid connected tuned filters. This method is developed by the interpolation of different set of angles. The simulation results are presented for the proposed control method.**

Index Terms—**Harmonic distortion, multilevel systems, optimization methods, pulse width modulation converters.**

I. INTRODUCTION

One important application of multilevel converters is focused on medium and high power conversion [1]. At present research is going on the development of new and optimized techniques for this type of converters to improve the quality of the output waveform. The available multilevel topologies are the neutral point clamped, flying capacitor, and cascaded H-bridge converters (CHB) [2]. The cascaded H-bridge converter constructed from a series cascade of three-level H-bridges. This cascaded connection of the converter makes it to produce high quality, high voltage waveforms by utilizing low or medium voltage switching devices. This functionality makes this converter an desirable option for grid connected applications such as uninterruptible power supplies, static reactive volt ampere compensators, series and shunt compensators, etc.[3]-[4].

The use of low-voltage insulated-gate bipolar transistors at high-power levels usually demands a reduction in switching frequency in order to make sure that losses caused by the imperfect nature of practical switching devices does not significantly reduce the converter efficiency. Selective harmonic elimination (SHE-PWM), total harmonic distortion minimization, and selective harmonic mitigation (SHM-PWM) methods are used to produce waveforms with low switching frequency and to improve the waveform quality. As the first approximation of the harmonic distortion avoidance, the selective harmonic elimination pulse width modulation (SHEPWM) technique, which was first introduced in 1973, is an effective technique for the elimination of low order harmonics in two-level high-power inverters.

For these methods, mathematical functions can be derived using the Fourier analysis, which may be solved to meet a certain predefined objective in the waveform [5]-[6]. The waveform objectives may include the complete elimination (SHE-PWM) or reduction (SHM-PWM) of certain harmonics in the output waveform in order to meet a particular harmonic code for a certain application [7]. The derived functions are transcendental and nonlinear in nature, can be solved for a range of modulation indices using different methods. The solutions are stored in lookup tables (LUTs) for use with an appropriate converter control scheme.

In CHB based inverters, it may be sure that each cell of the inverter has to draw equal energy form the dc source connected. This can be achieved over a single or several fundamental cycles. This would ensure that these sources discharge at the same rate and that each cell of the cascade is utilized evenly. In applications due to the pattern of the switching angles and the unequal duty cycle of each device, distortion may be present in the converter waveform.

To attain the optimal harmonic performance, it was found that a large number of different waveform solutions are required to influence the power flow through a CHB converter [9]. By decoupling the cells and independently controlling the modulation index of each cell separately reduces the need of large number of solutions. Regrettably, this reduction in the number of solutions potentially reduces the waveform quality of the CHB converter because the degrees of freedom available in the multilevel converter waveform are not fully utilized.

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This paper presents a SHM-PWM control method based on multilevel waveforms which allows the required control of power flow in a CHB converter by fully utilizing the waveform degrees of freedom. The proposed method uses the interpolation of LUT-based solutions for a number of imbalances thus reduce the need of very large LUTs apparent in previous methods to control the power flow through the H-bridges asymmetrically.

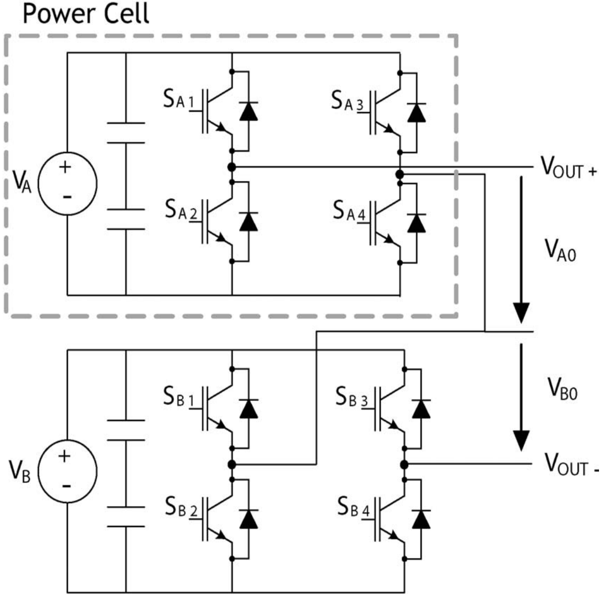

Fig. 1. Five-level cascaded H-bridge converter based on the series connection of two three-level power cells.

