CASCADED H-BRIDGE CONVERTERS WITH NON EQUAL DC LINK VOLTAGE USING SELECTIVE HARMONIC MITIGATION TECHNIQUE

G. Mounika
M. Tech Scholar, Department of EEE
Vignana Bharathi Institute of Technology, Aushapur, Ghatkesar, Telangana, India.

G. Indira Rani
M. Tech Assistant Professor, Department of EEE
Vignana Bharathi Institute of Technology, Aushapur, Ghatkesar, Telangana, India

ABSTRACT-The emergence of multilevel converters has been in increase since the last decade. These new types of converters are suitable for high voltage and high power application due to their ability to synthesize waveforms with better harmonic profile. A cascaded H-bridge converter (CHB) 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 or selective harmonic mitigation (SHM-PWM) are capable of pre programming the harmonic profile of the output waveform. Such modulation methods may, however, not perform optimally if the dc links of the CHB are imbalanced. This paper presents Three-Cell Cascaded Converters a new SHM-PWM control strategy which is capable of meeting grid codes even under unequal dc link voltages. Simulation results are presented to validate the proposed control method.

Index Terms—MATLAB *Simulink,* Harmonic distortion, multilevel systems, pulse width modulation converters.

I.INTRODUCTION

MULTILEVEL converters have become the focus of research in recent years as a result of their suitability for high-power applications [1]. Amongst the available topologies are the neutral point clamped, flying capacitor, and cascaded H-bridge converters (CHB) [2]. The latter is constructed from a
Series cascade of H-bridges. This connection enables the converter to produce high quality, high voltage wave forms while 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 reactive volt ampere compensators, series and shunt compensators, etc. [3].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, and selective harmonic mitigation (SHM-PWM) methods are known to produce wave forms 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 predefined objective in the waveform. The waveform objectives may include complete elimination (SHE-PWM) or reduction (SHM-PWM) of certain harmonics in the generated waveform ran 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 (LUTs) for use with an appropriate converter control scheme.

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. In it was found that a large number of different waveform solutions are required in order to manipulate the power flow through a CHB converter while 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 LUTs potentially reduces the waveform quality of the CHB converter as the degrees of freedom available in the multilevel converter waveform are not fully utilized.
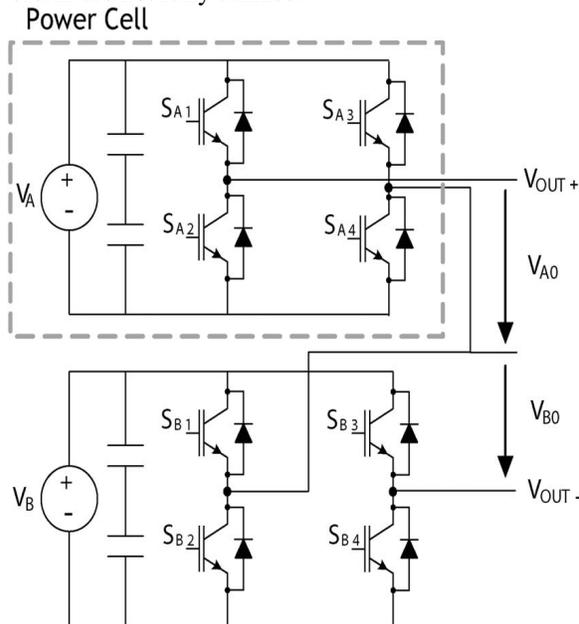

Fig. 1. Two cell cascaded H-bridge converter based on the series connection of two cell power cells.

This paper presents Three-Cell Cascaded Converters a new SHM-PWM control strategy which is capable of meeting grid codes even under unequal dc link voltages. The method is based on the interpolation of different sets of angles obtained for specific situations of imbalance. The proposed control method the interpolation of LUT based solutions for a number of imbalances to control the power flow through the H-bridges asymmetrically, thus avoiding the requirement of very large LUTs apparent in previous methods Simulation and results are presented to validate.

