# Multi-Dimensional Modulation Technique for Cascaded Multilevel Converters

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***Abstract*—Multilevel cascaded H-bridge converters have found industrial application in the medium voltage high power range. In this paper, a generalized modulation technique for this type of converters based on a multi-dimensional control region is presented. Using the multi-dimensional control region, it is shown that all previous modulation techniques are particularized versions of the proposed method. Several possible solutions to develop a specific implementation of the modulation method are addressed in order to show the potential possibilities and the flexibility of the proposed technique. In addition, a feed-forward version of this technique is also introduced to determine the switching sequence and the switching times avoiding low harmonic distortion with unbalanced dc voltages. Experimental results are shown in order to validate the proposed concepts.**

***Index Terms*—Cascaded multilevel converters, modulation algorithm.**

## I. Introduction

MULTILEVEL converters are especially designed to be used in applications where a high power demand and a high quality of the output waveforms are required [1]–[4]. Several topologies have found industrial acceptance: the already classical 3-level neutral point clamped (3L-NPC), Cascaded H-Bridge (CHB) and four level Flying Capacitor (4L-FC) [4]; and the more recent active NPC (ANPC) [5], the modular multilevel converter (MMC) [6], [7] and the five level H-bridge NPC (5L-NPC) [8], [9].

This paper focuses on the CHB, which is commercially available by several manufacturers and covers a power range of 0.15 to 120MW, output voltages up to 13.8kV, output frequency up to 330Hz, and is available in 7, 9, 11, 13 and 17-level configurations (3, 4, 5, 6, and 9 cells per phase respectively), with 18, 30 and 36 multipulse diode rectifiers and even with a regenerative option (2-level 3-phase VSI front end per cell) [10]–[14]. The industrial CHB is composed of low voltage IGBTs, is modulated with phase shifted PWM, and features air-cooling system. Currently their main application fields are pump, fans, compressors, extruders, kneaders, mixers, crushers, agitators, and conveyors in the medium voltage range [15]. In addition, it has been recently proposed for other applications like: photovoltaic power conversion system [16], [17], wind power conversion [18], and traction with medium frequency isolation transformer [19], [20]. In particular the CHB has great potential for reactive power compensation and active filter applications, since no multipulse transformer-rectifier circuit is necessary (which is his main drawback compared to other multilevel topologies) [21], [22].

The modulation of multilevel converters is a important research focus during the last years. In order to determine the switching of the CHB, several modulation strategies have been developed. Multi-carrier based pulse width modulation (PWM) (such as level-shifted PWM and phase-shifted PWM), space-vector modulation (SVM), hybrid modulation or time-based modulation techniques have been applied to CHB achieving a high performance [23]–[30]. Each modulation technique is focused on the optimization of some converter feature such as switching losses reduction, maximum effective switching frequency, even power distribution among the power cells, common-mode voltage minimization, minimum computational cost, etcetera. A good and brief classification of the most common modulation techniques for CHB is presented in [15], [31].

The CHB converter presents great possibilities due to its cascaded connection. Any optimization criterion can be studied developing the corresponding specific modulation technique. The aim of this paper is to introduce a new generalized modulation technique showing the potential of the CHB topology. In this paper, it will be demonstrated that all previous modulation techniques (multi-carrier PWM, SVM, hybrid modulation, etcetera) are only particular solutions of the proposed modulation technique. So, any other modulation strategy could be developed in order to optimize some converter feature. Considering the concepts introduced in this paper, new alternatives in the modulation strategies are opened. The proposed modulation strategy will be focused on the 2C-CHB topology but it will be extended for CHB with more than two H-bridges in section V.

As a second contribution of the paper, a feed-forward version of the proposed modulation strategy is introduced in order to avoid possible low harmonic distortion due to voltage unbalance in the dc sources of the converter.

This paper is an updated and extended version of a previously published paper in IEEE ICIT 2009 Conference [32] and

Manuscript received June 30, 2009. Accepted for publication April 12, 2010. 
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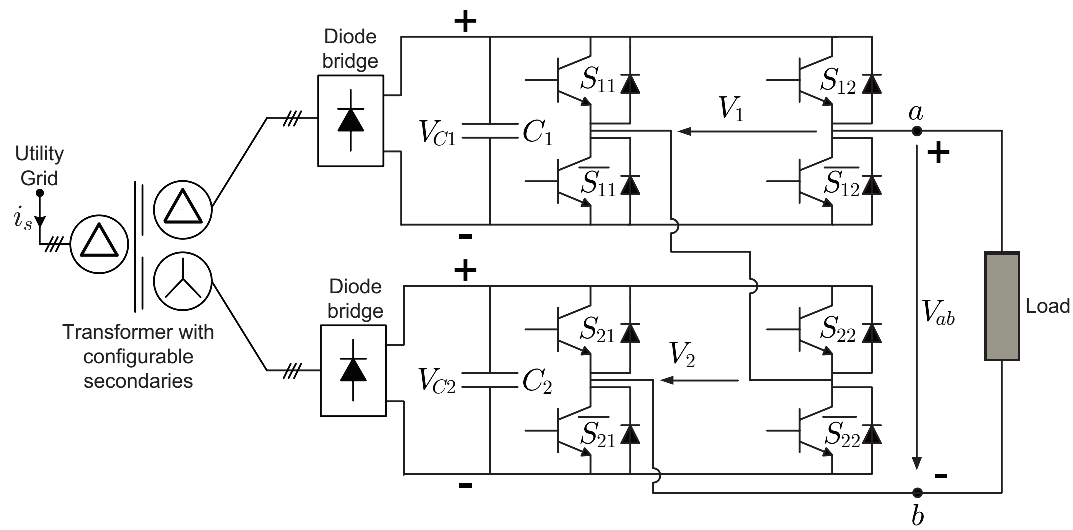


