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

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ABSTRACT:

Multilevel converters have received increased interest recently as a result of their ability to generate high quality output waveforms with a low switching frequency. This makes them very attractive for high power applications. A Cascaded HBridge converter is a multilevel topology which is formed from the series connection of H-Bridge cells. Optimized pulse width modulation techniques such as Selective Harmonic Elimination (SHE-PWM) or Selective Harmonic Mitigation (SHM-PWM) are capable of pre-programming the harmonic profile of the output waveform over a range of modulation indices. Such modulation methods may however not perform optimally if the DC links of the Cascaded H-Bridge Converter are not balanced. This paper presents a new SHM-PWM control strategy which is capable of meeting grid codes even under non-equal DC link voltages. The method is based on the interpolation of different sets of angles obtained for specific situations of imbalance. Both simulation and experimental results are presented to validate the proposed control method.

INTRODUCTION:

Multilevel converters have become the focus of research in recent years as a result of their suitability for high power applications. Amongst the available topologies are the Neutral Point Clamped (NPC), Flying Capacitor (FC) and Cascaded H-Bridge converters (CHB). The latter is constructed from a series cascade of three-level H-bridges.

This connection enables the converter to produce high quality, high voltage waveforms whilst utilizing low or medium voltage switching devices. This functionality makes this converter an attractive option for grid connected applications such as Uninterruptible Power Supplies, Static VAR compensators, Series and Shunt Compensators etc. The use of power electronic converters at high power levels usually demands a reduction in switching frequency in order to ensure 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 (THDM) and Selective Harmonic Mitigation (SHM-PWM) methods are known to produce waveforms with low switching frequency without compromising waveform quality.

For these methods, mathematical functions can be derived using the Fourier analysis of a general switched converter waveform which may be solved to meet a certain pre-defined objective in the waveform. The waveform objectives may include complete elimination (SHE-PWM) or reduction (SHM-PWM) of certain harmonics in the generated waveform or an optimization of this waveform in order for it to meet a particular harmonic code for a certain application. The derived functions, which are transcendental and nonlinear in nature, can be solved for a range of modulation indices using a variety of methods. The solutions can be stored in lookup tables for use with an appropriate converter control scheme.

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For CHB based inverter applications it may be desirable to ensure that each cell of the converter draws equal energy from the DC source that it is connected to. 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 where the DC sources are not exactly equal, distortion may be present in the converter waveform. This occurs because the switching angles for the modulation may have been derived assuming that the DC sources were equal and therefore complete harmonic elimination or the required level of harmonic suppression no longer occurs. It was found that a large number of different waveform solutions are required in order to manipulate the power flow through a CHB converter whilst achieving optimal harmonic performance.

This large number of solutions can be avoided by decoupling the cells and independently controlling the modulation index of each cell separately. Unfortunately, this reduction in the number of required lookup tables potentially reduces the waveform quality of the CHB converter as the degrees of freedom available in the multilevel converter waveform are not fully utilized. This paper presents a SHM-PWM technique based on multilevel waveforms which enables the required control of power flow in a CHB converter whilst fully utilizing the waveform degrees of freedom. The method uses the interpolation of

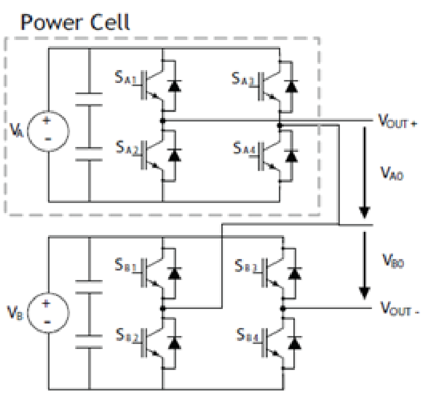

Fig. 1. Five-level cascaded H-bridge converter based on the series connection of two three-level power cells.

Lookup table based solutions for a number of imbalances to control the power flow through the H-Bridges asymmetrically, thus avoiding the requirement of very large lookup tables apparent in previous methods. Theoretical and simulated results are experimentally verified using a five level Cascaded H-Bridge topology operating as an inverter.

