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Multilevel Converters: an Enabling Technology for High Power Applications

Abstract—Multilevel converters are considered today as the state of the art power conversion systems for high power and power quality demanding applications. This paper presents a tutorial on this technology, covering the operating principles, the different power circuit topologies, modulation methods, technical issues and industry applications. Special attention is given to established technology already found in industry with more in depth and self-contained information, while recent advances and state of the art contributions are addressed with useful references. This paper serves as an introduction to the subject for the not familiarized reader, as well as an update or reference for academics and practicing engineers working in the field of industrial and power electronics.

Keywords—Multilevel converters, high power applications, power quality, power electronics.

I. INTRODUCTION

POWER CONVERTERS are an enabling technology for industrial processes powered by electric drive systems. They are potentially useful for a wide range of applications: transport (train traction, ship propulsion and automotive applications), energy conversion, manufacturing, mining and petro-chemical to name a few. Many of these processes have been continuously increasing their demand of power to reach higher production rates, cost reduction (large scale economy) and efficiency. The power electronics research community and industry have reacted to this demand in two different ways: one developing semiconductor technology to reach higher nominal voltages and currents (currently 8kV and 6kA) [1]–[3], while maintaining traditional converter topologies (mainly two level voltage and current source converters); and secondly, by developing new converter topologies, with traditional semiconductor technology, known as Multilevel Converters [4]–[9]. The first approach inherited the benefit of well known circuit structures and control methods. However, the newer semiconductors are more expensive, and by going higher in power, other power quality requirements have to be fulfilled introducing the need of power filters. The second approach uses the well known and cheaper semiconductors, but the more complex circuit structures came along with several challenges for implementation and control. Nevertheless, these challenges turned rapidly into new opportunities, since the more complex circuit structures enabled more control degrees of freedom that could be used to improve power conversion in several aspects, especially in relation to power quality and efficiency. This fact has boosted multilevel converter development during the last two decades, with a continuous evolution.

Multilevel converters are currently considered as one of the industrial solutions for high dynamic performance and power quality demanding applications, covering a power range from 1 to 30MW [4]–[9]. Among the reasons for their success are:

the higher voltage operating capability, lower common mode voltages, reduced voltage derivatives (dv/dt), voltages with reduced harmonic contents, near sinusoidal currents, smaller input and output filters (if necessary), increased efficiency and in some cases possible fault tolerant operation [4]–[9]. Recent contributions, especially dedicated to multilevel converters, like Special Sections in Journals [10]–[12], conference tutorials [13]–[17] and books or book chapters [18]–[21], show the importance reached by this technology nowadays. In addition, leading manufacturers in the field of power electronics and drives commercialize multilevel converters, covering a wide variety of topologies, control methods and applications [22]–[25].

Due to the power levels reached by this technology, it has become an important alternative for high-power medium-voltage fans, compressors, pumps, conveyors, ship propulsion drives, locomotive traction drives (including linear motor drives for maglev trains), and steel rolling mills, to name a few [26]–[31]. Recently, they have been proposed to enable new possibilities for several important applications like: electric and hybrid vehicles, wind energy conversion, photovoltaic energy conversion, uninterruptible power supplies, reactive power compensation and regenerative applications [6], [32]–[47], among others.

This paper presents a tutorial on multilevel converter technology. The compromise between the depth and span of the topic coverage has been settled in a way that provides a comprehensive introduction for the non expert electric and electronics engineers. Nevertheless, the state of the art, recent advances and trends are also addressed, which will interest the more familiarised power electronics engineer, from industry and academia.

The paper is organized as follows: the next section will introduce the multilevel converter conceptual background. The operating principle and main characteristics of different multilevel topologies and multilevel modulation methods are presented in section III and IV respectively. Section V is dedicated to review rectifier configurations for multilevel inverters for regenerative and non regenerative applications. Several operational and technological issues related to multilevel converters are addressed in section VI, which include: multilevel inverter modelling, dc-link voltage unbalance, and operation under faulty conditions. Some multilevel inverter applications are reviewed in section VII. Finally, a summary of relevant remarks are included in the conclusion in section VIII.

II. THE MULTILEVEL CONVERTER CONCEPT

Multilevel converters are power conversion systems composed by an array of power semiconductors and capacitive voltage sources that, when properly connected and controlled, can generate a multiple step voltage waveform with variable and controllable frequency, phase and amplitude. The stepped

waveform is synthesized by selecting different voltage levels generated by the proper connection of the load to the different capacitive voltage sources. This connection is performed by the proper switching of the power semiconductors.

The number of levels of a converter can be defined as the number of steps or constant voltage values that can be generated by the converter between the output terminal and any arbitrary internal reference node within the converter. Typically it is a dc-link node and it is usually denoted by N and called neutral. To be called a multilevel converter, each phase of the converter has to generate at least three different voltage levels. This differentiates the classic two-level voltage source converter (2L-VSC) from the multilevel family. Some single-phase examples of this concept and their respective waveforms are given in Fig. 1, for different number of levels. It is worth to mention that generally the different voltage levels are equidistant from each other in multiples of V_{dc} .

Two-level converters can generate a variable frequency and amplitude voltage waveform, by adjusting a time average of their two voltage levels. This is usually performed with pulse width modulation techniques [48]. On the other side, multilevel converters add a new degree of freedom, allowing the use of the voltage levels as an additional control element, giving more alternatives to generate the output waveform. For this reason, multilevel inverters have intrinsically improved power quality, characterized by: lower voltage distortion (more sinusoidal waveforms), reduced dv/dt , lower common mode voltages, which reduce or even eliminate the need of output filters.

When considering a three-phase system, the levels of one phase are combined with the levels of the other phases, generating more different levels in the line-to-line voltage. For a converter with n_p phase to neutral voltage levels, $n_{ll}=2n_p-1$ levels can be found in the line-to-line voltage (a zero level is redundant). Something similar happens in the three-phase load voltage, where combinations of the line voltages are produced, obtaining $n_{load}=2n_{ll}-1$ voltage levels. However, only n_p is used to refer to the number of levels of the converter, since these are the levels generated by the converter independently of the number of phases or the load connection type.

There are many ways to combine power semiconductors and capacitive dc sources to generate multilevel output voltages, however only some of them have become important from a practical point of view; these are analyzed in the following section.

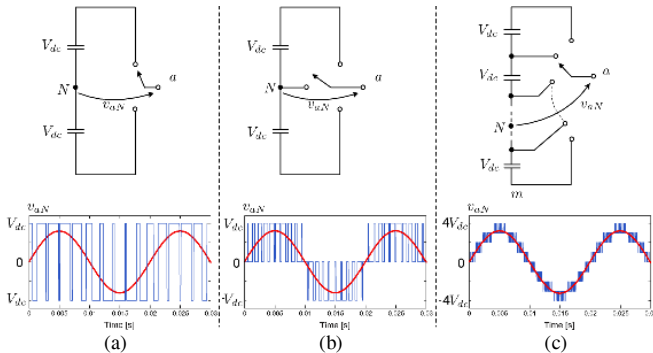


Fig. 1. Converter output voltage waveform: a) 2-level, b) 3-level, c) 9-level.

III. CONVERTER TOPOLOGIES

Over the years many different Multilevel Converter topologies have been reported [4]-[9]. They can be classified in two main groups, as shown in Fig. 2, depending on the number of independent dc sources used in their structure. The most known and established topologies are the Neutral Point Clamped (NPC) or diode clamped, the Flying Capacitor (FC) or capacitor clamped, and the Cascaded H-Bridge (CHB), each introduced for the first time in [49], [50] and [51] respectively. The FC and CHB are also referred as Multicell Converters (MC) due to their modular structure composed of several smaller power converters called power cells.

More recently, numerous variations and even combinations of these topologies have been presented, to satisfy particular applications requirements or to improve an operational feature. Some of these variations include the Active NPC (ANPC) [52], which produces a more equal semiconductor junction temperature distribution, enabling a substantial increase of the converter output current and power at nominal operation, compared to the regular NPC. Another variation is the Stacked Multicell Converter (SMC) [53]-[55], which basically can be described as a combination of serial and parallel connected flying capacitors power cells. This converter allows a higher voltage operation, reduction in capacitors volume and better quality output voltages than the traditional FC. The CHB, traditionally fed by equal dc voltage sources has also been modified by introducing an asymmetry in the dc voltage sources. This modified version is known as the asymmetric or hybrid CHB [56]-[61]. It generates considerably more output voltage levels than any other topology using less semiconductors and capacitors. Asymmetric or hybrid topologies have also been proposed based on the NPC structure [62].

A. Neutral Point Clamped Converters

A NPC converter is basically composed of two traditional two-level VSC stacked one over the other with some minor modifications. As can be seen in Fig. 3, the negative bar of the upper converter and the positive bar of the lower are joined together to form the new phase output, while the original phase outputs are connected via two clamping diodes to form the neutral point N , dividing the dc-link voltage in two. Now each power device has to block only the half of the total converter voltage, hence with the same semiconductor

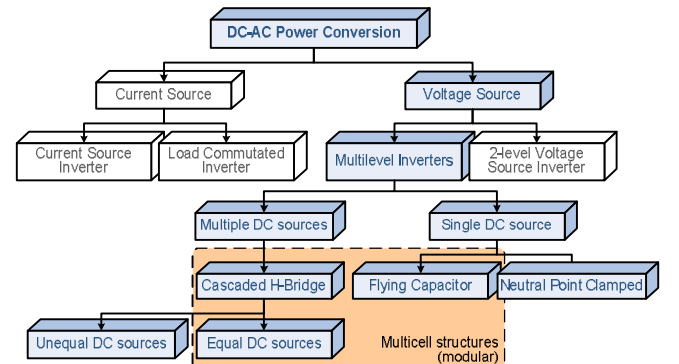


Fig. 2. Multilevel converters classification

technology, the power rating of the converter can be doubled. In addition, the neutral point enables the generation of a zero voltage level, obtaining a total of three different voltage levels.

The switching state of a converter is a set of signals used to control each switching device of the power circuit. They can modify its conduction state and the way the load is connected to the different nodes of the dc side circuit. Hence a particular switching state generates a corresponding output voltage level. For the NPC shown in Fig. 3, the switching signals S_{ij} , with the subscript i and j representing the corresponding phase (a , b or c) and switch number (1 or 2) respectively. Note that there are only two control signals per phase, the other two switches receive inverted gating signals to avoid the dc-link short-circuit. The gate signal is of binary nature representing by 0 the OFF state of the switch, and by 1 the ON state. Fig. 4 shows the three different switching states for one phase of the NPC and their corresponding output voltage levels. The obtained equivalent circuit is highlighted to show how the output node a is linked to the positive, neutral and negative nodes of the dc side circuit. Note that one of the four binary combinations $(S_{a1}, S_{a2}) = (1, 0)$ is not used since it does not provide a current flow path for the load. The same switching states can be applied for phases b and c .

The NPC topology can be extended to higher power rates and more output voltage levels by adding additional power switches and clamping diodes to be able to block higher voltages. Fig. 5 shows a phase of a five-level NPC converter. Here the name Diode Clamped (DC) makes more sense, since there are more voltage level clamping nodes than only the neutral N . Note that the number of clamping diodes needed to share the voltage increases dramatically. This fact together with the increasing difficulty to control the dc-link capacitor unbalance has kept the industrial acceptance of the NPC topology up to three levels only.

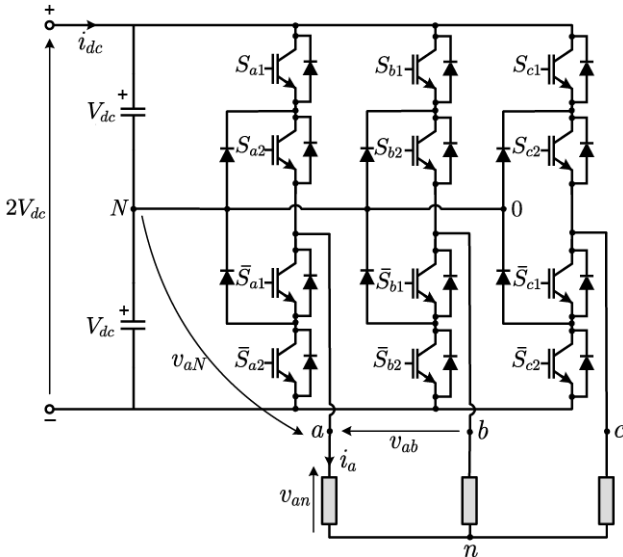


Fig. 3. Three-level Neutral Point Clamped power circuit.