Fig. 1. Two-cell cascaded H-bridge inverter (2C-CHB) connected to the grid through a transformer with configurable secondaries and diode bridges. This figure also shows the diagram of the test-bench used to obtain the experimental results.

is organized as follows: The proposed generalized modulation method for CHB is presented in section II. The feed-forward version of this modulation technique is presented in section III. The experimental results of the proposed method are introduced in section IV. The extension of the method to be applied to CHB with more than two cells is introduced in section V. Finally, the conclusions of the work are summarized in section VI.

## II. Proposed Modulation Technique for Cascaded Multilevel Converters

The objective of a modulation technique is to generate a phase voltage $V_{ab}$ similar to the desired phase voltage $V_{ab}^*$ as much as possible. This objective can be written as

$$V_{ab} \rightarrow V_{ab}^*. \tag{1}$$

In order to achieve a desired phase voltage $V_{ab}^*$ averaged over a switching period $T_{sw}$, the output voltages of the cells of the CHB ($V_i$ for cell $i$) can take multiple values. In fact, in the 2C-CHB case, there are infinite values of the average output voltage of each cell $\delta_1$ and $\delta_2$ which fulfill

$$V_{ab} = \delta_1 + \delta_2, \tag{2}$$

$$\delta_i = \int_0^{T_{sw}} V_i dt. \tag{3}$$

The states of each H-bridge can take values 0, 1 or 2 being the H-bridge output voltage $-E$, 0 or $E$ respectively. The gate driver signals for the power semiconductors of the H-bridge $i$ depending on its state $H_i$ are listed in Table I.

The proposed modulation technique is based on the representation of the control region of the CHB and secondly a geometrical determination of the switching sequence.

TABLE I
Gate driver signals depending on the H-bridge $i$ state

| H-bridge $i$ voltage $V_i$ | H-bridge $i$ state $H_i$ | Gate driver signals |
|---|---|---|
| $-V_{Ci}$ | 0 | $S_{i1}$=1 and $S_{i2}$=0 |
| 0 | 1 | $S_{i1}$=0 and $S_{i2}$=0 |
| 0 | 1 | $S_{i1}$=1 and $S_{i2}$=1 |
| $V_{Ci}$ | 2 | $S_{i1}$=0 and $S_{i2}$=1 |

### A. Control Region of the Cascaded H-bridge Converter

In order to consider all the possible values of the output voltage of H-bridge $i$ ($V_i$ with $i$ =1,...,$m$) to achieve $V_{ab}^*$ in a $m$-cell CHB, a $m$-dimensional orthogonal control region can be defined where each axis is devoted to represent the output voltage of each H-bridge. For instance, in the 2C-CHB case the control region is formed by two axes $V_1$ and $V_2$ as is represented in Fig. 2. The possible switching states of the converter are placed on the control region taking into account that it is assumed that $V_{C1}$=$V_{C2}$=$E$ volts. Each switching state of the 2C-CHB is named $H_1H_2$ where $H_1$ and $H_2$ are the states of the H-bridge 1 (upper cell) and the H-bridge 2 (lower cell) respectively.

Equation (2) can be graphically represented on the control region. In Fig. 2, it is shown a possible solution to generate $V_{ab}^*$ defining voltages $\delta_1$ and $\delta_2$. In addition, several examples of this concept are also shown in Fig. 2, where $V_{ab}^*$=$-1.2E$, $V_{ab}^*$=0.8$E$ and $V_{ab}^*$=1.7$E$. As a consequence of (2), the slope of the solutions set to generate a specific $V_{ab}^*$ is always 135º in the 2C-CHB. All those combinations of $\delta_1$ and $\delta_2$ over a single 135° line have the same output phase voltage, hence leading to redundant switching combinations. An example to see this fact would be $\delta_1$=$E$ and $\delta_2$=0 corresponding to the switching state 21 and the combination $\delta_1$=0 and $\delta_2$=$E$ corresponding to switching state 12 which are connected by a 135° line.