Cascaded H-Bridge Converters:

Several three-level power cells, formed using full H-bridges, can be series connected to build a converter with a higher number of levels as can be observed from Fig. 1. This can be extended to produce converters with as many levels as required for a particular application. In general, if n power cells are connected in series to build the converter and all the cells have the same DC voltage, the number of levels that can be achieved 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. If different DC voltages are used, as is the case in an asymmetric CHB converter, the number of levels can be increased. For example, using two cells, up to nine levels may be achieved in the output waveform. This topology is presented in Fig. 1 where VA is the DC voltage of the upper cell and VB represents the voltage of the lower cell. However, this increase in voltage levels is achieved at a cost of reduced converter structure modularity.

A. The problem of imbalance

Each cell of a CHB converter must be fed from an isolated DC source to avoid short circuits. Divergences of the DC link voltages from the desired or assumed values will have an effect on the operation of the converter. If the converter is designed to operate with balanced DC link voltages and this is not the case then the converter is said to be operating under non-equal DC link voltages. Such operation may have an undesirable effect on the output voltage waveform of the converter. This is especially the case when pre-computed modulation strategies such as SHE-PWM or SHM-PWM are used as the angles may have been

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derived under the assumption that the DC link voltages are balanced. The SHE-PWM methods require special considerations when used in multilevel converters with non-equal DC link voltages. In many applications it is desirable to share the power flow amongst all the cells equally in order to avoid overheating of some specific switching devices and consequently extend the lifetime of all the elements of the converter. Other, more complicated, CHB based converter structures may require the power flow to be controlled asymmetrically through the converter cells as was required in. In both cases, assuming that the current is undistorted, the power flow from each cell of the converter can be determined by considering the fundamental frequency component of each cell only. It is possible to manipulate SHE-PWM and SHM-PWM techniques to control the power flow through a CHB converter as was shown.

The method considered the use of a low switching frequency SHE-PWM to control power flow through the cells of a CHB converter whilst still producing high quality waveforms. Unfortunately, a disadvantage of the approach presented is that a specific set of angles must be calculated for each possible imbalance scenario for the converter and therefore a very large number of lookup tables and a complicated lookup table 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 lookup tables.

SHM-PWM PRINCIPLE

A. Three-level converters

Fourier analysis can be used to study a typical three-level waveform with k switching angles _i (i=0,...,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:

$$H_j = \frac{4}{j\pi}\sum_{i=0}^{k-1}\left[(-1)^i \sin(j\alpha_i)\right] \quad (1)$$

This expression can be used to set a specific value for each harmonic amplitude using the switching angles as degrees of freedom. The well known SHE-PWM technique is based on this theory i.e. the switching angles are used to set the amplitude of the fundamental harmonic and cancel a set of specific harmonics. 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_/4Vdc. 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 canceled using k switching angles. In balanced three-phase topologies without a neutral connection, the triplen harmonics are also canceled and so it is possible to eliminate a very high number of the low order harmonics with a low switching frequency.

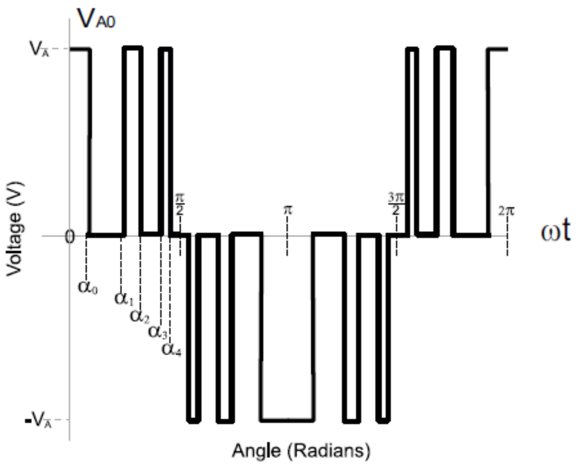

Fig. 2. Three-level pre-programmed PWM switching pattern with five switching angles (_0,_1,_2,_3,_4). Typical output waveform of the top power cell represented in Fig.1

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 canceled:

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$$H_1 = \frac{4}{\pi}\sum_{i=0}^{k-1}\left[(-1)^i \sin(\alpha_i)\right]$$
$$0 = \frac{4}{j\pi}\sum_{i=0}^{k-1}\left[(-1)^i \sin(j\alpha_i)\right],$$
$$\text{where } j = 3, 5, 7, 9, 11, \ldots, q. \qquad (2)$$