II. CASCADED H-BRIDGE CONVERTERS

Higher number of output voltage levels can be observed by the series connection of several three-level generated single full H-bridge as can be observed from Fig. 1. The number of series connected single full H-bridge is depends on the number of output levels required for particular application. In usual, if n power cells having the same dc voltage are connected in series to build the converter, the number of levels that can be obtained is 2n + 1. This topology is named the n-cell CHB converter, and it presents a high level of modularity and redundancy as well as an ability to produce high quality output voltage waveforms.

In the applications of the multilevel converter it is necessary to avoid the overheating of the switching devices by suitable power flow among all the cells equally in order to extend the lifetime of all the elements in the converter [9]. In the topology of the multilevel converter the other, more complicated, CHB-based converter structures may require the power flow to be controlled asymmetrically through the converter cells. In both cases, assuming that the current is undistorted, the power flow from each cell of the converter can be decided by take in to account that the fundamental frequency component of each cell only. It is feasible to operate SHE-PWM and SHM-PWM techniques to control the power flow through a CHB converter as was shown in [9].

The method reflects the use of a low switching frequency SHE-PWM to control power flow through the cells of a CHB converter while still producing high quality waveforms. The disadvantage of this approach presented in [9] is that a definite set of angles must be calculated for each possible imbalance scenario for the converter, and therefore a very large number of LUTs and a complex LUT selection scheme would be required to practically implement the method. This paper presents a method which may overcome this disadvantage by attempting to interpolate between LUTs.

III. SHM-PWM PRINCIPLE

A. *Three-Level Converters Three-Cell Converters*

Fourier analysis can be used to study a typical three level waveform with k switching angles $\alpha i(i = 0, \ldots, k-1)$ (Fig. 2). The amplitude of each harmonic can be obtained using the following expression where Hj is the amplitude of the jth harmonic:

$$H_j = \frac{4}{j\Pi}\sum_{i=0}^{k-1}[(\_-1)^i \sin(\mathrm{j}\alpha_i)] \qquad (1)$$

(1)

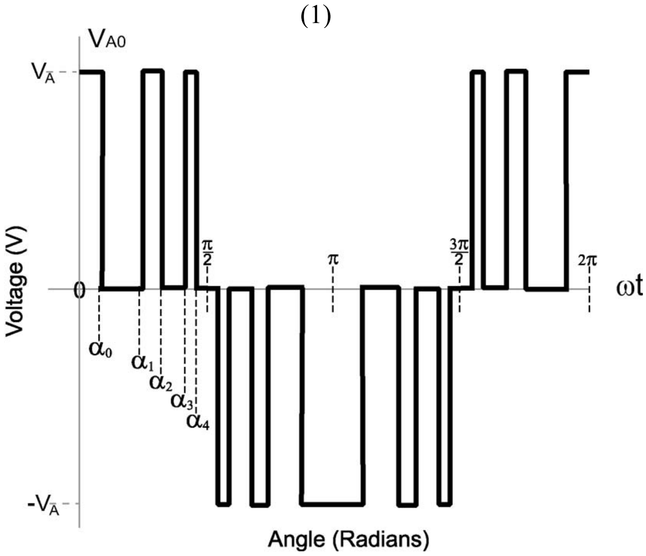

Fig. 2. Three-level preprogrammed PWM switching pattern with five switching angles ($\alpha 0$, $\alpha 1$, $\alpha 2$, $\alpha 3$, $\alpha 4$). Typical output waveform of the top power cell represented in Fig. 1.