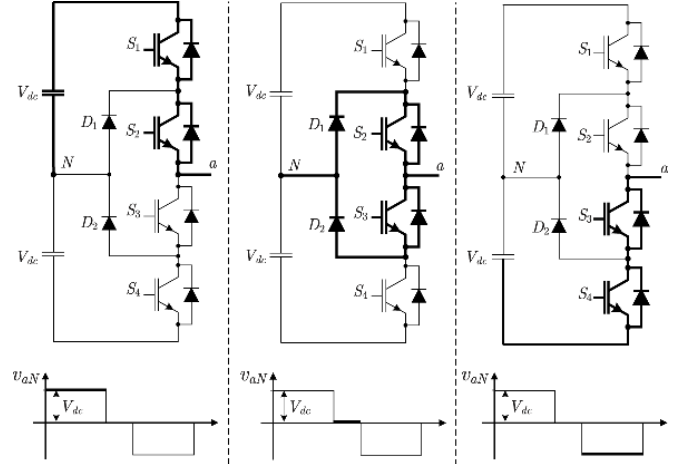


Fig. 4. Three-level NPC switching states and corresponding output voltage levels.

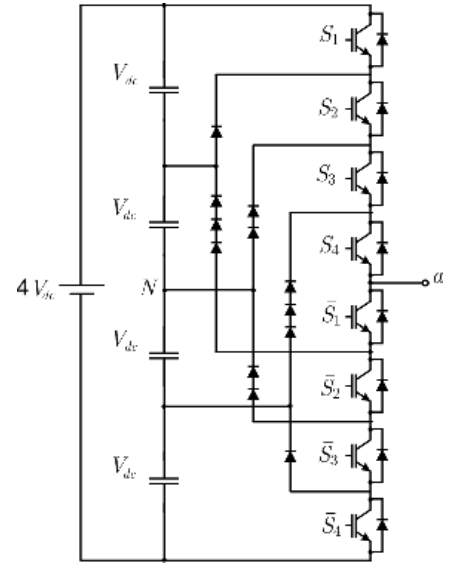


Fig. 5. A phase of a five-level NPC.

B. Flying Capacitor Converters

The FC topology is in some way similar to the NPC, with the main difference that the clamping diodes are replaced by flying capacitors as can be seen in Fig. 6. Here the load cannot be directly connected to the neutral of the converter to generate the zero voltage level. Instead, the zero level is obtained by connecting the load to the positive or negative bar through the flying capacitor with opposite polarity respect the dc-link. Like with the NPC only two gating signals are necessary per phase to avoid dc-link and flying capacitor short-circuit. However, in the FC the inverted gating signals are related to different switching devices as shown in Fig. 6. The switching states and their equivalent power circuits with the corresponding output voltage levels are illustrated in Fig. 7.

Another difference with the NPC is that the four combinations of (S_{a1}, S_{a2}) are allowed. Only three are shown in Fig. 7. The middle circuit in Fig. 7 shows $(S_{a1}, S_{a2}) = (1, 0)$, which generates the zero level. The same level is obtained with $(S_{a1}, S_{a2}) = (0, 1)$. This property is known as voltage level redundancy, and can be used for control or optimization purposes.

Perhaps the main and most important difference with the NPC topology is that the FC has a modular structure, and can be more easily extended to achieve more voltage levels and higher power rates. This can be easily observed by redrawing the FC as illustrated in Fig. 8, where an additional pair of switching devices and a capacitor are connected to form a four-level FC converter. Note that each pair of switches together with one capacitor forms a power cell or module. They can be connected one after the other, and each one provides one additional voltage level to the output. The addition of power cells increases the number of voltage level redundancies, which can be used as extra degrees of freedom for control or optimization purposes.

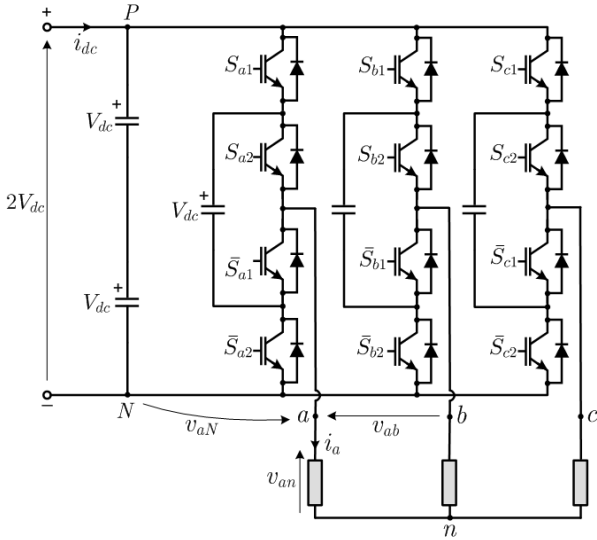


Fig. 6. Three-level Flying Capacitor power circuit.

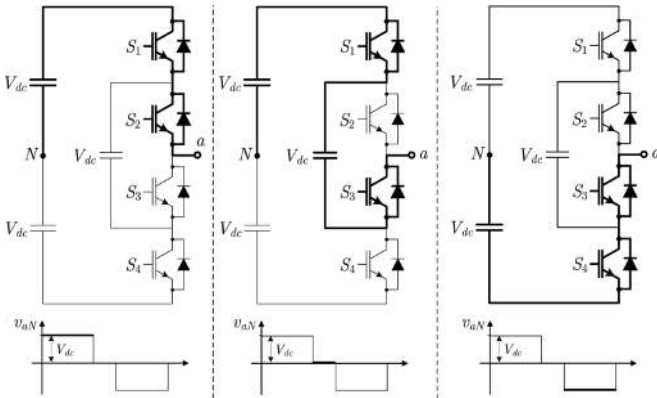


Fig. 7. Three-level FC switching states and corresponding output voltage levels.

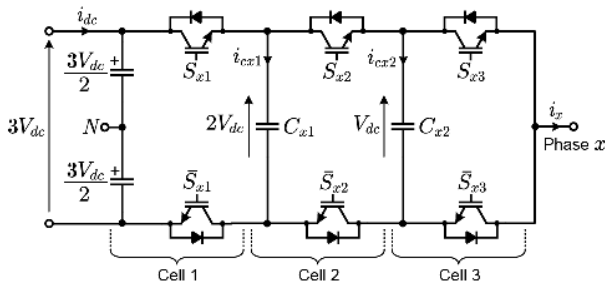


Fig. 8. Four-level FC (only one phase shown).

C. Cascaded H-bridge Converters

Cascaded H-bridge Converters (CHB) are multilevel converters formed by the series connection of two or more single phase H-bridge inverters, hence the name. Each H-bridge corresponds to two voltage source phase legs, where the line-line voltage is the converter output. Therefore, a single H-bridge converter is able to generate three different voltage levels. Each leg has only two possible switching states, to avoid dc-link capacitor short-circuit, and since there are two legs, four different switching states are possible, although two of them have redundant output voltage. Fig. 9 shows the three different output voltage levels and their corresponding equivalent circuits. The zero level can be either generated connecting the phase outputs to the positive or the negative bars of the inverter (only the first one is illustrated in Fig. 9).

When two or more H-bridges are connected in series, their output voltages can be combined to form more different output levels, increasing the total inverter output voltage and also its rated power. Fig. 10 shows four H-bridges connected in series, and a qualitative example of their possible individual three-level output voltages. The total converter output voltage is also illustrated presenting nine different voltage levels. In general terms when connecting k H-bridges in series, $2k+1$ different voltage levels are obtained (two per H-bridge and the zero, common to all), and a maximum output voltage of kV_{dc} is possible.

CHB presents more redundancies than the previous topologies, since each H-bridge or power cell has one redundant switching state, and the series connection inherently introduces more redundancies.

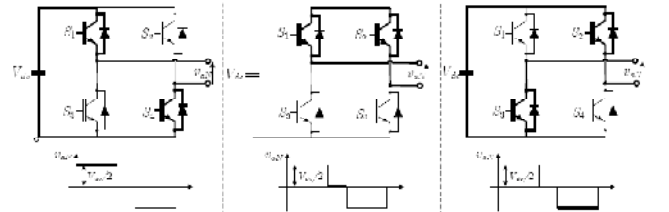


Fig. 9 Three-level H-bridge switching states (single phase).

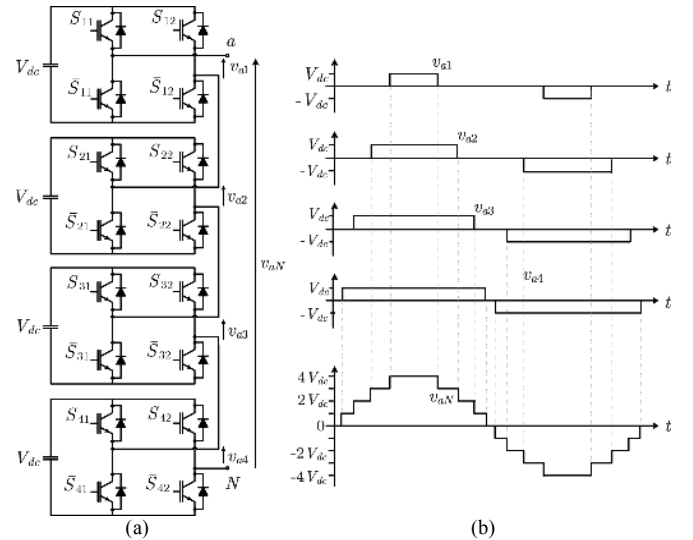


Fig. 10. Nine-level cascaded H-bridge: a) power circuit; b) output voltage waveform synthesis (single phase).

This can be clearly appreciated in Table I, where all the switching states of a 2-cell or 5-level CHB inverter are listed. The number of redundancies grows over-proportionally when increasing the number of cells. These redundancies and the natural modularity of this topology are advantages that enable fault tolerant operation as will be discussed later. Another advantage is the effective increase in the output voltage and power since all semiconductors have only to block V_{dc} . The main drawback is the fact that each H-bridge inverter needs an isolated dc-source, usually provided by a three-phase rectifier fed by a transformer. Hence, for a 3-phase 5-level inverter a three-phase transformer with six secondary three-phase windings and the corresponding diode bridges are necessary, increasing the volume and cost of the converter.

The H-bridge converters that are connected in series do not necessarily need to have the same dc input voltages. In fact a proper choice of voltage asymmetry between cells can produce a different combination of voltage levels and eliminate redundancies. As shown in Fig. 11, an asymmetry or voltage ratio of 1:3 for a 2-cell CHB leads to the same nine levels achieved with a 4-cell CHB of Fig. 10. The asymmetric fed topology achieves same output voltage quality with less hardware. However, in case of using the same power semiconductors technology the total output voltage is reduced, since the maximum blocking voltage of the device will limit the value of the permitted dc source.

Table I. 5-level CHB switching states

Total inverter output voltage	Switching state				Individual cell output voltage	
v_{aN}	S_{11}	S_{12}	S_{21}	S_{22}	v_{a1}	v_{a2}
$2V_{dc}$	1	0	1	0	V_{dc}	V_{dc}
V_{dc}	1	0	1	1	V_{dc}	0
			0	0		
	1	1	1	0	0	V_{dc}
0	0	0	1	0		
	0	0	1	1	0	0
	1	1	0	0		
	1	1	1	1		
	1	0	0	1	V_{dc}	$-V_{dc}$
$-V_{dc}$	0	1	1	0	$-V_{dc}$	V_{dc}
	0	1	0	0	$-V_{dc}$	0
	0	0	1	1	0	$-V_{dc}$
$-2V_{dc}$	0	1	0	1	$-V_{dc}$	$-V_{dc}$

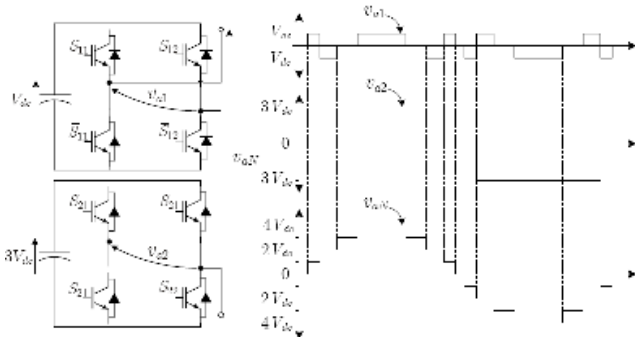


Fig.11 Nine-level H-bridge switching states (single phase).