The SHM-PWM technique was presented and is based on the idea 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 acceptable. 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 jth harmonic). The SHM-PWM technique can be formulated using a system of inequalities (3) which can be arranged into an objective function to be minimized using an optimization method as in 4.

$$\left|\frac{4M_aV_{dc}}{\pi} - H_1\right| \le L_1$$
$$\frac{1}{|H_1|}\frac{4}{j\pi}\sum_{i=0}^{k-1}\left[(-1)^i \sin(j\alpha_i)\right] \le L_j,$$
$$\text{where } j = 3, 5, 7, 9, 11, \ldots, 49. \qquad (3)$$

$$OF(\alpha_0, \ldots, \alpha_{k-1}) = \sum_{i=1,3,5,\ldots,49} c_i E_i^2 + c_{THD}THD. \quad (4)$$

The extra flexibility given by the SHM-PWM principle can be used for different objectives, for example reducing the

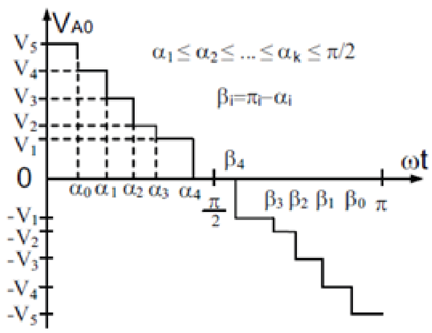

Fig. 3. Nine-level pre-programmed PWM switching pattern with tenswitching angles (_i, i=0; : : :,9). The waveform is symmetrical in order to eliminate the even harmonics.

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 _i (i=0,...,k □ 1) the Fourier analysis gives:

$$H_j = \frac{4}{j\pi}\left(V_1 \sin(\alpha_0) + \sum_{i=1}^{k-1}\left[V_i[\sin(j\alpha_i) - \sin(j\alpha_{i-1})]\right]\right) \qquad (5)$$

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 guarantee that all the cells are sharing the same power this system of equations needs to be modified. 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 canceled. The new system of equations can be formed with (6) and (7) considering that in (7) it is assumed that the angles of all the cells are rearranged to generate the suitable multilevel global waveform.

$$H_1 = \frac{4}{\pi}\sum_{i=0}^{k-1}\left[(-1)^i \sin(\alpha_{i-Cell-n})\right],$$
$$\text{where } n = 1, 2, \ldots, N \qquad (6)$$

$$0 = \frac{4}{j\pi}\left(V_1 \sin(\alpha_0) + \sum_{i=1}^{k-1}\left[V_i[\sin(j\alpha_i) - \sin(j\alpha_{i-1})]\right]\right),$$
$$\text{where } j = 3, 5, 7, 9, 11, \ldots, q. \qquad (7)$$

The SHM-PWM technique can also be applied to converters with more than three levels Using the SHM-PWM principle, based on reducing the harmonic amplitudes to a reduced but non-zero value, the system of equations changes to the system of inequalities detailed in (8) and (9).

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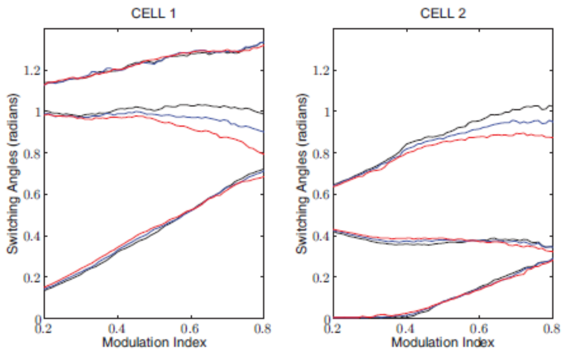
Again, in (9), it is assumed that the angles of all the cells are used to generate a global waveform as in Fig. 3. The whole system of equations can be grouped in the same objective function (4) shown in section III-A.

$$|\frac{4V_{dc}}{\pi} M_{a-Cell-n} - H_1| \leq L_1,$$
$$\text{where } n = 1, 2, \ldots, N \qquad (8)$$