### *B. Proposed Modulation Technique for the CHB topology*

The main contribution of this paper is to introduce a generalized multi-dimensional modulation technique, called in this paper $m$D-PWM, taking into account all the possible solutions that can be achieved by the CHB. The proposed technique initially assumes that the dc voltages of the H-bridges of the 2C-CHB are equal ($V_{C1}$=$V_{C2}$=$E$). However, a feed-forward modification of the $m$D-PWM technique will also be presented in section III in order to operate with any dc voltage value in the power cells. Initially, the technique is introduced for a 2C-CHB topology but it will be extended for a higher number of power cells in section V.

As it is shown in Fig. 2, any point belonging to the solutions set can be used as the chosen point to achieve the desired phase voltage $V_{ab}^*$. Each possible solution can be defined using its $(x,y)$ components denoted as $(\delta_2,\delta_1)$. As the dc voltages of the CHB are equal to $E$ volts, the average output voltage of H-bridge $i$ ($\delta_i$) has to fulfil that

$$\delta_i \in [-E, E]. \quad (4)$$

Since there are infinite solutions to generate $V_{ab}^*$, one particular point of the infinite solutions set has to be selected. This challenge can be embraced as an opportunity to take advantage of this degree of freedom, selecting the solution according to some design criterion.

Considering that the point has been chosen and $\delta_1$ and $\delta_2$ are determined, the switching states and the switching times of the 2C-CHB can be easily calculated using Table II. The mathematical description to obtain expressions of Table II is introduced in the appendix A at the end of this paper. The switching sequence is formed by two different switching states in each H-bridge $i$ ($H_{i1}$ and $H_{i2}$). The corresponding switching times for the H-bridge states are defined as $t_{i1}$ and $t_{i2}$ respectively fulfilling

$$t_{i1} + t_{i2} = T_{sw}. \quad (5)$$

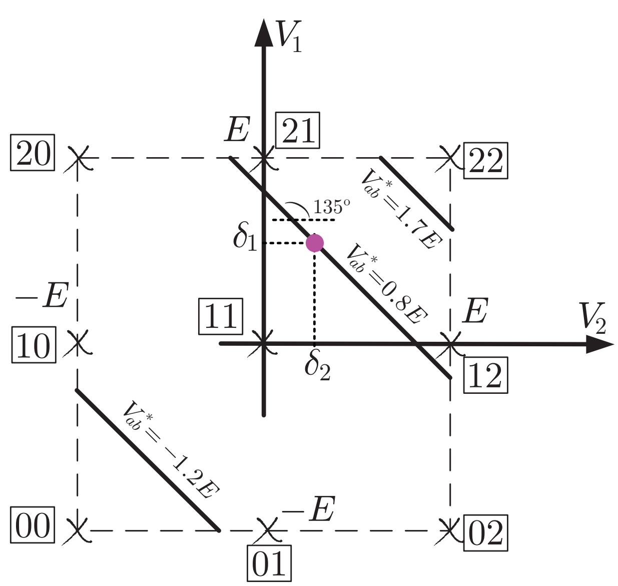


Fig. 2. Control region of a 2C-CHB with $V_{C1}$=$V_{C2}$=$E$. An example to generate $V_{ab}^*$ is considered using the voltages $\delta_1$ and $\delta_2$.

TABLE II
SWITCHING SEQUENCE AND SWITCHING TIMES CALCULATION OF THE PROPOSED $m$D-PWM TECHNIQUE

| $\delta_i$ | Switching Sequence | Switching Times |
|---|---|---|
| $>0$ | $H_{i1}$=1<br>$H_{i2}$=2 | $t_{i1} = \frac{E-\lvert\delta_i\rvert}{E}T_{sw}$ |
| $\leq 0$ | $H_{i1}$=1<br>$H_{i2}$=0 | $t_{i2} = \frac{\lvert\delta_i\rvert}{E}T_{sw}$ |

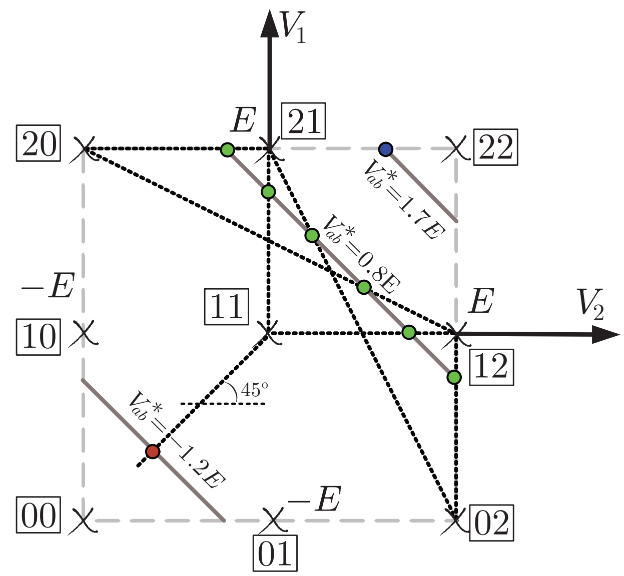


Fig. 3. Possible solutions using the unidimensional modulation technique to generate $V_{ab}^*$=0.8$E$, using PS-PWM to generate $V_{ab}^*$=−1.2$E$ and using LS-PWM to generate $V_{ab}^*$=1.7$E$

### *C. Particularizations of the $m$D-PWM Technique*

Each modulation technique present in the literature is based on the choosing of one specific solution in the control region used to generate $V_{ab}^*$. In order to show this fact, Fig. 3 is introduced where the points have been chosen according to several well-known modulation techniques.