II. 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. 3. 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 non-equal 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 V_A is the dc voltage of the upper cell and V_B represents the voltage of the lower cell. However, this increase in voltage levels is achieved at a cost of reduced converter structure modularity.

A. 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 [6]. 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 equal dc link voltages. Such operation may have an undesirable effect on the output voltage waveform of the converter. This is particularly the case when pre-computed modulation strategies such as SHEPWM or SHM-PWM are used as the angles may have been derived under the assumption that the dc link voltages are balanced. The SHE-PWM methods require special considerations when used in multilevel converters with equal dc link voltages.

In many applications, it is desirable to share the power flow among 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 in. The method considered 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. Unfortunately, a disadvantage of the approach presented in 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 LUTs and a complicated 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.

IIIHARMONIC ELIMINATION THEORY

By applying Fourier series analysis, the output voltage can be obtained. Fourier series is an infinite sum of

trigonometric functions that are economically related.

$$f(t) = a_0 + \sum_{n=1}^{\infty} C_n \cos(2\pi n f_0 + \varphi_n) \quad (1)$$

n= integer multiple,

The output voltage equation derived for different voltage sources is given below.

$$v(t) = \sum_{n=1,3,5}^{\infty} \frac{4v_{dc}}{n\pi}\left((v_1 \cos(n\varphi_1) + v_2 \cos(n\varphi_1) \dots v_s \cos(n\varphi_2)) \sin(n\omega t)\right) \quad (2)$$

Where S = No. of dc sources connected per phase

V1, V2, V3 = level of Dc voltage = Switching angles

For the above Fundamental peak voltage v (t), it is required to determine the switching angles and some lower order harmonics of phase voltage are zero. Among no of switching angles one is used for fundamental voltage selection and remaining (s-1) switching angles are needed to eliminate lower order harmonics. For a balanced three phase system, triple n harmonics are eliminated automatically by using line-line voltages so only non-triple n odd harmonics are present.

To minimize harmonic distortion and to achieve adjustable amplitude of the fundamental component, up to *s*-1 harmonic contents can be removed from the voltage waveform. To keep the number of eliminated harmonics at a constant level, all switching angles must satisfy the condition otherwise the total harmonic distortion (THD) increases dramatically. In order to achieve a wide range of modulation indexes with minimized THD for the synthesized waveforms, a generalized selective harmonic modulation method is proposed, output waveform is shown in Figure 2.
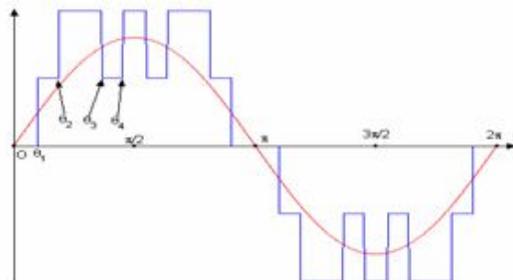

Fig. 2. Three-level pre-programmed PWM switching pattern with five switching angles

Hence the relation between the fundamental voltage and maximum voltage is given by modulation Index. It is given by m1, is the ratio of fundamental voltage v1 to the maximum voltage. The maximum voltage is given by

$$v_{1max} = \frac{4}{\pi} s V_{dc}$$

$$m = \frac{\pi v_1}{4 s V_{dc}} \quad (3)$$

For an 7- level inverter, there are 4 H-bridges per phase so, s=4 i.e., five degrees are available; one degree is used to control the magnitude of fundamental voltage and remaining degrees are used to eliminate 5th, 7th, 11th, and 13th order harmonic components. The above statements are given by

$$\cos(\theta_1) + \cos(\theta_2) + \cdots + \cos(\theta_s) = 4m_1$$

$$\cos(5\theta_1) + \cos(5\theta_2) + \cdots + \cos(5\theta_s) = 0$$

$$\cos(7\theta_1) + \cos(7\theta_2) + \cdots + \cos(7\theta_s) = 0$$

$$\cos(11\theta_1) + \cos(11\theta_2) + \cdots + \cos(11\theta_s) = 0$$

The above equation is a 4 transcendal equation known as Selective Harmonic Elimination. Here, , , , , are the unknown values.