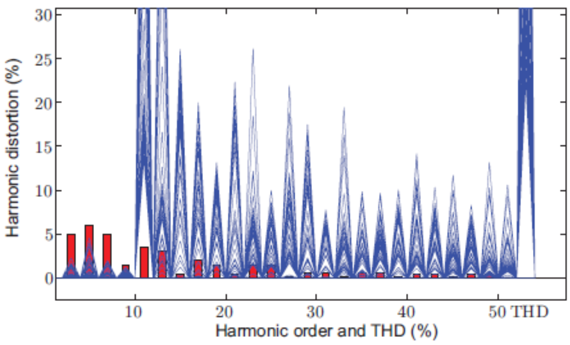
$$|H_j| \leq L_j,$$
$$\text{where } j = 3, 5, 7, 9, 11, \ldots, 49. \qquad (9)$$

RESULTS:

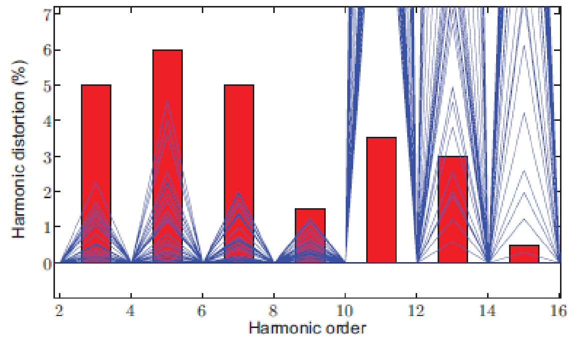
SHM-PWM switching angles for the case of two cells and three angles per cell in the Ma range from 0.20 to 0.80 for a balanced situation (black), an imbalance of 5% (blue) and an imbalance of 10% (red).



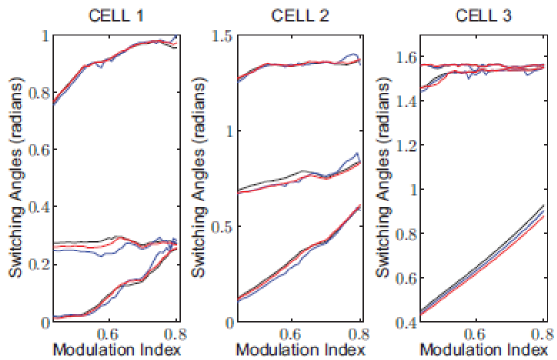
Global Harmonic content and THD (on the right) generated by the converter for each modulation index value for a (-3,3) imbalance and 0:20 < Ma < 0:80.



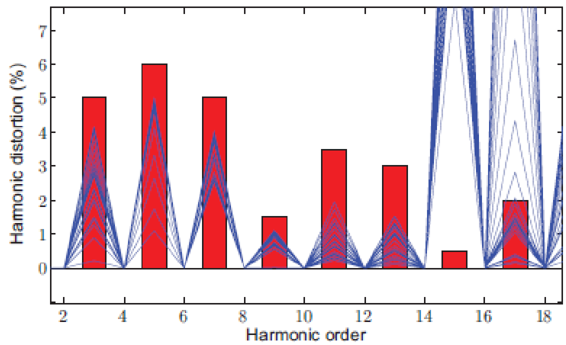
Detail of the low order harmonic amplitudes generated by the converter for each value of the modulation index for a (-3,3) imbalance and 0:20 < Ma < 0:80.



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.



Output spectrum for an imbalance of (-1.2,1,1.5) and 0:44 < Ma < 0:80.



Output spectrum for an imbalance of (-2.5,1,3) and 0:44 < Ma < 0:80.

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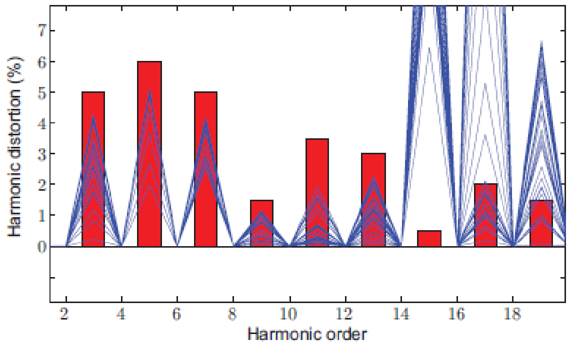

CONCLUSION:

This paper presents a new control strategy, based on the SHM-PWM technique that can tolerate different capacitor voltage levels for Cascaded H-Bridge Multilevel Converters. In comparison with other techniques, in this case it is possible to control the amplitude of each cell under balanced or nun balanced conditions with a reduced number of lookup tables whilst still producing very high quality waveforms at low switching frequency. An example of an application which may benefit from such a scheme is in a multilevel UPS. In this case the technique could be able to meet grid voltage standards even when the batteries are charged to different voltages. Different simulation results for two and three-cell converters have been included to show the viability of the technique. Experimental results supporting the method in a two-cell converter validating the technique for an imbalance range from 0% to 10% have been included.