The phase-shifted PWM (PS-PWM) technique achieves equal power distribution between the cells of the CHB [2]. In this way, if $V_{ab}^*$=−1.2$E$ is considered, the point on the control region used by the PS-PWM is that belonging the solutions set fulfilling that $\delta_1$=$\delta_2$=−0.6$E$. This makes that each cell provides the same average voltage to the output phase voltage. This example is represented in Fig. 3.

On the other hand, the level-shifted PWM (LS-PWM) can be also considered. In this case, the points to be used in the 2D control region are those fulfilling that

- The H-bridge 1 commutates when $|V_{ab}^*|$ is lower than $V_{C1}$ whilst H-bridge 2 generates zero volts. Therefore in this case, the points used by the LS-PWM technique are located in the vertical line $\delta_2$=0.
- The H-bridge 2 only commutates when $|V_{ab}^*|$ is greater than $V_{C1}$. In this case, the points used by the LS-PWM are located in the horizontal lines $\delta_1$=$-V_{C1}$ or $\delta_1$=$V_{C1}$ if

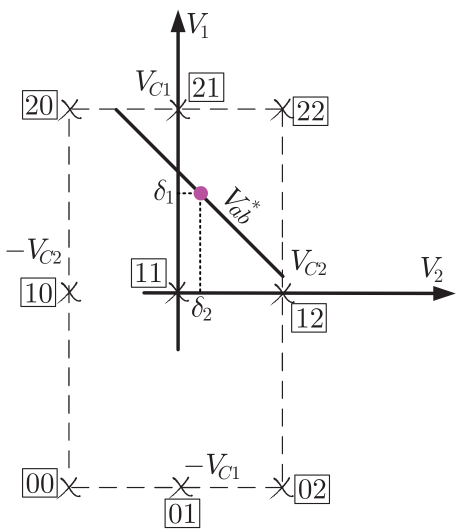


Fig. 4. 2D control region of the 2C-CHB with $V_{C1} > V_{C2}$. The control region changes with the actual dc voltages of the converter.

the sign of $V_{ab}^*$ is negative or positive respectively.

As an example, if $V_{ab}^*$=1.7$E$, the H-bridge 1 has to provide $E$ volts and H-bridge 2 has to provide $0.7E$ volts to the output. Therefore, $\delta_1$=$E$ and $\delta_2$=$0.7E$. This example is represented in Fig. 3.

Finally, the unidimensional modulation technique [33] is also considered. In this case, several switching sequences can be used depending on the switching redundancy of the 2C-CHB with equal dc voltages. For instance, if $V_{ab}^*$=0.8$E$, switching sequences 20-21, 21-11, 21-02, 20-12, 11-12 or 12-02 can be used. Therefore, six points on the control region can be chosen by the unidimensional modulation technique to generate $V_{ab}^*$. This example is represented in Fig. 3.

## III. Feed-forward Version of the $m$D-PWM Technique

All the previous calculations are only valid if the dc voltages of the 2C-CHB are balanced ($V_{C1}$=$V_{C2}$=$E$). In case of unbalanced dc voltages, the control region changes and the $m$D-PWM technique generates a distorted phase voltage as happens with all traditional PWM methods when the dc-link voltages are not fixed. The actual values of dc voltages $V_{C1}$ and $V_{C2}$ have to be used to determine the 2D control region in the case of unbalanced dc voltages. This is the basic concept of the feed-forward modulation techniques [34]–[36].

Considering the actual dc voltages, the 2D control region is limited by $V_{C1}$ and $V_{C2}$. In this case, it has to be fulfilled that

$$\delta_i \in [-V_{Ci}, V_{Ci}]. \quad (6)$$

As an example, the control region when $V_{C1}$>$V_{C2}$ is represented in Fig. 4. As in Fig. 2, a possible desired phase voltage $V_{ab}^*$ is represented. A new feed-forward generalized multi-dimensional modulation method (feed-forward $m$D-PWM) is proposed taking into account the actual dc voltages of the 2C-CHB. Using this technique the desired phase voltage

TABLE III
Switching Sequence and Switching Times calculation of the proposed feed-forward $m$D-PWM technique

| $\delta_i$ | Switching Sequence | Switching Times |
|---|---|---|
| $> 0$ | $H_{i1}$=1<br>$H_{i2}$=2 | $t_{i1} = \frac{V_{Ci}-\|\delta_i\|}{V_{Ci}} T_{sw}$ |
| $\leq 0$ | $H_{i1}$=1<br>$H_{i2}$=0 | $t_{i2} = \frac{\|\delta_i\|}{V_{Ci}} T_{sw}$ |

$V_{ab}^*$ obtained by the external controller is generated taking into account the actual dc voltages and avoiding errors in the switching sequence determination. The necessary calculations of the proposed feed-forward $m$D-PWM technique to determine the switching sequence and the corresponding switching times are summarized in Table III. The mathematical description to obtain expressions of Table III is introduced in the appendix A at the end of this paper. In addition, a discussion about how to select the redundant switching states is addressed in the appendix B at the end of this paper as well.