VRESULTANTMETHODFORTRANSCENDENTAL EQUATIONS SOLVING USING RESULTANT THEORY

$$a(x_1, x_2) = a_3(x_1)x_2^3 + a_2(x_1)x_2^2 + a_1(x_1)x_2^1 + a_0(x_1) = 0 \quad (5)$$

$$b(x_1, x_2) = b_3(x_1)x_2^3 + b_2(x_1)x_2^2 + b_1(x_1)x_2^1 + b_0(x_1) = 0 \quad (6)$$

$$a(x_1, x_2) = a_2(x_1)x_2^2 + a_1(x_1)x_2^1 + a_0(x_1) \quad (7)$$

$$(x_1)x_2^2 + \beta_1(x_1)x_2^2 + \beta_0(x_1) \quad (8)$$

$$\begin{bmatrix} b_0 x_1 & a_0 x_1 & 0 & 0 & 0 & 0 \\ b_1 x_1 & a_1 x_1 & b_0 x_1 & a_0 x_1 & 0 & 0 \\ b_2 x_1 & a_2 x_1 & b_1 x_1 & a_1 x_1 & b_0 x_1 & a_0 x_1 \\ b_3 x_1 & a_3 x_1 & b_2 x_1 & a_2 x_1 & b_1 x_1 & a_1 x_1 \\ 0 & 0 & b_3 x_1 & a_3 x_1 & b_2 x_1 & a_2 x_1 \\ 0 & 0 & 0 & 0 & b_3 x_1 & a_3 x_1 \end{bmatrix} \begin{bmatrix} -a_0 x_1 \\ \beta_0 x_1 \\ -a_1 x_1 \\ \beta_1 x_1 \\ -a_2 x_1 \\ \beta_2 x_1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

IV. SHM-PWM FOR BALANCING

Under unbalanced conditions, it is necessary to use a strategy to adjust the modulation index in order to share the power among all the cells. In, a method was presented based on the SHE-PWM technique that could tolerate 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 since it does not consider the multilevel waveform of the converter during angle calculation, a lower number of harmonics can be eliminated compared with the use of global multilevel solutions.

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, for a given number of switching angles, the amplitude of the fundamental harmonic of each cell is set to the desired value and a certain number of extra harmonics of the global waveform are considered to meet the grid code requirements. In this paper, three switching angles have been considered for CHB converters with two and three cells. For the case of two different cells up to four extra harmonics can be considered. When three cells are used up to six extra harmonic components can meet the grid code requirements .Since the number of degrees of freedom is equal to the number of switching angles, in this case the extra flexibility given by The SHM-PWM method is used to find a new set of solutions for equal dc-link imbalance conditions close to the previous one. To obtain the specific switching angles for a certain dc-link imbalance situation, a linear interpolation is used among different pre-calculated LUTs in order to be able to tolerate any imbalance up to a maximum unbalancing range (previously defined and considered when formulating the mathematical equations).Considering a multi-cell 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: ($X1$, $X2$. No) 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 to lerable imbalance of 3%, two LUTs, $S1$ (0, 0) and$S2$ (-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 instance, the range could be extended to tolerate an imbalance of up to6% using $S3$ (-6, 6), or 9% using $S4$(-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:
$$\alpha(i) = A\alpha \text{LUT1}(i) + B\alpha \text{LUT2}(i).$$
This interpolation method is advantageous when compared to other methods considered in literature as it limits the number of required LUTs that are needed to achieve the wave forms 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 $B = 2/3$.