By using this expression a specific value to each harmonic amplitude can be set using the switching angles as degrees of freedom. The well known SHE-PWM technique is based on this theory, i.e., the amplitude of fundamental harmonic and cancel of a specific set of harmonics are obtained by using these switching angles [5]-[6]. The relationship between the dc link voltage of the converter and the amplitude of the generated fundamental component is called the modulation index (Ma) and can be defined as $Ma = H1\pi/4V\mathrm{dc}$.As a result of half wave symmetry in the waveform, even harmonics have zero amplitude so the chosen harmonic orders would be 3, 5, 7, . . . and up to $k-1$ harmonics can be cancelled using k switching angles. In balanced three-phase topologies without a neutral connection, the triplen harmonics are also cancelled, and so it is possible to eliminate a very high number of the low-order harmonics with a low switching frequency.

Summarizing, the SHE-PWM technique for three-level converters is based on solving the following system of equations where q is the highest harmonic order that will be cancelled:

$$H_1 = \frac{4}{\Pi}\sum_{i=0}^{k-1}[(-1)^i \sin(\alpha_i)], 0 = \frac{4}{j\Pi}\sum_{i=0}^{k-1}[(-1)^i \sin(\mathrm{j}\alpha_i)]$$

Where j=3,5,7,9,11,….,q

(2)

The SHM-PWM technique was presented in [7] says that it is not necessary to completely cancel the harmonics in the converter ac waveform. Instead, they just have to be reduced to levels where they can be considered allowable. The maximum harmonic content for a grid-connected inverter can be obtained from the limits specified in the actual grid codes (*Lj* represents the limit for the *j*th harmonic).

The extra flexibility given by the SHM-PWM principle can be used for different objectives, for example reducing the THD, considering a higher number of harmonics using the same number of switching angles, or extending the modulation index range for the same set of valid solutions.

B. Extension to Converters with a Higher Number of Levels

Considering, for instance, a waveform similar to the pattern shown in Fig.3 but with *N* levels and *k* switching angles *αi* (*i* = 0, . . . , *k* − 1). The SHE-PWM can be applied with this kind of waveform. Again, solving the equations, the fundamental harmonic can be set to the desired value and *k* − 1 harmonics can be reduced to zero (*Hj* = 0 where *j* = 3, 5, 7, 9, 11, . . . , *q*).

In order to assure that all the cells are sharing the same power this system of equations needs to be altered. Instead of using the fundamental harmonic of the global waveform, the fundamental component generated by each cell is forced to be equal to the desired value. This way, for a *N*-cell converter working with *k* switching angles per cell only *N*(*k* − 1) extra harmonics can be cancelled. The new system of equations can be formed with (3) and (4) considering that in (4) it is assumed that the angles of all the cells are reordered to generate the appropriate multilevel global waveform. The SHM-PWM technique can also be applied to converters with more than three levels.

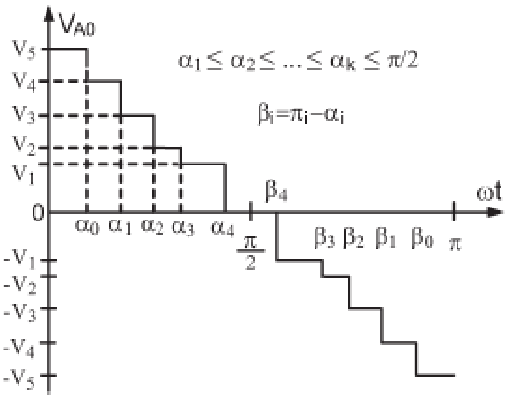

Fig. 3. Nine-level preprogrammed PWM switching pattern with ten switching angles (*αi*, *i* = 0, . . . , 9). The waveform is symmetrical in order to eliminate the even harmonics.

$$H_1 = \frac{4}{\pi}\left(\sum_{i=0}^{k-1}\left[(-1)^{\mathrm{i}}\sin(\alpha_{\mathrm{i-cell-n}})\right]\right)$$

where n=1,2,3,…N

(3)

$$0 = \frac{4}{j\Pi}(\mathrm{V}_1\sin(\alpha_0) + \sum_{i=1}^{k-1}[\mathrm{V}_i[\sin(\mathrm{j}\alpha_i) - \sin(\mathrm{j}\alpha_{i-1})]])$$

where j=3,5,7,9,11,…q (4)

There are several optimization methods such as Tabu Search, Ant Colony, or Particle Swarm [10] can be used to optimize the system. As in previous work, in this paper, the well known Simulated Annealing optimization method has been chosen because it can be adapted very easily to problems with many different constraints. In any case, it has to be observed that since the solutions are calculated only once and then are stored in LUTs for use with the power converter, the optimization method itself is of little importance.