It is important to notice that the proposed feed-forward $m$D-PWM technique is a generalization of the $m$D-PWM method because the feed-forward $m$D-PWM technique can be used in balanced or unbalanced dc voltage conditions. Moreover, the modulation strategy complexity of the feed-forward $m$D-PWM technique is equal to the $m$D-PWM technique complexity, which is very low.

## IV. Results of the Proposed feed-forward $m$D-PWM Technique for the 2C-CHB

The proposed feed-forward $m$D-PWM technique has been experimentally tested using the 5 kVA prototype of the 2C-CHB connected to a RL load (R=20Ω, L=15mH). In this prototype, as is represented in Fig. 1, the dc voltages are charged from the grid using a transformer with configurable secondaries for each cell. In this way, the dc voltage of the H-bridges can be charged to different voltage levels. The switching frequency is equal to 2 kHz. A pure 50 Hz sinusoidal waveform is the reference phase voltage with modulation index equal to 0.9.

As commented above, the PS-PWM makes that both cells generate the same output voltage average over a switching period achieving an average equal power sharing between the cells. In Fig. 5, the 2C-CHB with balanced dc voltages is tested using the points located in the diagonal of the 2D control region as the solutions to achieve the reference phase voltage $V_{ab}^*$. In this way, each cell provides the same average output voltage to the output. In addition, as in the conventional PS-PWM, there is a multiplicative effect on the switching frequency of the phase voltage ($m$ times the switching frequency of an H-bridge for a $m$-cell CHB converter).

On the other hand, the LS-PWM is also considered with balanced dc voltages and the result is depicted in Fig. 6. As expected, the H-bridge 1 only commutates when $|V_{ab}^*|$ is lower than $V_{C1}$ (100V in the experiment). Besides, H-bridge 2 only commutates when $|V_{ab}^*|$ is greater than $V_{C1}$.

Finally, in order to show the flexibility of the feed-forward $m$D-PWM method, a CHB with unequal dc sources (also known as asymmetrical CHB [37]) using a 2:1 ratio between the dc sources is analyzed. A well-known modulation technique for asymmetrical CHB is the hybrid modulation [38]. This modulation method determines the switching of the CHB providing a fundamental switching frequency for the high voltage power cell (H-bridge 1), while traditional PWM is used for the low voltage power cell (H-bridge 2) increasing the efficiency. Fig. 7 shows the control region of the 2C-CHB with $V_{C1}$=2$V_{C2}$=2$E$. A subspace containing only those combinations corresponding to the hybrid modulation is depicted by a zigzag line. The experimental result using this subspace is shown in Fig. 8. It can be seen that the switching frequency of the high voltage cell is minimized while the low voltage cell has a high switching frequency (2 kHz).

The average device switching frequency of the experimental results shown in the paper is equal to 1 kHz. Since its unipolar PWM, the effective frequency of the output of each cell is equal to 2 kHz and by the shift between the two-cell converter, the apparent switching of the complete CHB is 4 kHz. This fact can be observed in Fig. 5 since it is equivalent to PS-PWM. On the other hand, in Fig. 6 the device switches actually at 2 kHz but during a reduced time, hence the average is still 1 kHz, this is because this is similar to LS-PWM. The average switching frequency of 1 kHz is acceptable, but in practice with 3 cells or 6 cells in series it can be further reduced to easily 450 Hz. This analysis does not apply to Fig. 8, since this an asymmetric topology and here the high power cell has fundamental average switching frequency (very low) while the small power cell switches at 2 kHz average per device (with an apparent total output with 4 kHz due to the unipolar PWM). The proposed 2D-PWM technique can be applied with any switching frequency. Therefore, it can be applied to the same high-power high-voltage applications where conventional PWM techniques can be applied. If an extremely reduced switching frequency is required, other techniques such as the selective harmonic elimination technique should be used.