A. Extension to Three-Cell Cascaded Converters

For a three-cell converter, the imbalance may be shared among all of the cells in the converter. For this case, three LUTs are required as shown in (11), where X represents the percentage imbalance (referred to the average voltage), as previously noted

$$S_1 = (0,0,0), S_2 = (-\frac{2x}{3}, \frac{X}{3}, \frac{X}{3})$$
$$S_3 = (-\frac{X}{3}, -\frac{X}{3}, \frac{2X}{3},)$$

Care should be taken with the maximum imbalance which can be tolerated in this case as excessive values of X will inhibit the ability to linearly interpolate between LUTs (compared to low values of X).
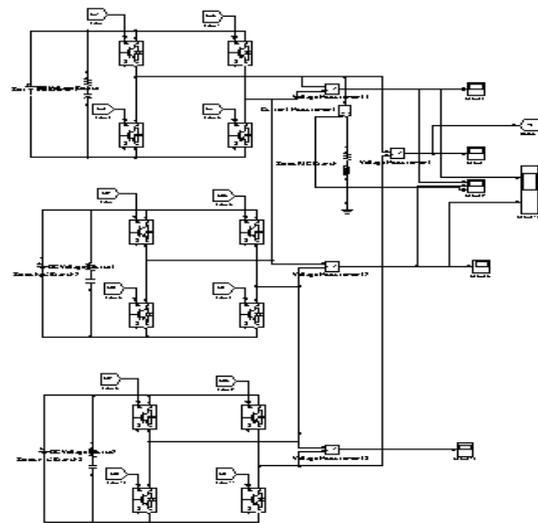

Fig.3.Three-Cell Converters-level cascaded H-bridge converter based on the series connection of two three-level power

The principle of the proposed method is based on exploiting the flexibility given by the SHM-PWM method to obtain a new set of solutions under different dc-link imbalance conditions but from a previous set of solutions in such a way that the switching angles are very similar. This leads with a very small variation form one table to the other allowing the use of linear interpolation between both tables to obtain all

the unbalancing conditions not directly stored in the LUTs. The Angles obtained from such similar sets of solutions should share the same characteristics in terms of power flow control and output spectrum.

We are assuming that the amplitude of each harmonic component corresponds to the linear interpolating of The corresponding amplitudes of each set of solutions (based on the linear property of the discrete Fourier transform). It should be noted that the linear system of equations can be solved offline and the solution computed by a DSP on demand.

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 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 margin of 0.01 radians
Between two consecutive switching angles has been taken into account as a valid safe margin. In the computing process the limits specified in the EN 50160 and 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. Shows the harmonic limits specified in these standards.
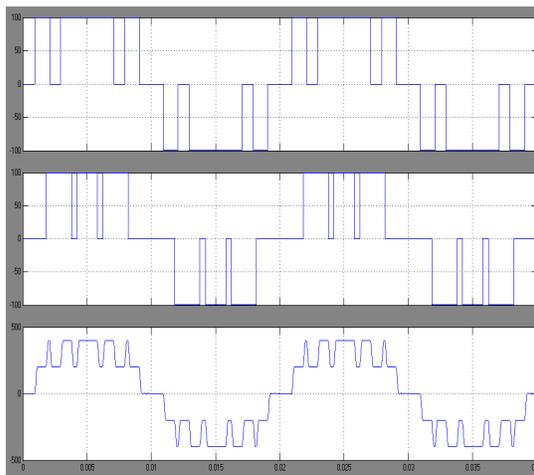

Fig. 4 Voltage of three cells and current(bottom) for an imbalance of 0%.The scales are 200 V/div, 0.5 A/div, and 5 ms/div.
and 0.20 <*Ma* <0.80 (more detailed in Fig. 6).All the values of the
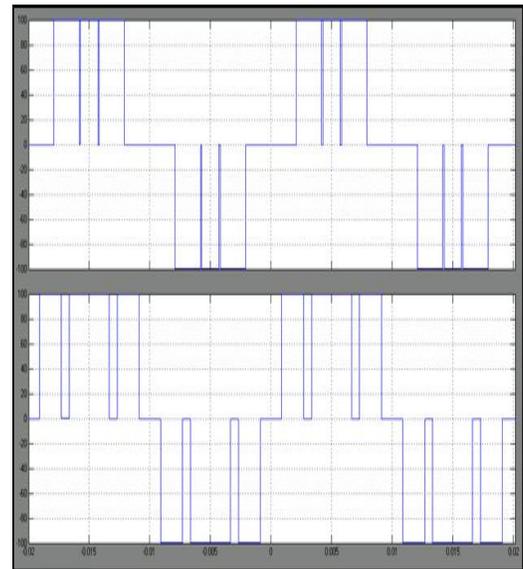