IV. SHM-PWM FOR BALANCING

Under imbalance conditions, it is necessary to use a strategy to adjust the modulation index in order to share the power among all the cells. In [9], a method was presented based on the SHE-PWM technique that could endure any imbalance situation by decoupling all of the cells of the converter. This required a single table of solutions, which could be applied to each H-bridge of the converter to independently control the power flow. The disadvantage of this method is that it eliminates lower number of harmonics compared with the use of global multilevel solutions since it does not use the multilevel waveform of the converter during angle calculation.

In the case of this paper, the global output waveform of the converter is used in order to increase the number of considered harmonics. Consequently, a higher number of harmonics can meet the grid code requirements increasing the quality of the output waveform. In this paper, three switching angles have been considered for CHB converters with two and three cells.

Considering a multicell cascaded converter, specific LUTs can be previously obtained for different unbalancing conditions. When the dc voltages of each cell are normalized, the imbalance of each cell can be referred as an increment or decrement with respect to the theoretical mean value. In the rest of the paper, the following nomenclature will be used to define the conditions of each LUT: (*X*1,*X*2, . . . , *Xn*) where *Xn* represents the imbalance of cell *n*, in percent, of the average desired voltage (perfect balanced situation). For example, considering a two-cell converter with a maximum tolerable imbalance of 3%, two LUTs, *S*1(0, 0) and *S*2(−3, 3) are required. Interpolation between the elements of these two LUTs can be used in order to find the required switching angles, which achieve the required waveform objectives over this 0–3% imbalance range. For higher imbalance conditions, extra LUTS could be added to extend the range. For example, the range could be extended to endure an imbalance of up to 6% using *S3(*−6, 6), or 9% using *S*4(−9, 9), etc. The linear interpolation between the switching angles stored in the two LUTs can be achieved using the following equation on each element of the two LUTs:

$$\alpha(\mathrm{i}) = \mathrm{A}\,\alpha_{LUT1}(\mathrm{i}) + \mathrm{B}\,\alpha_{\mathrm{LUT2}}(\mathrm{i}) \qquad (5)$$

This interpolation method is beneficial when compared with other methods considered in literature as it limits the number of required LUTs that are needed to achieve the waveforms objectives in the presence of a dc imbalance. For example, using the LUTs described above, for an imbalance of 1%, the constants would be $A = 1/3$ and $B = 2/3$. The next sections show some examples for both two and three-cell CHB converters.

V. SIMULATION RESULTS

This section presents the simulation results that have been obtained using the SHM-PWM technique in a two and a three-cell CHB converter. In order to obtain solutions, which could be easily implemented in a real converter, real power semiconductors have been considered. A minimum safe margin of 0.01 radians has been taken between two consecutive switching angles. In the computing process the limits specified in the EN 50160 and CIGRE WG 36-05 grid codes have been considered but any other could have been chosen. These standards include specific limits for each harmonic up to 49th harmonic the waveform THD calculated up to 40th harmonic. Table *I* shows the harmonic limits specified in these standards. Fig.4 shows the switching angles for a two-cell topology per H-bridge. Four extra harmonics are considered in the global waveform, and a maximum imbalance of 10% has been considered in the computing process.