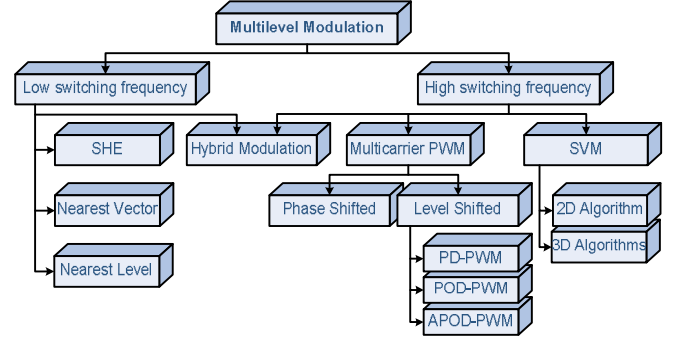


Fig. 12. Multilevel Converter Modulation Methods.

IV. MULTILEVEL CONVERTER MODULATION METHODS

Together with the development of multilevel inverter topologies appeared the challenge to extend traditional modulation methods to the multilevel case. On one hand there is the inherent additional complexity of having more power electronics devices to control, and on the other the possibility to take advantage of the extra degrees of freedom provided by the additional switching states generated by these topologies. As consequence, a large number of different modulation algorithms have been adapted or developed depending on the application and the converter topology, each one having unique advantages and drawbacks. A classification of the most common modulation methods for multilevel inverters is presented in Fig. 12. The modulation algorithms are here classified depending on the average switching frequency with which they operate, i.e., high or low. For high power applications high switching frequencies are considered those above 1 kHz.

A. PWM algorithms for multilevel converters

1) Phase Shifted (PS-PWM)

Phase Shifted PWM (PS-PWM) is a natural extension of traditional PWM techniques, specially conceived for FC [63] and CHB [64] converters. Since each FC cell is a 2-level converter, and each CHB cell is a 3-level inverter, the traditional bipolar and unipolar PWM techniques can be used respectively. Due to the modularity of these topologies, each cell can be modulated independently using the same reference signal. A phase shift is introduced between the carrier signals of contiguous cells, producing a phase shifted switching pattern between them. In this way, when connected together, the stepped multilevel waveform is originated. It has been demonstrated that the lowest distortion can be achieved when the phase shifts between carriers are $180^\circ/k$ or $360^\circ/k$ for a CHB or FC converter respectively (where k is the number of power cells). This difference is related to the fact that the FC and the CHB cells generate 2 and 3 levels respectively. A 7-level CHB example of the operating principle is illustrated in Fig. 13.

Since all the cells are controlled with the same reference and same carrier frequency, the switch device usage and the average power handled by each cell is evenly distributed. For the case of the CHB this means that multi-pulse diode rectifiers can be used to reduce input current harmonics. For the FC, the advantage of the even power distribution is that once the flying capacitors are properly charged (initialized

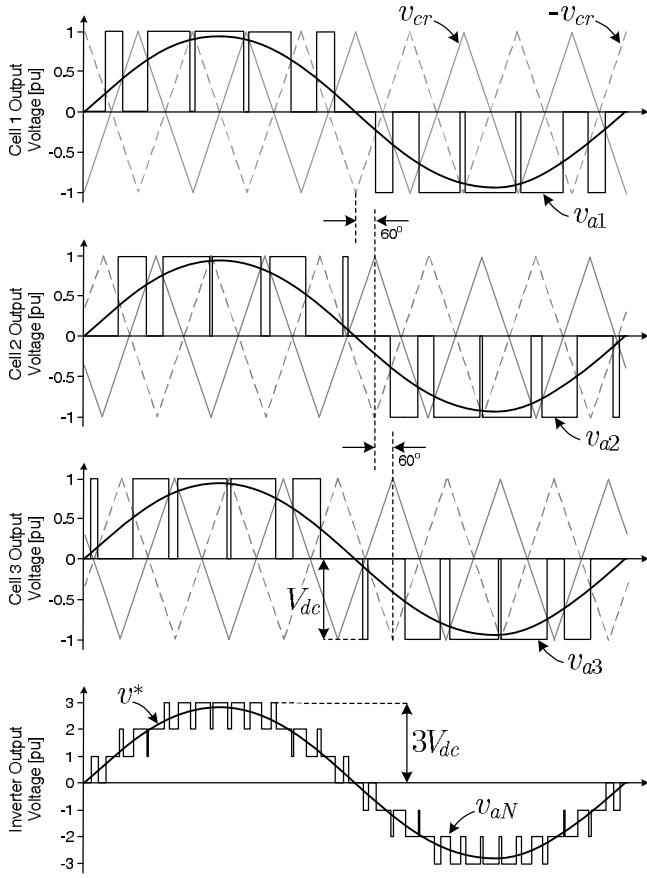


Fig 13. Three-cell (7-level) PS-PWM waveform generation for CHB.

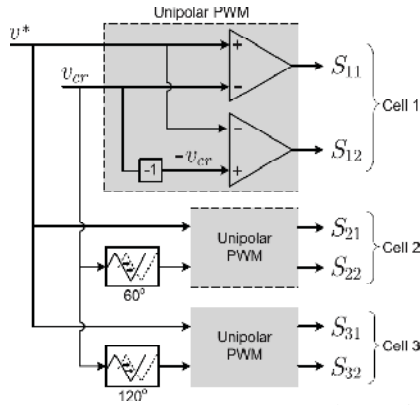


Fig 14. Three-cell (7-level) PS-PWM control diagram, for CHB.

to their corresponding values) no unbalance will be produced due to the self balancing property of this topology [65],[153], hence there is no need to control the dc-link voltages. Another interesting feature is the fact that the total output voltage has a switching pattern with k times the frequency of the switching pattern of each cell. This multiplicative effect is produced by the phase shifts of the carriers. Hence better THD is obtained at the output, using k times lower frequency carriers. The corresponding implementation diagram is illustrated in Fig. 14. Note that the same nomenclature is used for the gating signals S_{xy} as for those defined in Fig. 10(a), only here it is used for three cells instead of four.

2) Level Shifted (LS-PWM)

Level Shifted PWM (LS-PWM) is the natural extension of bipolar PWM for multilevel inverters. Bipolar PWM uses one carrier signal which is compared to the reference, to decide between two different voltage levels, typically the positive and negative busbars of a VSI. By generalizing this idea, for a multilevel inverter, $m-1$ carriers are needed. They are arranged in vertical shifts instead of the phase shift used in PS-PWM.

Each carrier is set between two voltage levels, therefore the name level shifted. Since each carrier is associated to two levels, the same principle of bipolar PWM can be applied, taking into account that the control signal has to be directed to the appropriate semiconductors, in order to generate the corresponding levels. The carriers span the whole amplitude range that can be generated by the converter. They can be arranged in vertical shifts, with all the signals in phase with each other, called Phase Disposition (PD-PWM), with all the positive carriers in phase with each other and in opposite phase of the negative carriers, known as Phase Opposition Disposition (POD-PWM), and finally Alternate Phase Opposition Disposition (APOD-PWM) which is obtained by alternating the phase between adjacent carriers [66]. An example of these arrangements for a 5-level inverter (thus 4 carriers) is given in Fig. 15(a), (b) and (c) respectively.

This modulation method is especially useful for NPC converters, since each carrier can be easily associated to two power switches of the converter. In Fig. 16 a qualitative example for a 3-level NPC is illustrated. From Fig. 16(a) it can be observed that the times during which the value of the reference is greater than the value of both carriers, the upper switches are turned on connecting the load to the positive busbar. During the times the reference value is between both carriers ($v_{cr2} \leq v^* \leq v_{cr1}$), the output is connected to the neutral point N . Finally the times in which the reference value is lower than both carriers, the lower switches are turned on, connecting the load to the negative busbar. The control diagram that performs this algorithm is shown in Fig. 16(b). Note that the gating signals of Fig. 16(b) are defined for the 3-level NPC as show in Fig. 4.

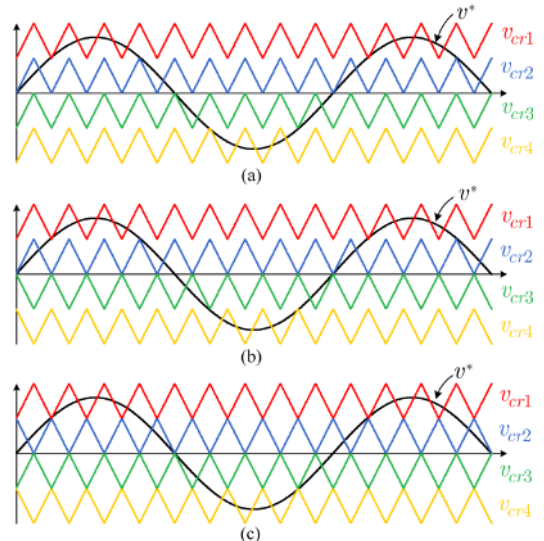


Fig 15. LS-PWM carrier arrangements: a) PD, b) POD, c) APOD.

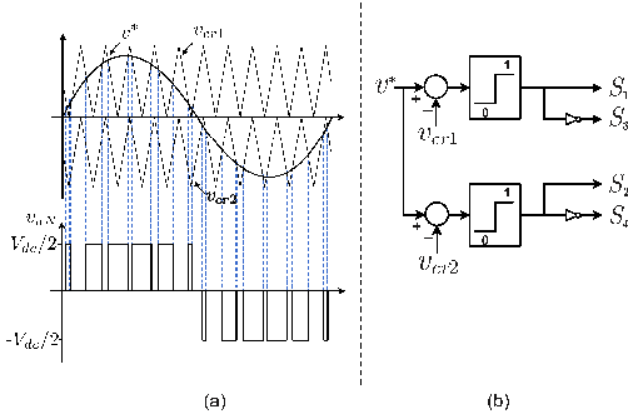


Fig 16. LSPWM for NPC: a) waveform generation, b) control diagram.

LS-PWM leads to less distorted line voltages since all the carriers are in phase compared to PS-PWM [18]. In addition since it is based on the output voltage levels of an inverter, this principle can be adapted to any multilevel converter topology. However, this method is not preferred for CHB and FC, since it causes an uneven power distribution among the different cells. This generates input current distortion in the CHB and capacitor unbalance in the FC compared to PS-PWM.

3) Hybrid PWM Modulation

Hybrid PWM (H-PWM) is an extension of PWM for CHB with unequal dc sources [8]. The main challenge is to reduce the switching losses of the converter by reducing the switching frequency of the higher power cells. Therefore, instead of using high frequency carrier based PWM methods in all the cells, the high power cells are operated with square waveform patterns, switched at low frequency, while only the small power cell is controlled with unipolar PWM.

Consider for example a three-cell (in each phase) CHB inverter with $V_1 < V_2 < V_3$ as the three unequal dc source voltage values. Then, the square wave operation for cell 3 can be obtained by simply comparing the reference to $\pm h_3 = \pm(V_1 + V_2)$ as shown in the control diagram in Fig. 17. The output of this comparator indicates if this cell is generating $-V_3$, 0 or V_3 at the output. Considering a sinusoidal reference, the generated output voltage for cell 3 using this comparator is shown in Fig. 18(a), switching at fundamental frequency (each switch has a turn on and turn off during one cycle). The difference between the reference v^* and this output v_{a3} , is the error or the unmodulated part of the reference, which is left for modulation to the other two cells. Hence, this difference can then be used as reference for cell 2. Again a comparator $\pm h_2 = \pm V_1$ is used to generate the output of cell 2 (note that in general the comparator level for cell k is

, i.e., the sum of the smaller dc sources (to avoid over-modulating references for the smaller cells). For the example, the output waveform in Fig. 18(b) is obtained, with few commutations per cycle. In the same way as with cell three, the square wave operation of cell two is a gross approximation of its reference, therefore this new error (difference between v^* and v_{a2}) becomes the reference for the last cell. Since there are no more cells left, and this is the one with the lowest

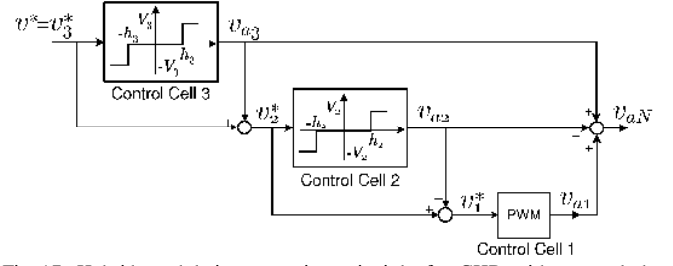


Fig 17. Hybrid modulation operating principle for CHB with unequal dc sources.