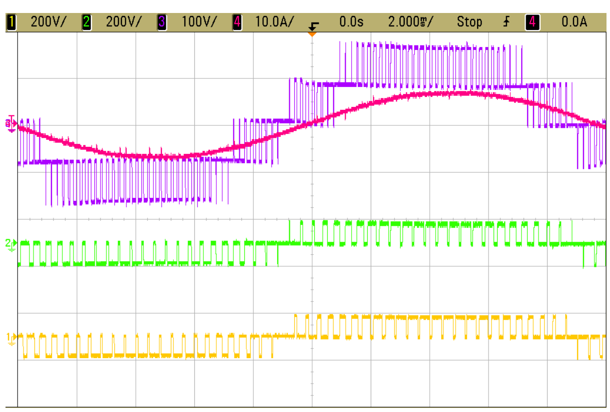


Fig. 5. Results of the proposed feed-forward $m$D-PWM technique achieving equal power distribution between the H-bridges of the 2C-CHB. From top to bottom: phase voltage $V_{ab}$ (100V/div) and phase current (10A/div), output voltage of upper H-bridge $V_1$ (200V/div), output voltage of lower H-bridge $V_2$ (200V/div).

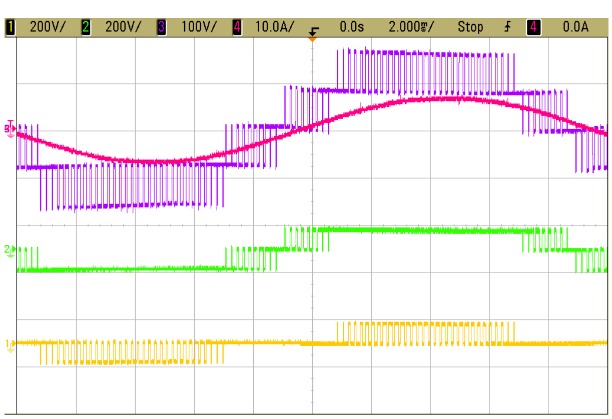


Fig. 6. Results of the feed-forward $m$D-PWM technique for the 2C-CHB working as a level-shifted PWM technique. From top to bottom: phase voltage $V_{ab}$ (100V/div) and phase current (10A/div), output voltage of upper H-bridge $V_1$ (200V/div), output voltage of lower H-bridge $V_2$ (200V/div).

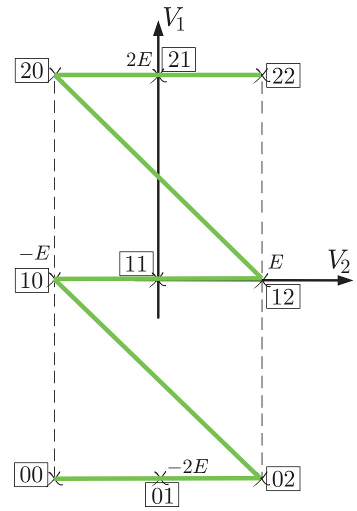


Fig. 7. Hybrid modulation solution in the 2D control region to generate $V_{ab}^*$ with dc voltage ratio equal to 2:1 in the 2C-CHB.

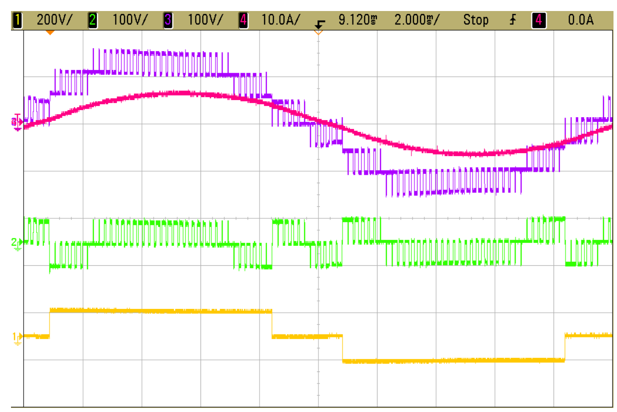


Fig. 8. Results of the feed-forward $m$D-PWM technique for the 2C-CHB working as a hybrid PWM technique. From top to bottom: phase voltage $V_{ab}$ (100V/div) and phase current (10A/div), output voltage of lower H-bridge $V_2$ (100V/div) and output voltage of upper H-bridge $V_1$ (200V/div).

## V. EXTENSION OF THE FEED-FORWARD $m$D-PWM TECHNIQUE FOR CHB WITH MORE THAN TWO CELLS

The feed-forward $m$D-PWM technique can be extended for CHB with more than two cells. In order to carry out this extension, an axis has to be devoted to represent the output voltage of each H-bridge in the control region. When the three-cell CHB (3C-CHB) is considered, the control region is a prism centered in the origin of coordinates with size $2V_{C1}\times2V_{C2}\times2V_{C3}$ (a cube if equal dc sources are used). This concept is illustrated in Fig. 9 assuming that $V_{C1}$=$V_{C2}$=$V_{C3}$ to simplify the representation. In the three-cell case, instead of having lines with 135° here the solutions set to obtain a desired phase voltage $V_{ab}^*$ are in planes which are orthogonal to vector (1,1,1) fulfilling

$$V_{ab} = \delta_1 + \delta_2 + \delta_3. \tag{7}$$

Once $\delta_1$, $\delta_2$ and $\delta_3$ are determined in order to improve some feature of the CHB, Table III can be directly applied to each H-bridge in order to determine the switching sequence and the switching times.