Fig 5.simulation output waveform and current (bottom) for an imbalance of10%. The scales are 100 V/div, 0.25 A/div, and 5 ms/div.

  Switching angles give very low theoretical final imbalance for all the conditions considered in the computing process. It must be noted that this strategy can be very useful to tolerate low unbalancing conditions of Fig. 4. Voltage of three cells and current (bottom) for an imbalance of 0%.The scales are 200 V/div, 0.5 A/div, and 5 ms/div. Fig. 5. Global output waveform and current (bottom) for an imbalance of10%. The scales are 100 V/div, 0.25 A/div, and 5 ms/div .Harmonics can be controlled using a low number of switching angles. Using a three-cell topology and three angles per cell, it ssssis 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, 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 for use in systems which may present higher imbalance situations.
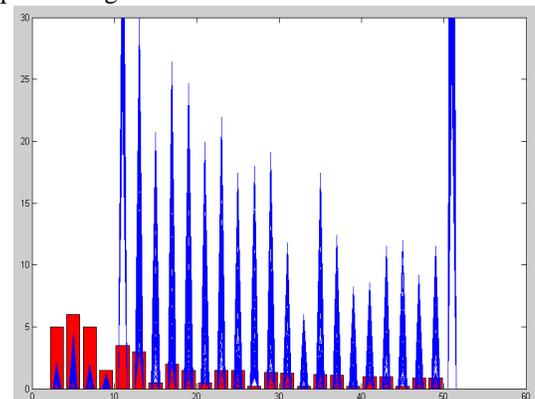

Fig.6. Global harmonic content and THD (on the right) generated by theconverter for each modulation index value for a (−3, 3) imbalance

modulation index from 0.2 to 0.8 and allthe conditions of imbalance from 0% to 5%.
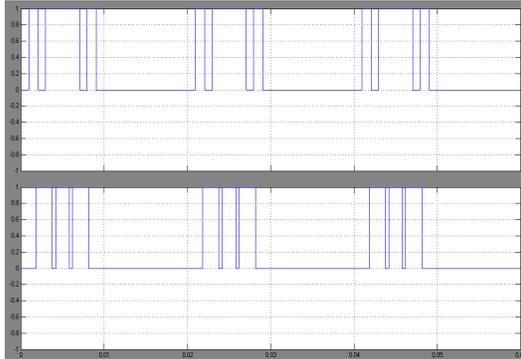

Fig. 7. Three-cell preprogrammed PWM switching pattern with five switching angles

Fig.6.represents the 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).All the values of the modulation index from 0.2 to 0.8 and all the conditions of imbalance from 0% to 5%.Fig. 7. Represents the Three-cell preprogrammed PWM switching pattern with five switching angles