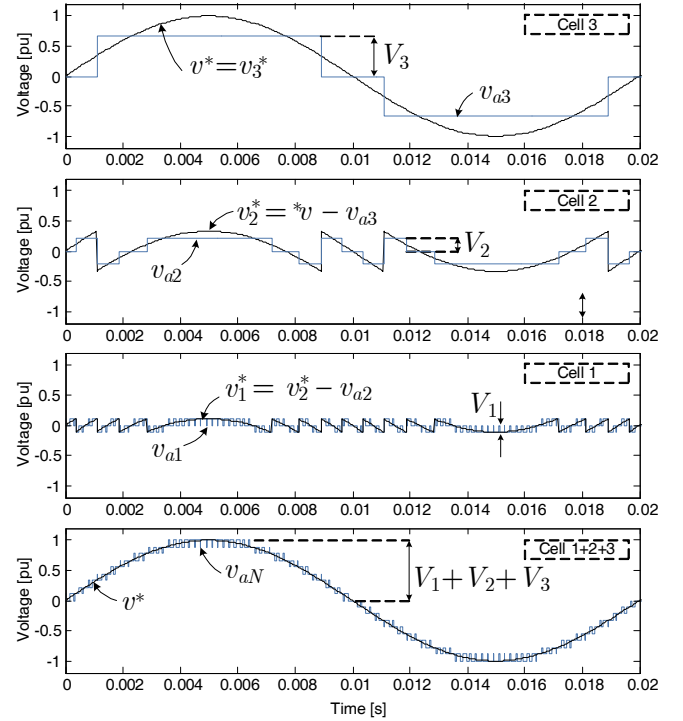


Fig 18. Output voltages for CHB with unequal dc sources for Hybrid modulation.

power, the square wave operation is replaced by traditional unipolar PWM as shown in the control diagram of Fig. 17. The reference and output of cell one is given in Fig. 18(c). The series connection of the cells delivers a total output voltage $v_{aN} = v_{a1} + v_{a2} + v_{a3}$, as the one illustrated in Fig 18(d), which looks like a traditional high frequency PWM multilevel waveform pattern, while in fact only the low power cell is operating at higher switching frequencies, improving the converter efficiency. This method is only feasible if the dc-link voltages of the higher power cells are integer multiples of the small one, and $V_3 \leq 2(V_1 + V_2)$ and $V_2 \leq 2V_1$, otherwise over modulation in the small power cell will occur. The optimal asymmetry that fulfills these conditions for a three-cell inverter is $V_1:V_2:V_3 = 1:2:6$, and is the example shown in Fig. 18, leading to 19 different voltage levels).

B. Space vector modulation algorithms for multilevel converters

The space vector modulation (SVM) algorithm is basically also a PWM strategy with the difference that the switching times are computed based on the three-phase space vector representation of the reference and the inverter switching states, rather than the per-phase in time representation of the

Many SVM algorithms based on the previous concept have been reported, they differ in how the three nearest vectors are chosen, how the times are computed, the sequence used to generate the vectors and computational effort necessary for implementation. In [67] a coordinate transformation is introduced to the α - β plane, shifting the complex axis β from 90° to 60° with respect the α axis, also called hexagonal coordinates or h - g plane. The advantage is that when normalized, each vector can be expressed by two integer values in the h and g axis, instead of fractional complex

components of the β axis. This greatly simplifies the determination of the three closest vectors to the reference, since they can be located using round functions (floor and ceil). In addition the ON times can also be easily obtained as the fractional parts of the reference in the h and g axis.

Another very low computational cost method is presented in [67]. This method is based on the decision based pulse width modulation developed for conventional two-level converters [48]. This iterative algorithm is based on the determination of the switching sequence and the duty cycles only considering a sextant of the inverter state space region shown in Fig. 19. This is achieved rotating the space vector reference to its equivalent in the first sextant in order to facilitate the calculations. This algorithm presents the advantage compared with other methods of eliminating complex mathematical calculations in the switching sequence determination. In addition, the numeric computation of the ON times is reduced to a simple addition.

An alternative SVM method, based on this iterative algorithm is presented in [67], the main difference is that the space vectors and their ON times are calculated using very simple geometrical considerations. In this geometrical algorithm, the rotation needed in the iterative algorithm is avoided reducing the computational cost even more. Moreover, the low computational cost of this method is always the same and it is independent of the number of levels of the converter.

The geometrical modulation algorithm uses as input the normalized reference voltage vector, in order to be independent of the dc-link voltage and the numbers of levels of voltages of the converter. In this way, the state space vectors of the converter are placed in the control region in geometrical positions denoted by entire values between 0 and n_p-1 , where n_p is the number of levels of the multilevel converter. Also, this reference voltage is normalized again scaling the imaginary part dividing it by $\sqrt{3}$ [69]. By doing this, the control region is defined by 45° slope triangular regions and it allows using very simple on-line computations to determine the switching sequence and the ON times.

3) SVM algorithms for multilevel unbalanced systems

In power converters with neutral connection (usually also named unbalanced systems), the two-dimensional α - β plane is not enough to fully represent the converter system, since the common mode voltages and currents through the neutral are not considered. An additional γ component (3^{rd} dimension) is introduced,

$$\gamma = (v_a + v_b + v_c)/3. \quad (3)$$

The reference vector and the converter switching states are now mapped into this 3D region, originating 3D-SVM methods.

a) Three-dimensional SVM algorithm for multilevel converters.

The α - β - γ representation offers interesting information about the zero sequence component of currents and voltages, but the additional dimension adds complexity to the modulation algorithm [71]. Therefore the natural Cartesian coordinates are used for 3D multilevel converter modulations to facilitate these calculations. An extension of the geometrical

α - β algorithm introduced in previous section has been reported for the three-dimensional Cartesian a - b - c plane in [71]. In the 3D-SVM method the nearest four space vectors to the reference vector are considered (four because now the reference voltage vector is mapped into the 3D space). After a normalization of the reference voltage vector, the control region is defined by a cube with vertexes in positions from 0 to n_p-1 in each axis a , b and c . This cube is formed by a certain number of sub-cubes depending on the number of the levels of the converter. As an example, the state space vectors of a three-phase three-level converter are shown in Fig. 20. In this space vector representation, the switching states are defined as 0, 1 and 2 corresponding to previously defined states -, 0 and + respectively. This 3D-SVM algorithm considers the sub-cube where the reference vector is located. Thanks to the normalization of the desired reference voltage vector, the closest vector of this sub-cube to the origin is easily calculated as the integer part of each component of the reference voltage vector.

In each sub-cube, the four nearest state space vectors to the reference vector must be identified [71]. The sub-cubes are divided in six regular tetrahedrons so the 3D-SVM has to find out the tetrahedron where the reference vector is located, because the vertexes of this tetrahedron are the state space vectors which will be used for modulation and form the switching sequence. The determination of the tetrahedron is a very fast algorithm with low computational cost because it implies simple comparisons. Finally, in [71] a table summarizing the switching sequence and the duty cycles corresponding to each tetrahedron is presented. The numeric calculations of the ON times are reduced to simple additions. This reduces significantly the computational requirements and enables this technique to be used as a modulation algorithm in those applications where a 3D vector region is required (systems with or without neutral, with unbalanced load, with triplen harmonics), and it is independent of the number of levels of the converter. Finally, it is important to notice that the 3D-SVM can also be applied to multilevel balanced systems achieving zero common mode voltage.

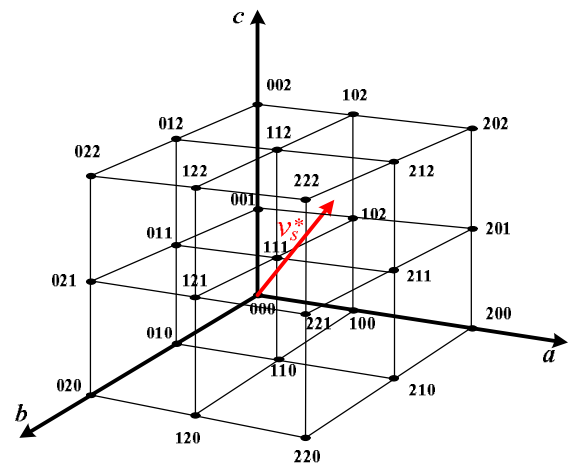


Fig. 20. State space vectors of a three-phase three-level converter using the 3D Cartesian coordinates. This control region is plotted using the normalized phase-to-neutral voltages

b) *SVM algorithms for multilevel four-leg, four-wire inverters.*

A wide range of industrial applications use four-leg and four-wire converters (4L-4W) since they provide more zero sequence control capability. This can be applied to active power filters or neutral current compensator applications for compensating harmonics and zero sequence. Four-leg converters have voltage vectors with γ component different of zero leading to the use of three-dimensional (3D) representations.

A generalized and low computational cost 3D-SVM algorithm for four-leg multilevel converters was proposed in [72]. This 3D algorithm is a generalization of that proposed in [71]. Compared with [71], as the topology changes, the state space vectors of the converter also changes. However, once the sub-cube is known, almost all the necessary calculations to determine the switching sequence and the duty cycles are exactly the same. This 3D-SVM technique optimizes the switching sequence minimizing the number of commutations for 4L-4W converters. As for the 3L-3W case, the low computational cost of this method is always the same and it is independent of the number of levels of the converter.

In general, one of the advantages of SVM techniques for multilevel converters is the reduction of computation and implementation complexity compared to carrier based PWM algorithms, because the number of carriers does not increase as the number of converter levels increases. This advantage makes the digital implementation of the algorithms easier. In addition, the vector redundancies and the switching sequences can be used for other control purposes and be designed according to a specific criterion depending on the application. It has to be noticed that in order to achieve a proper time average, the modulation period T_s is small, leading to high switching frequencies, comparable to carrier based PWM (above 1kHz), and therefore are not useful for very high power applications.

C. *Other modulation and control algorithms for multilevel converters*

1) *Selective Harmonic Elimination (SHE)*

Converters for very high power applications are usually controlled with low switching frequency algorithms, below 1kHz. If traditional carrier based PWM methods were used reducing the carrier frequency to these levels, low order harmonics will appear in the output voltage, increasing distortion which consequently will translate into performance problems. Selective Harmonic Elimination (SHE), is a low switching frequency PWM method developed for traditional converters, in which a few (generally from 3 to 7) switching angles per quarter fundamental cycle are pre-defined and pre-calculated via Fourier analysis to ensure the elimination of undesired low order harmonics [48]. Basically, in SHE the Fourier coefficients or harmonic components of the pre-defined switched waveform with the unknown switching angles are equaled to zero for those undesired harmonics, while the fundamental component is equaled to the desired reference amplitude. This set of equations is solved offline using numerical methods, obtaining a solution for the angles.

This concept has also been extended for multilevel waveforms [73]-[75]. The basic idea is kept, i.e., a previously

defined voltage waveform with a fixed number of switching angles, like the one in Fig. 21, is generated by the converter. By pre-calculating appropriately these switching angles, a number of undesired low order harmonics can be eliminated in the output voltage. With m switching angles in a quarter cycle, m control degrees of freedoms are obtained, from which $m-1$ can be used to eliminate undesired harmonics and the last one to control the amplitude of the fundamental component for reference tracking. As with traditional SHE this can be achieved by computing the corresponding Fourier coefficients of the predefined waveform with the switching angles as unknown variables

$$h_n = \frac{4V_{dc}}{n\pi} \sum_{k=1}^m \cos(n\alpha_k), \quad (4)$$

where h_n is the amplitude of harmonic n . Note that $\alpha_1 < \alpha_2 < \dots < \alpha_m < \pi/2$. The harmonics that should be eliminated are set to zero. The set of equations is then solved using numerical methods several times to cover a wide range of modulation indexes (amplitudes for the fundamental component). The solutions (angles) are stored in a look up table, which is then used to modulate the converter.