If the number of power cells of the CHB increases, equation (7) can be extended fulfilling

$$V_{ab} = \sum_{i=1}^{m} \delta_i, \tag{8}$$

for a $m$-cell CHB and the graphical representation is lost but the concept remains valid. It can be noticed that while the number of cells of the CHB increases, the possible solutions to obtain an specific $V_{ab}^*$ also increases and more degrees of freedom appear in order to determine the point ($\delta_m$,...,$\delta_1$) to be used.

## VI. CONCLUSIONS

In this paper, a generalized modulation method called $m$D-PWM and based on a multi-dimensional control region for the $m$-cell cascaded H-bridge converter has been introduced. In each axis of this control region is represented the output voltage of each H-bridge $V_i$. Infinite solutions can be used in order to generate the desired phase voltage reference $V_{ab}^*$ as a linear combination of the possible switching states of the converter.

Using voltages $\delta_i$, the switching sequence and the switching times are easily calculated. The $m$D-PWM technique only implies very simple calculations and the computational cost is very low. Moreover, the feed-forward version of the $m$D-PWM technique has been also introduced in order to operate with any value of the dc voltages of the CHB. This fact avoids possible distortion in the output voltage and current when the dc voltages of the CHB are not balanced. It has to be noticed that the addition of the feed-forward concept does not increase the computational cost of the modulation technique.

The potential use of the multi-dimensional control region has been shown particularizing for a two-cell CHB (2C-CHB). In fact, it has been shown that all the modulation techniques are particularizations which can be plotted in the control region. As infinite solutions can be used to carry out the modulation, different optimization criteria can be used in order to choose the final point of the multiple solutions set (defined by voltages $\delta_i$) in order to improve some feature of the power converter operation. As an example of the use of the multiple solutions, some conventional modulation techniques such as the PS-PWM and the LS-PWM have been tested. Besides, the feed-forward $m$D-PWM technique has been tested emulating other modulation techniques such as the hybrid modulation (to reduce the switching losses of the high voltage cell).

The feed-forward $m$D-PWM technique has been extended to be applied to CHB with any number of H-bridges. In addition, it is important to notice that the proposed idea can be applied to power converters formed by the series connection of power cells with any topology (not only H-bridges).

## VII. APPENDIX A: MATHEMATICAL DERIVATION OF THE $m$D-PWM MODULATION METHOD

Depending on the sign of the voltage $\delta_i$, two different cases appear:

1) $\delta_i \geq 0$: If $\delta_i$ is equal to zero, then state 1 has to be applied the complete switching period $T_{sw}$. If $\delta_i$ is equal to the dc voltage of the H-bridge $i$ ($\delta_i$=$V_{Ci}$), then state 2 has to be applied the complete switching period $T_{sw}$. For other values, the switching time of state 1 is equal to $T_{sw}(V_{Ci} - \delta_i)/V_{Ci}$ and the switching time of state 2 is equal to $T_{sw}\delta_i/V_{Ci}$.
2) $\delta_i \leq 0$: If $\delta_i$ is equal to zero, then state 1 has to be applied the complete switching period $T_{sw}$. If $\delta_i$ is equal to minus the dc voltage of the H-bridge $i$ ($\delta_i$=$-V_{Ci}$), then state 0 has to be applied the complete switching period $T_{sw}$. For other values, the switching time of state 1 is equal to $T_{sw}(V_{Ci} + \delta_i)/V_{Ci}$ and the switching time of state 2 is equal to $-T_{sw}\delta_i/V_{Ci}$.

Both cases can be reduced to only one where the switching time of state 1 is equal to $T_{sw}(V_{Ci}-|\delta_i|)/V_{Ci}$ and the other switching time (state 2 or 0) is equal to $T_{sw}|\delta_i|/V_{Ci}$. These calculations are summarized in Table III. Data from Table II are a particular case of these expressions assuming the dc voltage balanced case $V_{C1}$=$V_{C2}$=$E$.

## VIII. APPENDIX B: ABOUT THE SELECTION OF THE REDUNDANT SWITCHING STATES

In order to introduce the criteria to select the redundant switching states, it can be considered the following example. Consider that the two-cell CHB dc voltage values are equal to $V_{C1}$=50V and $V_{C2}$=50V. In the example, an external controller has determined that the output voltage of the converter has to be equal to 70V and $\delta_1$=45V and $\delta_2$=25V. The switching sequence determined by the 2D-PWM is equal to:

- Cell 1:

$$\begin{aligned} &\text{Switching sequence} := 1 - 2, \\ &\text{Dwelling times} := t_1 = T_{sw}\frac{50-45}{50} = 0.1T_{sw}, \\ &\qquad t_2 = T_{sw}\frac{45}{50} = 0.9T_{sw} \end{aligned} \tag{9}$$