A. 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.
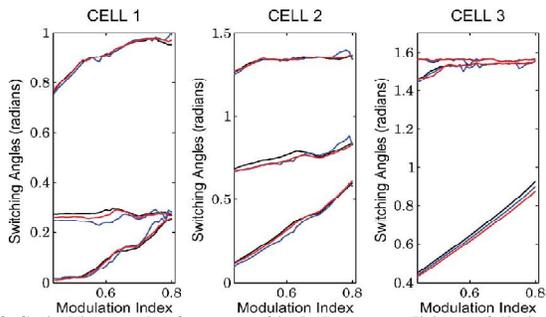

Fig.8. Switching angles for a set of imbalance conditions of $(0, 0, 0)$ in black,$(-2, -2, 4)$ in red and $(-4, 2, 2)$ in blue.
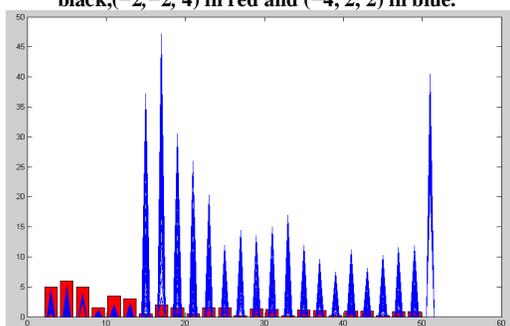

VII. CONCLUSION

Fig . 9.Outputspectrum for an imbalance of $(-1.2, 1, 1.5)$ and $0.44 <Ma <0.80.$
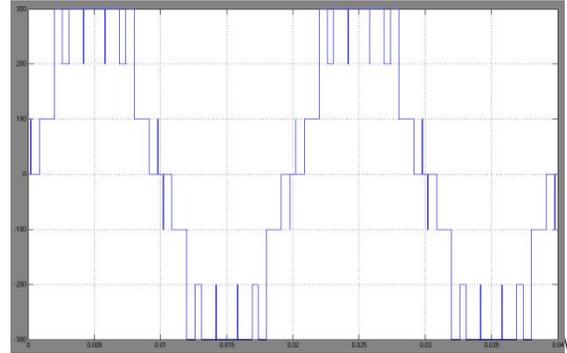

Fig. 10 .Output spectrum for an imbalance of $(-2.5, 1, 3)$ and $0.44 <Ma <0.80.$

Fig.9 presents the spectrum obtained for an imbalance of $(-1.2, 1, 1.5)$ for the range $0.44<Ma <0.80$. It can be observed that for all the values of Ma the lower harmonic components are below the limits specified in the grid code. Using the same set of angles but for an imbalance of $(-2.5,1, 3)$ produces the output spectrum.

Fig.6 presents the spectrum obtained for an imbalance of $(-1.2, 1, 1.5)$ for the range $0.44<Ma <0.80$. It can be observed that for all the values of Ma the lower harmonic components are below the limits specified in the grid code. Using the same set of angles but for an imbalance of $(-2.5,1, 3)$ produces the output spectrum presented in Fig. 9.

The low order Harmonics is meeting the grid code. Again, 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. It must be noted that this strategy can be very useful to tolerate low unbalancing conditions because a high number of Fig. 10. Voltage of both cells and current (bottom) for an imbalance of 0%.The scales are 200 V/div, 0.5 A/div, and 5 ms/div. Fig. 6. Global output waveform and current (bottom) for an imbalance of 10%.

The scales are 100 V/div, 0.25 A/div, and 5 ms/div. Harmonics can be controlled using a low 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, 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 for use in systems which may present higher imbalance situations.

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 unbalanced Conditions with a reduced number of LUTs while still producing very high quality waveforms at low switching frequency. An example of applications 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% to10% have been included.

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G.Mounika received B.Tech degree in Electrical and Electronics Engineering from Anurag College of engineering in 2012 and currently pursuing M.Tech in Electrical and Electronics Engineering with PE&ED specialization from Vignana Bharathi Institute of Technology, Aushapur, Ghatkesar, Rangareddy (dist), and Telangana. Her research interests include Power Electronics, Power Quality, Electrical Drives, FACTS and Control Systems.

Mrs.G.Indira Rani presently working as Assistant professor in VBIT Engineering College, Aushapur, Ghatkesar, Rangareddy, Telangana, India. She received the B. Tech degree in Electrical & Electronics Engineering from BVCEC, JNTU, and Hyderabad. And then completed her M.Tech in Electrical & Electronics Engineering with PE&ED specialization at GNITS, JNTU, Hyderabad. She has a teaching experience of 9 years. Her areas of interest are Power System, Power Electronics and Electrical Drives, FACTS, Switchgear and Protection.