As an example for a three-level converter, like the NPC, a typical waveform considering three switching angles ($\alpha_1, \alpha_2, \alpha_3$) is given in Fig. 22. The corresponding fourier series is given by

$$v_{aN} = \frac{4V_{dc}}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \{ \cos(n\alpha_1) + \cos(n\alpha_2) + \cos(n\alpha_3) \} \sin(n\omega t) \quad (5)$$

From this equation, three coefficients of the Fourier series can be forced to a desired value, naturally the first coefficient corresponds to the fundamental component and is set to the desired modulation index, while usually the 5th and 7th coefficient are set to zero (for 5th and 7th harmonic elimination)

$$\begin{aligned} M \cdot \frac{\pi}{4} &= \cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) \\ 0 &= \cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) \\ 0 &= \cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) \end{aligned} \quad (6)$$

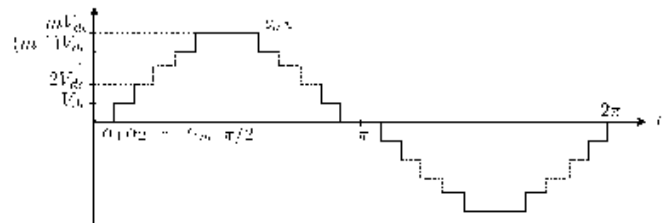


Fig. 21. Multilevel selective harmonic elimination (SHE).

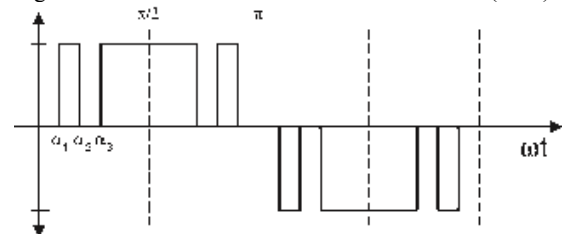


Fig. 22. Three-level selective harmonic elimination (SHE).

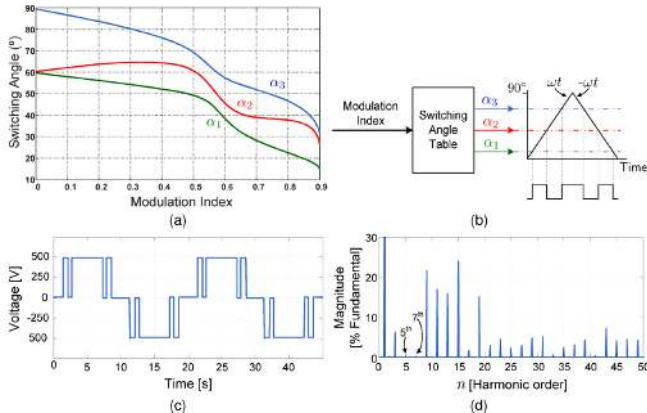


Fig. 23. Three-level selective harmonic elimination: a) angles solution, b) implementation diagram, c) output voltage, d) output voltage spectrum.

where M is the modulation index. The third harmonic and its multiples are usually not eliminated using SHE, since they are naturally eliminated by the three-phase load connection. Figure 23 shows the angles obtained for this example, the implementation diagram, and the output voltage with its corresponding spectrum, from which can be appreciated that the 5th and 7th harmonic are effectively eliminated.

Note that there is no control over the non eliminated harmonics, which usually tend to increase, since the eliminated harmonic energy present in the switched waveform is redistributed over the other ones. If these harmonic levels are not suitable for a particular application, additional angles can be introduced, eliminating more harmonics. For high power grid connected converters there are very demanding grid codes making necessary several angles, which increases the switching frequency and losses, or introduces the use of additional filters. In this case a variation on SHE called Selective Harmonic Mitigation technique (SHM) is more suitable. The main difference with SHE is that it does not forces the angles to completely eliminate the harmonics by setting them to zero. Instead inequalities are used to limit the harmonic content to acceptable values [76]. In this way, the harmonic spectrum of the obtained waveforms can fulfil current grid codes regulations for the integration of energy systems into the distribution grid. The great advantage of SHM compared with SHE is the reduction (or even elimination) of the necessary grid connection filters, without sacrificing the power quality of the system. This leads to a reduction of the economical cost, volume and weight of the overall power system.

For converters with higher number of levels, like CHB, SHE is also known as staircase modulation, because of the stair-like shape of the voltage waveform. The basic idea is identical to SHE, the difference is that each angle is associated to a particular cell. The operating principle of this technique is to connect each cell of the inverter at specific angles to generate the multilevel output waveform producing only a minimum of necessary commutations [21]. The operating principle is illustrated in Fig. 24, note that only one angle needs to be determined per power cell. These angles can be computed using the same principles of SHE exposed before.

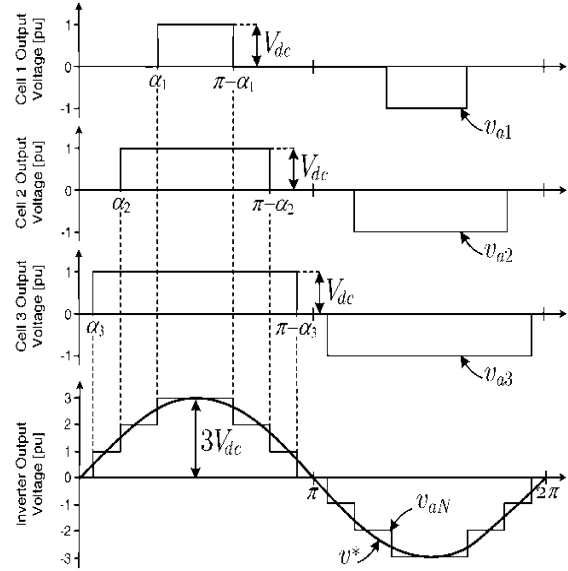


Fig. 24. Seven-level staircase modulation for CHB.

The main advantage, like in SHE is that the converter switches very few times per cycle, reducing the switching losses to a minimum. In addition low order harmonics are eliminated, facilitating the reduction of output filter volume, weight and cost.

All these methods require numerical algorithms to solve this set of equations, which are performed for several modulation indexes, leading to important calculations that are impossible to run in real time with current microprocessors, and thus are executed offline. Therefore, the solutions are stored in look up tables, and interpolation is used for those unsolved modulation indexes. This makes SHE based modulation algorithms not suitable for high dynamic performance demanding applications.

2) Nearest Vector Control

Another low switching frequency method is Nearest Vector Control (NVC), which is also known as space vector control (not to be confused with the motor drive control technique with the same name). It was introduced in [77], as an alternative to SHE or Staircase Modulation, to provide a low switching frequency modulation method, without the offline requirements and poor dynamic performance from SHE. The basic idea is to take advantage of the high number of voltage vectors generated by a multilevel converter, by simply approximating the reference to the closest voltage vector that can be generated in the α - β plane, without even need of modulation. Therefore this method is referred to as nearest vector control instead of modulation, since no time average approximation of the reference is performed.

This operating principle is illustrated in Fig. 25, where the state space vectors for an 11-level multilevel inverter are illustrated, with a zoom to the NVC operating principle. Each circle is one of the possible voltage vectors generated by the inverter, they are surrounded by hexagons that represent the boundary of the area in which they are the closest available vector. The red dashed line is the voltage space vector reference (v_s^*) trajectory through the complex plane. Hence,

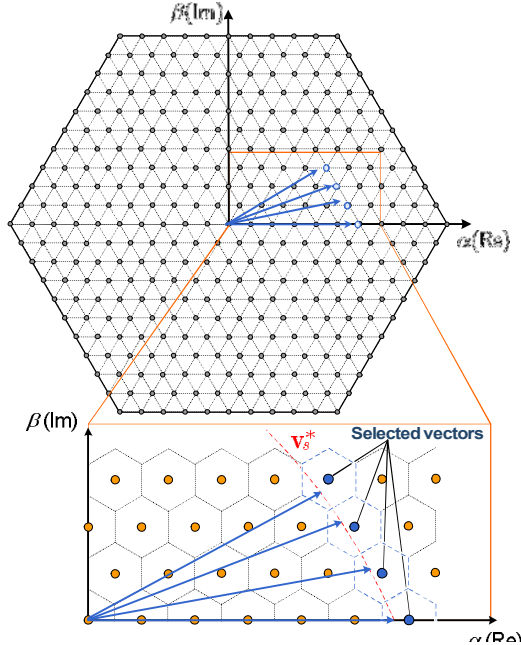


Fig. 25. Multilevel nearest vector control operating principle.

When the reference falls into a certain hexagon, the corresponding vector will be generated by the inverter. The selected vectors according to the illustrative example in Fig. 25 are highlighted in blue.

The natural selection of the closest vector produces a strong reduction in the number of commutations, since no commutations are forced by a modulator, reducing in this way the switching losses. This method, however, does not eliminate low order harmonics (like SHE), and due to its inherent low and variable switching frequency nature, can introduce low order harmonics in the load voltage. This can be compensated by using multilevel converters with a high number of levels (usually above seven), which have a more dense state space vector availability, resulting in a better vector approximation (smaller error). They also have an intrinsic low THD due to the small dv/dt , reducing the effect of the low order harmonics. An alternative method that also reduces the common mode voltages is presented in [78].

These methods have very simple operating principles, however, the implementation is not as straight forward, since an algorithm capable of finding numerically the closes vector needs to be programmed. This technical issue can be found in detail in [77], [78].

3) Nearest Level Control or Round Method

The Nearest Level Control (NLC) also known as the round method, is somehow the per-phase time domain counterpart of NVC. **Error! No se encuentra el origen de la referencia.**, [79]. Basically, the same principle is applied but to voltage levels instead of space vectors, thus selecting the nearest voltage level that can be generated by the inverter to the desired output voltage reference. Unlike with SVC where the three phases were controlled directly with the vector selection, here the three phases are controlled independently with their respective 120° phase shifted references. The main advantage is that the algorithm is greatly simplified in relation to NVC,

since it is much easier to find the closest level than the closest vector. In fact, the output voltage level selection is reduced to a unique simple expression per phase

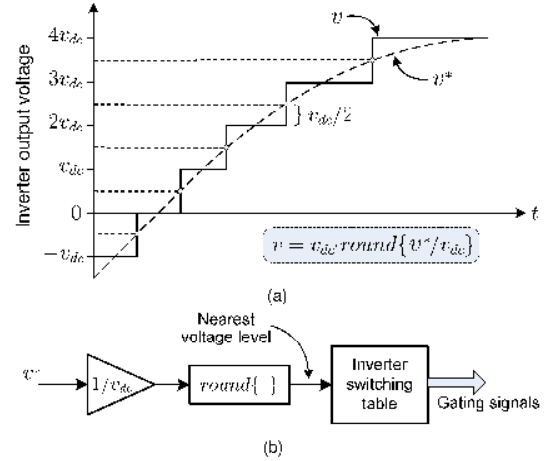


Fig. 26. Nearest level selection: (a) Waveform synthesis, (b) Control diagram.

—, (7)

where V_{dc} is the voltage difference between two levels (usually the dc link voltage in CHB), which is used to normalize the phase output voltage reference. The normalized value is then evaluated using the round function (or nearest integer function), which is defined such that $f_{round}\{x\}$ is the integer closest to x . Since this definition is ambiguous for half integers, the additional convention is that half integers are always rounded to even numbers, for example, $f_{round}\{1.5\} = 2$. This nearest integer multiplied by V_{dc} corresponds to the closest voltage level to the reference, and thus is generated by the inverter.

The operating principle is illustrated in Fig. 26(a) for the first quarter cycle of a sinusoidal reference. Note that the maximum approximation error is $V_{dc}/2$. The implementation of the nearest voltage level generation is presented in Fig. 26(b). As can be seen in Fig. 26(a), the round function inherently produces only one commutation between two voltage levels and a maximum dv/dt of V_{dc} , unless the reference presents large step changes.