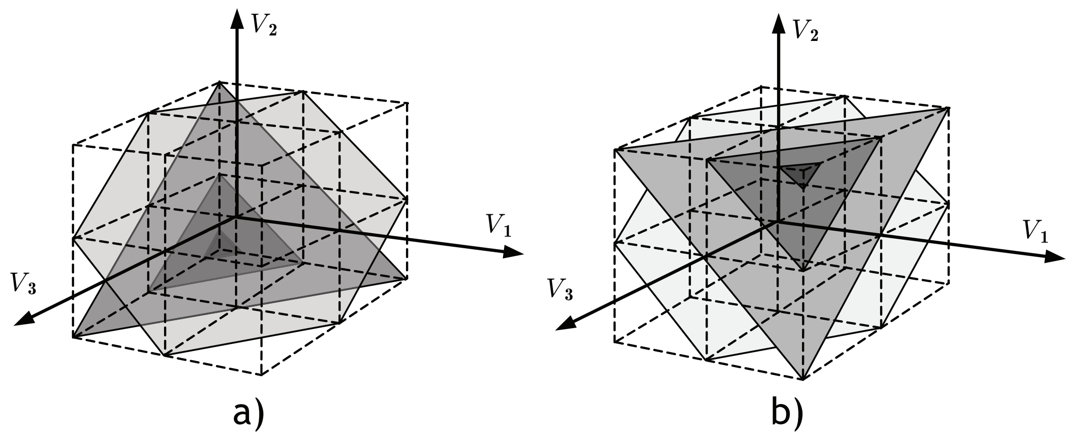


Fig. 9. Control region of a three-cell CHB when $V_{C1}$=$V_{C2}$=$V_{C3}$. The multiple solutions to generate each desired phase voltage $V_{ab}^*$ form planes orthogonal to vector (1,1,1). a) Solutions when $V_{ab}^*$ is negative b) Solutions when $V_{ab}^*$ is positive

- Cell 2:

$$\begin{aligned} &\text{Switching sequence} := 1-2, \\ &\text{Dwelling times} := t_1 = T_{sw}\frac{50-25}{50} = 0.5T_{sw}, \\ &\qquad t_2 = T_{sw}\frac{25}{50} = 0.5T_{sw} \end{aligned} \tag{10}$$

Considering the complete CHB with the obtained results, the final switching sequence of the two-cell CHB is equal to 11-21-22 and the corresponding switching times are $0.1T_{sw}$, $0.4T_{sw}$ and $0.5T_{sw}$ respectively.

Consider as a second example that the two-cell CHB dc voltage values are equal to $V_{C1}$=50V and $V_{C2}$=50V. In the example, an external controller has determined that the output voltage of the converter has to be equal to 70V and $\delta_1$=25V and $\delta_2$=45V. The switching sequence determined by the 2D-PWM is equal to:

- Cell 1:

$$\begin{aligned} &\text{Switching sequence} := 1-2, \\ &\text{Dwelling times} := t_1 = T_{sw}\frac{50-25}{50} = 0.5T_{sw}, \\ &\qquad t_2 = T_{sw}\frac{25}{50} = 0.5T_{sw} \end{aligned} \tag{11}$$

- Cell 2:

$$\begin{aligned} &\text{Switching sequence} := 1-2, \\ &\text{Dwelling times} := t_1 = T_{sw}\frac{50-45}{50} = 0.1T_{sw}, \\ &\qquad t_2 = T_{sw}\frac{45}{50} = 0.9T_{sw} \end{aligned} \tag{12}$$

The final switching sequence of the two-cell CHB is equal to 11-12-22 and the corresponding switching times are $0.1T_{sw}$, $0.4T_{sw}$ and $0.5T_{sw}$ respectively.

As can be observed from the previous examples, the switching sequence and the dwelling times are determined and a maximum of one switching per cell is needed to carry out the switching sequence. Both examples obtain very similar switching sequences. Only the middle switching state is different (state 21 or 12 in examples 1 and 2 respectively). The switching states 21 and 12 are redundant because both states generate the same voltage in the balanced dc voltage case ($V_{C1}$=$V_{C2}$). From the example, it can be observed that both states are not used in the same switching sequence. The use of the state 21 or 12 is imposed by the election of the values of $\delta_1$ and $\delta_2$. So, the determination of the value of $\delta_1$ and $\delta_2$ (calculated by an external controller or a simple selection criterion) directly imposes the switching states to be used in the switching sequence.

As an example of this fact, the switching losses minimization can be included as the optimization criterion in order to determine the $\delta_i$ values. In fact, the hybrid modulation shown in Fig. 8 is developed minimizing the switching of the high voltage H-bridge. Applying this optimization, the high voltage cell only commutates when is needed. In this way, an extremely low switching frequency is achieved in the high voltage cell as can be observed in Fig. 8 (upper H-bridge waveform).

## ACKNOWLEDGMENT


The authors gratefully acknowledge financial support provided by the Chilean National Fund of Scientific and Technological Development (FONDECYT), under grant number 1080582, and by the Universidad Tecnica Federico Santa Maria. In addition, this work has been supported by the Jose Castillejo Spanish Program and the Spanish Science and Education Ministry under Project TEC2007-61879.


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