Table. I Grid code EN50160 requirements+ Quality grid code CIGRE WG 36-05

Odd Non Triplen Harmonics		Odd Triplen Harmonics		Even Harmonics	
Order (n)	Limit (Li)	Order (n)	Limit (Li)	Order (n)	Limit (Li)
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				

A. *Two Cell Converters*

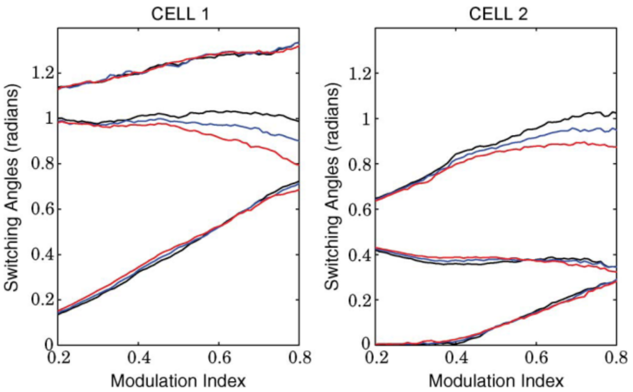

Fig. 4. SHM-PWM switching angles for the case of two cells and three angles per cell in the *Ma* range from 0.20 to 0.80 for a balanced situation (black), an imbalance of 5% (blue) and an imbalance of 10% (red).

In Fig.5, the harmonic content obtained for an imbalance of 3% for the complete modulation index range from 0.2 to 0.8 in steps of 0.01 can be observed. It can be seen that in all the cases the lowest harmonics are fulfilling the grid code. The bars on this figure represent the limits specified in the grid code. The triangular waveforms show the amplitude of the corresponding harmonic component for each value of *Ma* in the whole range. A detailed plot showing the lowest order harmonics is presented in Fig.6.

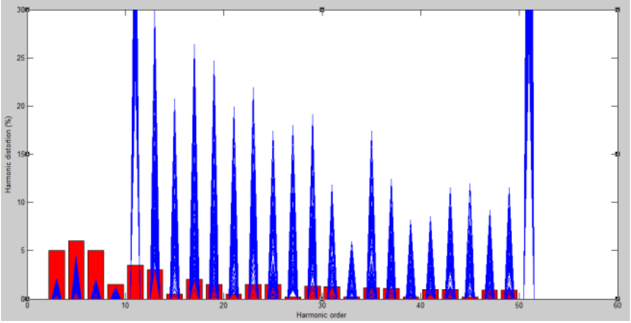

Fig. 5. Global harmonic content and THD (on the right) generated by the converter for each modulation index value for a (−3, 3) imbalance and $0.20 < Ma < 0.80$ (more detailed in Fig. 6).

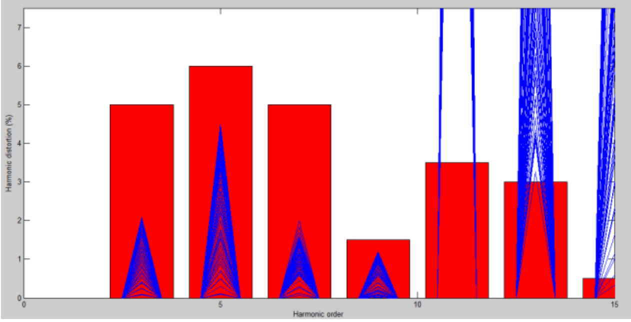

Fig. 6. Detail of the low-order harmonic amplitudes generated by the converter.

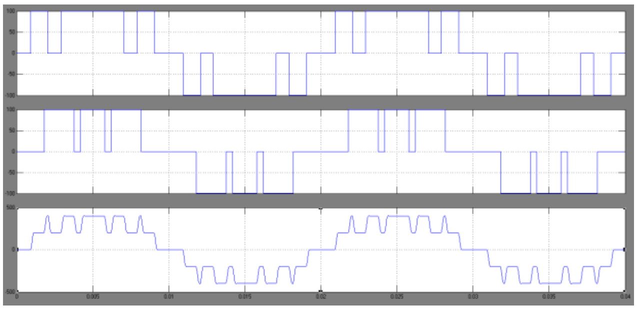

Fig. 7. Voltage of both cells and current(bottom) of two cell cascaded converter.

B. *Three Cell Converters*

This section presents simulation results obtained using a three-cell converter. Fig.8 shows the switching angles corresponding to a set of imbalance conditions of (0, 0, 0), (−2, −2, 4) and (−4, 2, 2) for the three cells.