It is worth to mention that this method is not a modulation technique, since there are no reference tracking by time average synthesis between two levels. Instead, the stepped waveform is generated as an approximation to the reference. Although the voltage waveform is very similar to the one obtained with staircase modulation, it does not eliminate specific harmonics, because it is not really a modulation. Therefore, this control method, like NVC, is not effective for converters with a reduced number of levels, since the approximation error becomes relevant. Hence it is aimed to be used in converters with a high number of levels to avoid important low order harmonics at the ac side. The main advantage is its conceptual and implementation simplicity and the efficiency achieved with this method. An adaptive modulation method that solves this problem by introducing a duty cycle calculation to NLC and has been proposed [160], at expense of a more advanced control algorithm.

It is also worth to mention that there are other control algorithms that select the switching state and switching times of multilevel converters, but are not a modulation or control stage dedicated to the converter, instead they are a direct consequence of the overall system controller. This is the case of direct torque control of ac motors, where the switching states and transitions are directly obtained from the torque and flux controller of the motor [161],[162]. Another method where the switching states and switching times are directly computed by the controller is Finite Control Set Model Predictive Control, which has also been applied to multilevel converters [163].

V. RECTIFIERS FOR MULTILEVEL INVERTERS

Multilevel inverters like NPC and FC require a medium voltage dc source [49],[50], while in CHB inverters several isolated dc sources are needed [51]. To provide these dc voltages, different topologies of rectifiers can be used. Each proposed configuration provides different possibilities to cancel harmonics in the input current minimizing the impact on the ac network.

These rectifiers can be divided into non-regenerative, i.e. diode based and regenerative or active front end (AFE) rectifier.

A. Non regenerative rectifiers

Three-phase full bridge diode based rectifiers provide a low input energy quality due to the six pulse current, which has high harmonic content, specially low order harmonics. However when several of these rectifiers are used in combination with a multi-pulse transformer it is possible to cancel low order characteristics harmonics and provide a nearly sinusoidal multi-pulse input current [21].

The basic configuration corresponds to the double bridge rectifier fed by a delta-delta-ye transformer, which is shown on Fig. 27. Each six pulse rectifier generates characteristics current harmonics of the same amplitude but, due to the phase angle between the transformer secondaries, the 5th and 7th harmonics are cancelled. This principle can be extended when more rectifier are used, reducing or even eliminating a number of harmonics two times the number of diode rectifiers used. To produce a proper harmonic cancellation the phase angle between secondaries must be $60^\circ/m$, where m is the number of rectifiers [64].

In NPC and FC inverters the dc voltage is obtained using several diode rectifiers in series producing a single dc source for the complete converters (for all three phases). Therefore, the power is equally distributed between each rectifier and the current harmonics can be almost canceled. The number of necessary rectifiers in series will depend on the rated voltage of the dc-link.

When a CHB inverter is used, each individual rectifier is used to produce an isolated dc source for each H-bridge. Hence, the power delivered by each rectifier depends only on the load of the corresponding phase. Therefore, to reduce harmonic distortion, the rectifiers are connected to the transformer secondaries in groups of three (one of each phase) with the same angle displacement, like it is shown in Fig. 28.

Generally each cell of a CHB inverter is fed by a three-phase diode rectifier (for non-regenerative applications), like the one shown in Fig. 29. Single phase rectifiers can also be

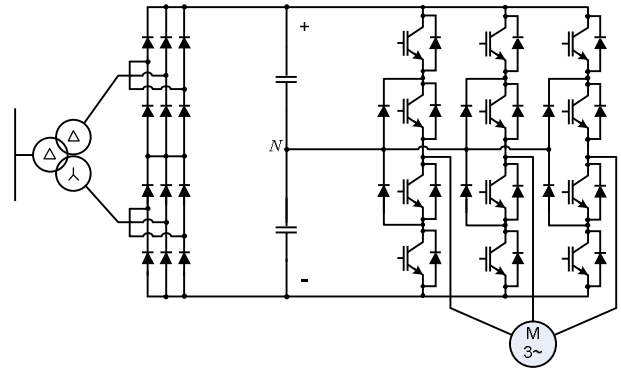


Fig. 27. Double diode-based rectifier in combination with a delta wye transformer.

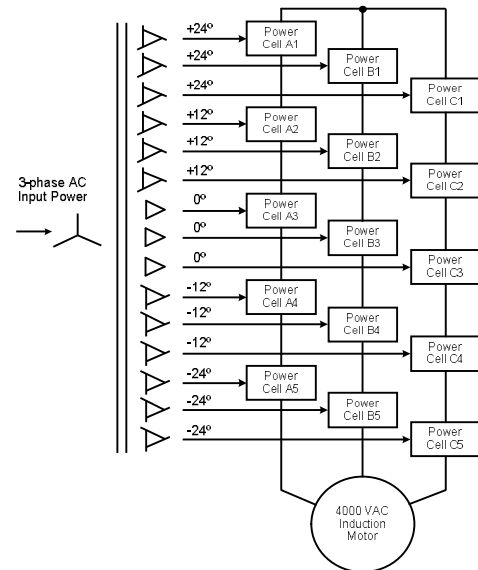


Fig. 28. Multipulse transformer feeding 11-level cascaded inverter.

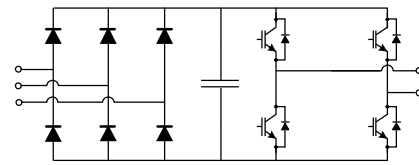


Fig. 29. Single phase rectifier based power cell.

used reducing the number of components and simplifying the transformer design [81], however at expense of an increase in the input current harmonics.

Diode rectifiers are directly affected by ac networks disturbances, producing variations on the dc voltage [82]. Usually, the control scheme of the inverter can reject these perturbations, providing a stable energy to the load. However, when a controlled dc voltage is required a controlled or semi-controlled thyristor-based rectifier can be used, like it is shown on Fig. 30 used with a flying capacitor converter. In addition, with a controlled rectifier it is possible to keep a constant dc voltage, protecting the dc capacitor from over voltages and reducing the requirements of the inverter controller.

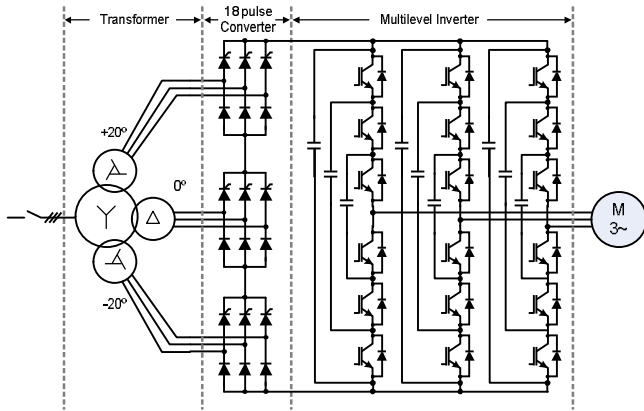


Fig. 30. Semicontrolled rectifier in combination with a 18-pulse transformer to provide a regulated dc voltage.

In general terms, multilevel converters using several rectifiers and a proper transformer configuration provide a good quality input current. However, the main drawback of these rectifiers appears when regenerative loads are fed, reducing the efficiency of the system by introducing resistive chopper circuits to dissipate the extra energy entering the dc link. An alternative for this inefficient approach is the use of a regenerative rectifier.

B. Regenerative rectifiers

Several loads like elevators, trains and downhill conveyors need to regenerate energy back into the ac network. Power converters based on diode rectifiers does not provide regenerative operation, requiring resistive chopper to handle this energy and reducing the overall efficiency [46].

Regenerative converters based on active rectifiers can take the energy provided by the load and put it back on the ac network, increasing the efficiency of the power conversion system, especially when the load regenerates constantly, like downhill conveyors [45].

Replacing the diode rectifier and the transformer with the same inverter topology, a back-to-back configuration is obtained. These configurations are shown in Fig. 31 for a NPC inverter and Fig. 32 for a FC inverter. These rectifier configurations have been successfully implemented in regenerative conveyor in the mining industry [83] and wind energy conversion [84]. The main advantage of this scheme, besides its regenerative operation, is that the same hardware is required for both rectifier and inverter side. Only different

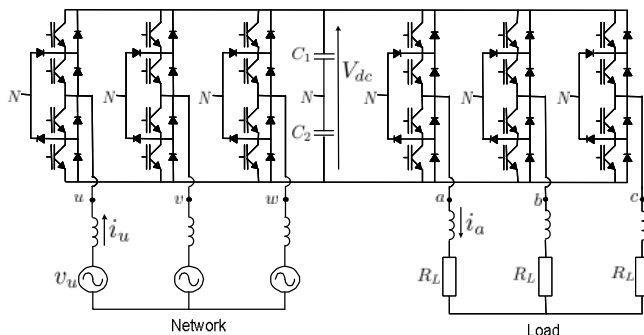


Fig. 31. Back-to-back NPC configuration.

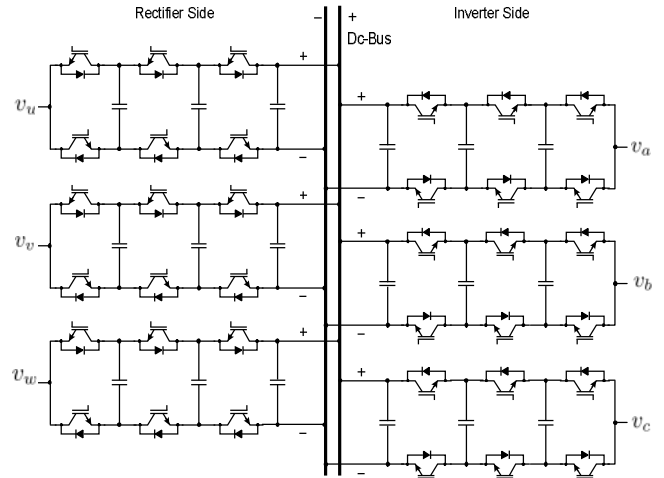


Fig. 32. Back-to-back FC configuration.

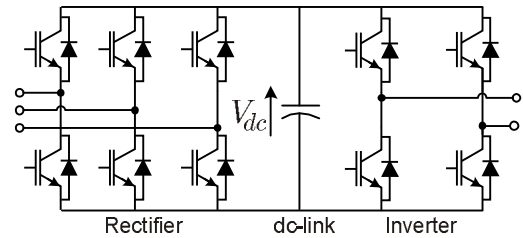


Fig. 33. Three-phase AFE rectifier-based power cell.

control strategies are required. The rectifier control is not only used to control the dc link voltage, but also employed to control the input current at will, obtaining lower distortions than with the diode rectifier with multipulse transformer. Moreover, since the input current can be controlled by the rectifier there is no special need of winding angle shifts in the transformer, simplifying its design.

In CHB converters the diode rectifier is replaced by a three-phase voltage source rectifier or active front end (AFE) rectifier for each power cell, providing the regenerative operation as needed. However, the input transformer cannot be eliminated, because it is needed in order to provide the required isolated dc sources. Usually this AFE is a three-phase rectifier like the one shown in Fig. 33. On the other hand, several single-phase regenerative rectifiers configurations have been proposed [85], in order to reduce switch and components count. Here the transformer can also be simplified, since no winding angle shifts are necessary.

VI. OPERATIONAL AND TECHNOLOGICAL ISSUES

A. Dc-link voltage balance for NPC inverters

The balance of the dc-link capacitors voltage is one of the most important concerns in NPC multilevel converters. Many control strategies to achieve this balance have been presented in the last years [86]–[98].

In general, most of these strategies use the well known technique based on choosing between redundant state space vectors. As was introduced in the SVM section, two state vectors are redundant if they are located in the same position of the α - β plane. For instance, switching state vectors (0,-,-) and (+,0,0) are redundant as can be observed from Fig. 19.

Therefore, redundant vectors generate the same phase-to-neutral load voltages, and hence there is no difference from the load point of view to use either of them. However, from the inverter point of view the redundant space vectors have different effects on the dc link capacitor voltages, and therefore they can be used for balance control.

By measuring the dc voltage unbalance (difference between capacitor voltages) and the sign of the load phase currents, it is possible to choose the redundant vector that tends to balance the dc voltages. This is always necessary for NPC topologies, where the dc-link unbalance is a common problem. FC inverters do have natural balancing when used with PS-PWM, although for other modulation methods or for a faster dc link balance dynamics, the same concepts based on state redundancies can be applied. Traditional CHB inverters do not have voltage unbalance problems, since they are fed by independent dc sources. However, variations on the CHB, for example where only one cell is fed by a dc source while the others are floating, also require this type of unbalance algorithms [159].