REFERENCES:

[1] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L.G. Franquelo, B. Wu, J. Rodriguez, M.A. Perez, and J.I. Leon. Recent advances and industrial applications of multilevel converters. Industrial Electronics, IEEE Transactions on, 57(8):2553–2580, 2010.

[2] J. Rodriguez, L. G. Franquelo, S. Kouro, J. I. Leon, R. C. Portillo, M. A. M. Prats, and M. A. Perez. Multilevel converters: An enabling technology for high-power applications. Proceedings of the IEEE, 97(11):1786–1817, November 2009.

[3] H. Akagi, S. Inoue, and T. Yoshii. Control and performance of a transformerless cascade PWM STATCOM with star configuration. IEEE Transactions on Industry Applications, 43(4):1041–1049, July/August 2007.

[4] E. Villanueva, P. Correa, J. Rodriguez, and M. Pacas. Control of a single-phase cascaded h-bridge multilevel inverter for grid-connected photovoltaic systems. IEEE Transactions on Industrial Electronics, 56(11), November 2009.

[5] P. Cortes, A. Wilson, S. Kouro, J. Rodriguez, and H. Abu-Rub. Model predictive control of multilevel cascaded h-bridge inverters. Industrial Electronics, IEEE Transactions on, 57(8):2691–2699, 2010.

[6] S. Vazquez, J.I. Leon, J.M. Carrasco, L.G. Franquelo, E. Galvan, M. Reyes, J.A. Sanchez, and E. Dominguez. Analysis of the power balance in the cells of a multilevel cascaded h-bridge converter. Industrial Electronics, IEEE Transactions on, 57(7):2287–2296, 2010.

[7] J.I. Leon, S. Kouro, S. Vazquez, R. Portillo, L.G. Franquelo, J.M. Carrasco, and J. Rodriguez. Multidimensional modulation technique for cascaded multilevel converters. Industrial Electronics, IEEE Transactions on, 58(2):412–420, 2011.

[8] F. Khoucha, S. M. Lagoun, K. Marouani, A. Kheloui, and M. El Hachemi Benbouzid. Hybrid cascaded h-bridge multilevel-inverter induction-motor-drive direct torque control for automotive applications. IEEE Transactions on Industrial Electronics, 57(3):892–899, March 2010.

[9] W. Song and A.Q. Huang. Fault-tolerant design and control strategy for cascaded h-bridge multilevel converter-based statcom. Industrial Electronics, IEEE Transactions on, 57(8):2700–2708, 2010.

[10] A.I. Bratcu, I. Munteanu, S. Bacha, D. Picault, and B. Raison. Cascaded dc–dc converter photovoltaic systems: Power optimization issues. Industrial Electronics, IEEE Transactions on, 58(2):403–411, 2011.

[11] Hasmukh S. Patel and Richard G. Hoft. Generalized techniques of harmonic elimination and voltage control in thyristor inverters: Part i harmonic elimination. IEEE Transactions on Industry Applications, 9(3):310–317, May 1973.

[12] Hasmukh S. Patel and Richard G. Hoft. Generalized techniques of harmonic elimination and voltage control in thyristor inverters: Part II voltage control techniques. IEEE Transactions on Industry Applications, 10(5):666–673, September 1974.

[13] L. G. Franquelo, J. Napoles, R. C. P. Guisado, J. I. Leon, and M. A. Aguirre. A flexible selective harmonic mitigation technique to meet grid codes in three-level PWM converters. IEEE Transactions on Industrial Electronics, 54(6):3022–3029, December 2007.

[14] A. Mehrizi-Sani and S. Filizadeh. An optimized space vector modulation sequence for improved harmonic performance. IEEE Transactions on Industrial Electronics, 56(8), August 2009.

[15] Na He, Dianguo Xu, and L. Huang. The application of particle swarm optimization to passive and hybrid active power filter design. IEEE Transactions on Industrial Electronics, 56(8):2841–2851, August 2009.