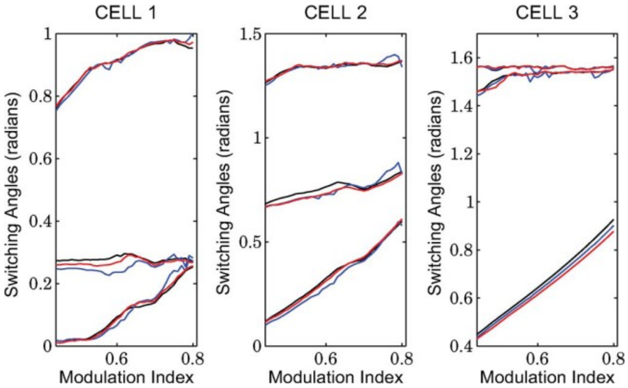

Fig. 8. Switching angles for a set of imbalance conditions of (0, 0, 0) in black, (−2, −2, 4) in red and (−4, 2, 2) in blue.

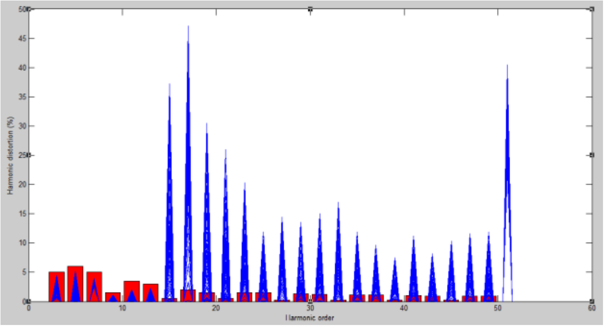

Fig. 9. Output spectrum for an imbalance of (−1.2, 1, 1.5) and 0.44 < *Ma* < 0.80.

It can be observed from the above figures that for all the values of *Ma* the lower harmonic components are below the limits specified in the grid code. For three-cell converters, the simulation results obtained using the presented switching angles give very low theoretical final imbalance for all the conditions considered in the computing process.

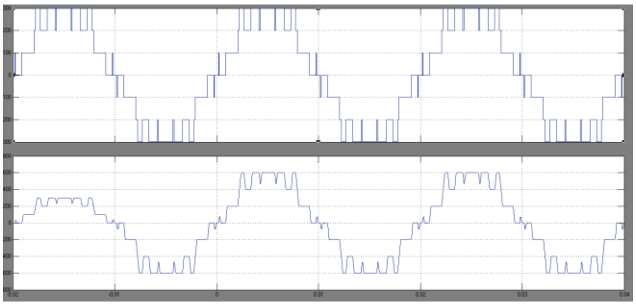

Fig. 10. Global output waveform and current(bottom) of three cell cascaded converter.

It must be noted that this strategy can be very useful to tolerate low unbalancing conditions because a high number of harmonics can be controlled using a lower number of switching angles. Using a three-cell topology and three angles per cell, it is possible to set the amplitude of the fundamental component and to control up to six undesirable harmonic components. In comparison with the decoupled technique presented in [9], a higher number of harmonics can be controlled using a lower number of switching angles. This technique could however be used in conjunction with the decoupled technique presented in [9], for use in systems which may present higher imbalance situations.

VI. CONCLUSION

A new method named SHMPWM to generate preprogrammed switching patterns to meet grid codes has been presented. The proposed SHMPWM technique adapts the power system's behavior in the new scenario, where high quality is demanded by the electrical utilities and grid codes have to be fulfilled. The proposed method is based on the calculation of three-level PWM switching patterns by using optimization methods, taking into account grid codes and technological implementation requirements of the power devices. All the harmonics and the THD are considered as a global problem to optimize the behavior of the complete system, fulfilling specific and actual grid codes. The proposed SHMPWM method deals with the problem as a global optimization random search over the continuous space, where all the harmonics and the THD are taken into account and are bounded by the applied grid code. In this way, they are mitigated to be below the limit imposed by the applied grid code. An example of applications, which may benefit from such a scheme, is in a multilevel UPS. Different simulation results for two and three-cell converters have been included to show the viability of the technique.

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