It should be noticed that when increasing the number of levels of the converter, the number of redundant vectors in the control region increases over-proportionally. In fact, the number of state vectors for an n_p -level converter is n_p^3 and the number of redundant vectors (NRV) can be determined using the expression

$$NRV = n_p^3 - 1 - \sum_{i=1}^{n_p-1} 6i. \quad (8)$$

The increasing number of redundancies makes difficult the design of a criterion to choose the most convenient redundant vector to control the voltage unbalance. In addition, sometimes the dc voltages balance in multilevel converters cannot be achieved depending on the modulation index and the power factor of the load [99].

Moreover, even if the dc voltages can be controlled around their desired values, additional low frequency harmonics appear in the dc voltages, which can affect the modulator performance. This problem is not exclusive to multilevel inverters, it is common to all voltage source inverters, and has direct relation with the dc link capacitance value and the rectifiers input frequency and the inverters output frequency. Some recent modulation strategies have been presented in order to minimize the oscillations of the dc voltages in multilevel converters. These strategies are capable of reducing the unbalance and oscillations of the dc voltages at expense of increasing the power semiconductors switching frequency [96]-[98]. Other modulation methods take into account the dc voltage unbalance using feed-forward strategies to compensate the oscillations within the modulation stage, generating a pre-compensated output voltage which cancels the distortion produced by these low frequency components [100]-[103].

In conclusion, the balance of the dc voltages of NPC multilevel converters has been an important research drive over the last decades. Nowadays, NPC converters have an important industrial presence in medium voltage drives, and hence this issue can be considered as a solved problem for three level inverters.

B. Multilevel converter modeling

Modeling and simulation of multilevel converter systems are fundamental tasks for their analysis and design process. In addition to the problems related to conventional power converter systems, the modeling of multilevel converters presents new challenges that the engineer has to overcome, mainly due to the more complex power circuit and more available switching states.

Due to the wide range of topologies and operating principles available in multilevel converters, several modeling approaches have been derived. However, all of them take into account the fact that the converter periodically switches among a finite set of different switching states that lead to different transitory power circuits. In [104] it can be found a detailed and systematic classification of models for dc-dc power electronic converters. Since most of modeling techniques for three-phase multilevel converters have been derived from those applied to dc-dc converters, this

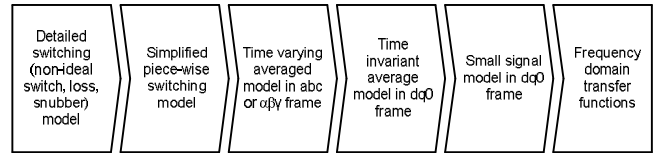


Fig. 34. Most common modelling techniques in multilevel converters.

classification can be considered as a reference for the variety of models that can be found. The description of this wide range of models is out of the scope of this paper so only the most relevant and recently reported ones will be introduced in this section. Figure 34 shows the main modeling techniques used to analyze, design and simulate multilevel converters. In addition, the figure shows the order in which each model is deduced from the previous one.

1) Detailed switching models

The use of powerful and advanced circuit simulation software packages as SPICE or SABER for power electronics converters has been widely reported. The simulation results, when carried out successfully, gives very detailed information about the behavior of the power converter but this modeling simulation technique has some serious drawbacks: 1) Good user defined models for semiconductor switches are needed to get feasible results [105]-[107]; 2) A very realistic circuit characterization is needed to avoid convergence problems and to obtain a stable simulation [108], [109]; 3) And due to the fact that those software packages are designed for circuit simulation, integration in the model of control systems or modulators is possible only with low complexity systems [110], [111] being almost impossible for complex control schemes and advance modulation techniques.

2) Simplified piece-wise switching model

Due to the switching action, which is common on power electronics circuits and hence on multilevel converters, the system periodically switches among a finite set of different circuit topologies. Electrical analysis of each configuration can be made, obtaining a set of differential equations that describe the dynamics of the converter for every switching state. For the compactness of the system equations to be derived, one switching functions can be defined for each

possible configuration of the switches. The switching function takes value '1' when the switches states correspond to that switching function and takes value '0' in any other case.

With the aid of switching functions and considering ideal switches (negligible commutation times and saturation voltages), every converter topology can be represented by a state equation model of the system given by

$$\frac{dx}{dt} = Ax + Bu, \quad (9)$$

where x are the chosen system variables, u is the input vector and A and B matrices elements are the switching functions and linear elements parameters values.

Usually this modeling approximation used under idealized conditions but similar state-space models are not hard to obtain for more elaborate, less idealized and different topologies, for instance, capacitors ESR, switches conduction losses and saturation voltages. Simulations carried out with these models include the switching behavior of the circuit so the ripple on currents and non sinusoidal magnitudes can be analyzed. On the other hand, the controller is hard to derive from these models and only some control techniques, as sliding mode control (bang-bang), can be directly applicable.

3) Time varying averaged models in α - β - γ planes.

The generalized state-space averaging method [112], [113] is a widely used tool for large signal dynamic modeling of power converters. The method is based on the fact that a waveform $x(t)$ can be approximated on the interval $(t - T, t]$ to any desired accuracy by the Fourier series:

$$x(t) = \sum_{k=-n}^{k=n} \langle x \rangle_k(t) e^{jk\omega t} \quad (10)$$

where $\omega = 2\pi / T$ and

$$\langle x \rangle_k(t) = \frac{1}{T} \int_{t-T}^t x(\tau) e^{-jk\omega \tau} d\tau \quad (11)$$

In (11), $\langle x \rangle_k(t)$ is the k^{th} complex coefficient of the Fourier series expansion and n is an integer. If n approaches infinity, the approximation error becomes zero. In most cases it suffices to consider only a few terms (one or two harmonics) but sometimes higher order harmonics are necessary to correctly model the dynamics of the system magnitudes [114], [115]. The application of this method to the state-space model is based on the following two important properties of the Fourier coefficients:

$$\begin{aligned} \frac{d}{dt} \langle x \rangle_k(t) &= \left\langle \frac{d}{dt} x \right\rangle_k(t) - jk\omega \langle x \rangle_k(t) \\ \langle xy \rangle_k(t) &= \sum_{n=-\infty}^{n=\infty} \langle x \rangle_{k-n}(t) \langle y \rangle_n(t) \end{aligned} \quad (12)$$

Applying those properties, both sides of the state-space equation can be expanded to any desired number of terms to find the dynamic of the time evolution of every signal with the desired degree of accuracy.

The generalized state-space averaging method has been applied to different multilevel converters topologies: for NPC [116], [117], FC [114], [115] and CHB [118]. It must be noticed that all these contributions use carrier based PWM

modulation strategies in order to obtain an analytical representation of the switching functions and in this manner achieve the application of the method. This is a serious drawback since other modulation strategies, as SVM cannot be directly integrated in the model to achieve the application of the averaging method. To solve this limitation, instead of averaging the converter state equations, the characteristics or waveforms associated with each of the components in the converter can be directly averaged. This approach is used in [119] and [120] for three and five-level NPC converters respectively where, due to the characteristics of this topology, an additional approximation in the switches is necessary to obtain a unique averaged circuit valid all over the range of existence of the control inputs.

The idea behind the circuit averaging is to work on the schematic replacing the switches (nonlinear elements) by equivalent voltage or current sources. Since the averaged circuit still fulfils the Kirchhoff's Laws, once the switches have been replaced by the corresponding sources, the model of the converter can be developed directly by circuit analysis techniques. In [121] this averaging method is applied to a five-level CHB. Modeling methods have also been developed for the α - β - γ plane [119], [122].

4) Time invariant averaged models in $dq0$ frame.

Previous methods considered large signal time varying models, since ac quantities are time varying even in steady state. From control design point of view, it would be more suitable to have time invariant models. Considering a balanced sinusoidal system, without harmonics, it can be transformed into the $dq0$ rotating reference frame [114], in which the ac system variables appear fixed. In this way, the model equations will correspond to time invariant systems. However, usually nonlinear models are obtained, hence nonlinear control techniques such as feedback linearization [123], nonlinear quadratic optimal control [124], or neural networks [125] should be considered for controller design.

5) Small signal model in $dq0$ frame.

The modeling techniques described previously provide models that are time varying or in most cases nonlinear. Assessing stability, designing and evaluating controllers with nonlinear models is usually difficult and requires application of specific and complex control techniques as it has been stated in the previous section. In addition, the application of nonlinear controllers is not systematic and each system configuration must be studied in order to accommodate the technique to the model characteristics.

Small signal analysis is crucial to evaluate nominal operating conditions, being the linearization the most common systematic and generally successful approach to obtain the small signal model of the converter. The linearization makes sense when applied to a time invariant models, so the small signal model is usually obtained from the averaged time invariant in $dq0$ reference frame. In [126] and [118] a detailed description of the small signal models for a multilevel FC and CHB can be found respectively.

C. Multilevel Inverter fault tolerant operation

There is a growing interest from industry to reduce stop times and increase availability through system monitoring, fault detection, fault diagnosis and fault tolerant operation. This can result in cost reduction, increased productivity and even safety improvements. This is a challenging task, not easy to achieve with traditional power converters. Instead, multilevel converters (particularly FC and CHB inverters) have several characteristics that make it possible: they have modular and scalable structures and they have redundant switching states as seen previously. Several contributions of fault detection and tolerant operation for the FC, CHB and even for the NPC have been reported [127]-[140].

In power converters the failures types can be DC-link short circuit to ground, DC-link capacitor bank short circuit, open circuit damage of switches, short circuit damage of switches line-to-line short circuit at load terminals and single line to ground fault at machine terminals. All these kind of failures are mostly related to the power semiconductors, the gate drivers and the dc-link capacitors.

To be able to achieve fault tolerant operation it becomes necessary to have knowledge about the type of fault and where it has occurred. Therefore, fault detection and fault diagnosis are required. A straightforward fault detection mechanism is to measure currents and voltages across all the components. This alternative is very precise, but not a cost effective solution, considering the amount of components available in a multilevel converter. Another fault detection scheme relies on the output voltages and currents measurements, thus reducing the number necessary sensors, but the detection dynamics depends on the load characteristics [127]. Another alternative fault detection method, used in NPC inverters to detect open circuit faults, is to sense the pole voltages [128]. The pole voltage includes information of switching states in the NPC inverter, concerned by the dc-link but not affected by the load. During abnormal operating conditions, the pole voltage is determined by the direction of the phase current and the switching state for each phase. In this condition, it is necessary to discriminate whether the outer or inner switch is the faulty one and bypassed it using auxiliary switches [128]. The previous discrimination can be done comparing the pole voltage with the switching pattern. If the voltage remains in zero when a switching pattern is applied the direction of the current defines which of the outer switches has failed. On the other hand, if the current remains at zero when a switching pattern is applied the sign of the pole voltage defines which inner switch has failed.

In [129]-[132], the characteristic high frequency harmonics produced by FS-PWM are used to detect a faulty power cell in FC and CHB converters. Using Phase-Shifted PWM, the carriers of frequency f_{cr} for each cell are shifted in such a way that no f_{cr} component should appear in the output voltage. However, under fault condition, the magnitude of the phasor, related with the faulty cell changes, then a component at frequency f_{cr} appears in the output voltage. Once the presence of the component at f_{cr} has been detected, the angle of the resulting phasor is calculated. This angle gives information about which one is the faulty cell. Thus by only measuring the three output voltages of the converter (only three sensors) a

fault can be detected, instead of using, for example, 24 measurements to detect semiconductor malfunction in a three-phase five-level CHB. Fig. 35 shows this fault detection method when a fault has occurred at $t=1.6s$ [132] in a closed loop system operation.

Once a fault has been detected, the power circuit can be reconfigured isolating the defective part. This is why it can be more easily achieved for FC and CHB, since they are modular in structure.

For the NPC more hardware will be needed in order to provide sufficient flexibility to isolate a defective part of the circuit. In Fig. 36 two approaches of additional hardware are highlighted in different color, the one on the right is an additional NPC inverter leg connected through triacs to all the phases, hence the one experiencing a fault can be isolated and replaced. This solution can be found in more detail along with other reconfigurations for the NPC in [141]. The solution shown on the left in Fig. 36 is based on an additional FC inverter leg with its output connected to the neutral point of

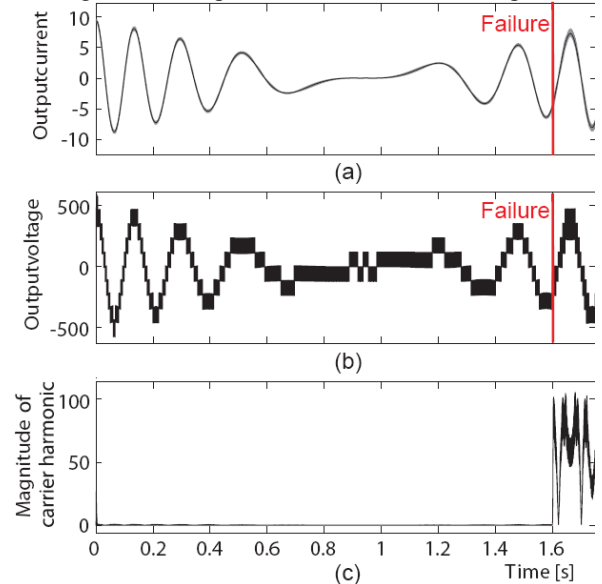


Fig. 35 Fault detection in a CHB a) load current, b) inverter output voltage, c) fault detection by monitoring the amplitude of the f_{cr} component.

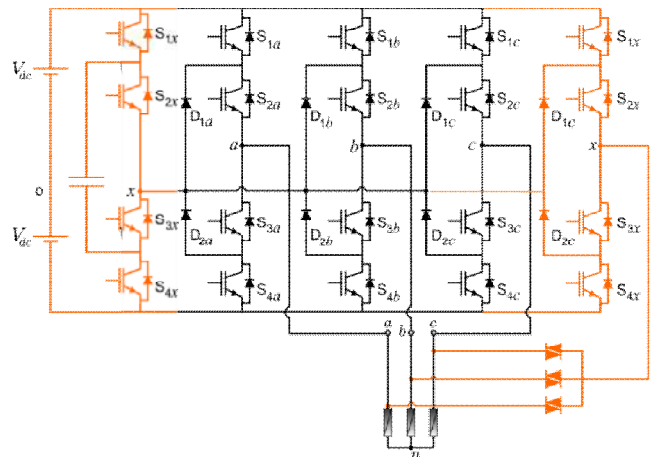


Fig. 36. Two alternatives of modifications to the NPC topology for fault operating capability: left with additional FC inverter leg, at the right with additional NPC inverter leg.

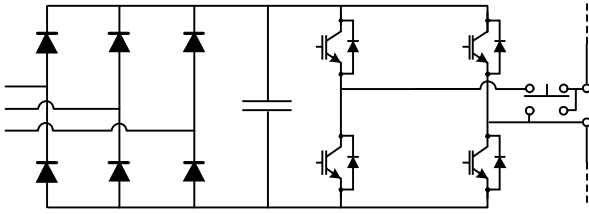


Fig. 37. CHB power cell for fault tolerant capability.

the NPC. This additional leg can be used to control the dc link voltage and provides the extra hardware necessary for fault tolerant operation. More details on this solution can be found in [140].

In [136],[137] fault tolerant operation of CHB is analyzed. A switch is added in each power cell of a CHB as shown in Fig. 37 in order to bypass the cell in case of failure. Hence the converter will reduce its output voltage in the phase where the cell has been bypassed leading to unbalanced voltages, although it will continue operating. Nevertheless, this unbalance can be corrected in two ways: bypassing the same amount of cells in all phases of the converter (this will reduce the total power delivered by the converter); or by changing the

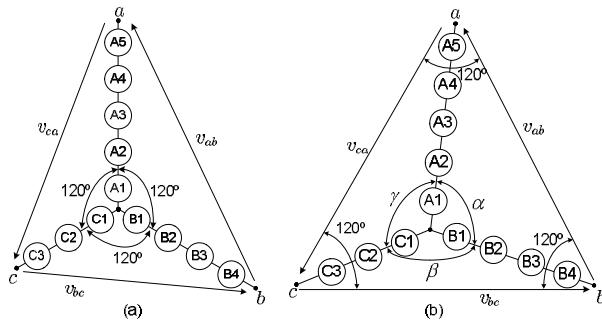


Fig. 38. Phase and line voltages for a 11-level, 5-cell CHB converter with two faulty cells in phase c and one in phase a : a) cells are bypassed an unbalanced operation is obtained, b) cells are bypassed and the references have been changed in angle achieving balanced operation.

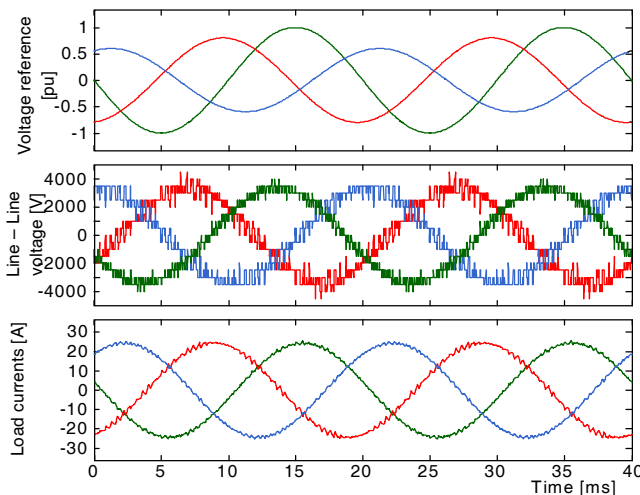


Fig. 39. Fault tolerant operation of a 11-level, 5-cell CHB converter with two faulty cells in phase c and one in phase a : a) unbalanced references, b) balanced line-line voltages, c) load currents.

angle between the references of each phase, in such way that the line voltages are balanced. This solution can be

appreciated in Fig. 38, where the phase voltages of an 11-level (5 power cells per phase) CHB is presented with two bypassed cells in phase c and one in phase a . In Fig. 38(a) the failure cells are only bypassed producing an unbalance output voltage. In 38(b) the reference voltage for each output phase is changed in order to balance the line to line voltage and maximize its value. Results for this method are shown in Fig. 39. Note how the change in the angles introduced for the references make them look unbalanced, instead, the line-line voltage and load currents appear completely balanced.

VII. MULTILEVEL CONVERTER APPLICATIONS.

As mentioned earlier, multilevel converters have found an important market penetration in high power medium voltage applications, where the power range and power quality limitations of classic topologies, justifies their use. In this section some well established and other under development multilevel converter applications are presented. They are organized by field of application.

A. Energy and power systems.

Grid connected systems, such as flexible AC transmission Systems (FACTS), regenerative converters, renewable energy

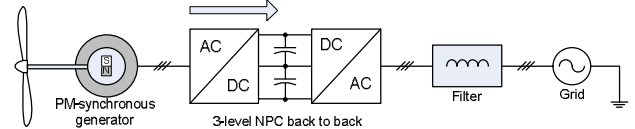


Fig. 40. Three-level NPV back to back for wind energy conversion.

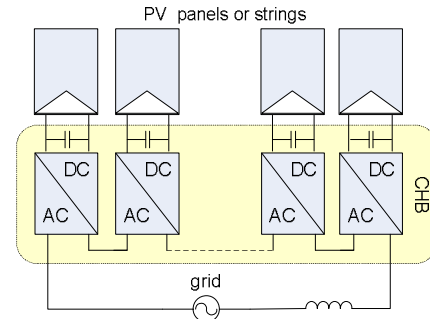


Fig. 41. Grid connection of PV system using CHB.

to grid system, to name a few, share a main development drive: power quality and efficiency. And because several of these applications are going higher in power levels, it is no wonder that multilevel converters have attracted attention as a convenient solution. Nowadays, the integration problem is one of the main concerns of renewable energy providers because new grid codes related to this topic have been presented in recent years and they are now coming into effect. This has motivated research and development in multilevel converter technology for grid connection of renewable energy sources [36]. In particular wind energy conversion benefits in terms of efficiency of larger wind turbines that today can reach up to 5MW. Therefore, multilevel topologies have been proposed, mainly NPC back to back configurations [36], [142] [143], as the one in Fig. 40. Note that the ac-dc/dc-ac converter corresponds to the one shown in Fig. 31.

Photovoltaic (PV) power conversion systems are not yet in the multilevel power rate range. Nevertheless, there are some photovoltaic farms reaching levels of several tens of megawatt, and it is expected to increase with the photovoltaic technology development and cost reduction. Here multilevel converters can also become relevant, since PV strings can be used as dc sources for multilevel topologies. Since there is no need of a rectifier stage the multilevel power circuit is greatly reduced. In addition the multilevel converter can provide control for both maximum power tracking and input power factor. Moreover, it reduces the need for a filter, can improve efficiency (lower switching frequencies can be applied), can eliminate the need of step-up transformers or boost elevator circuits if enough PV sources can be connected in series. Several works using CHB connected to the grid have been reported for PV power conversion [36]. Figure 41 shows the configuration analyzed in [144] and [145].

On the other hand, an actual problem of the electrical grid is the power distribution control and management. In this case, FACTS have been introduced as the solution in order to enhance the controllability and the power transfer capability of the network. Among the many different technologies covered by FACTS, the most interesting one for multilevel converters is in distributed energy applications, where the development of Active Filters (AF), Static Compensators (STATCOM), Dynamic Voltage Restorers (DVR) and Unified Power Flow Controller (UPFC) can provide instantaneous and variable reactive power in response to grid voltage transients, enhancing the grid voltage stability [146]-[149]. These devices (AF, STATCOMs, DVRs and UPFCs) are currently gaining importance due to the harmonic spectrum requirements from the energy providers and the requirement of riding through the voltage sags imposed by the grid codes all over the world. As examples, the diagram of a three-level diode-clamped converter working as a STATCOM and a scheme of a multilevel converter working as a UPFC are shown in Fig. 42 and Fig. 43 respectively, more details can be found in [146]. Other applications include utility adapters, for example to connect a three-phase grid of 50 Hz and a single-phase 16 2/3-Hz for railway application [150].

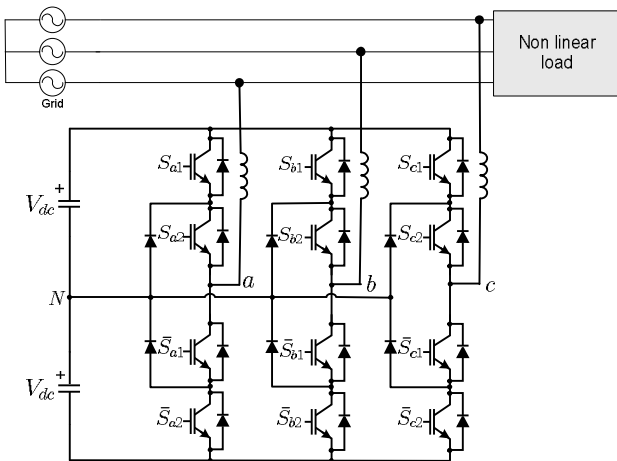


Fig. 42. STATCOM based on a three-level diode-clamped topology.

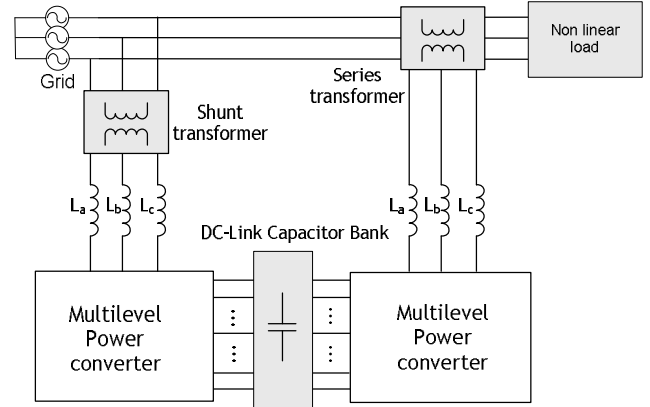


Fig. 43. UPFC based on multilevel converter topologies.

B. Production

Multilevel converter can be found in almost any medium voltage high power motor drive application, having found widespread presence in the petrochemical industry (pumps and compressors), cement industry (high power fans), metal industry (steel rolling mills) and mining industry (copper grinding mills and conveyors for ore transportation), among others. This last one is exposed in the next section.

1) Regenerative Conveyors

Downhill conveyors are used in the mining industry as an alternative to transport the ore produced in the mine to another mining process. Fig. 44 shows an example of a downhill

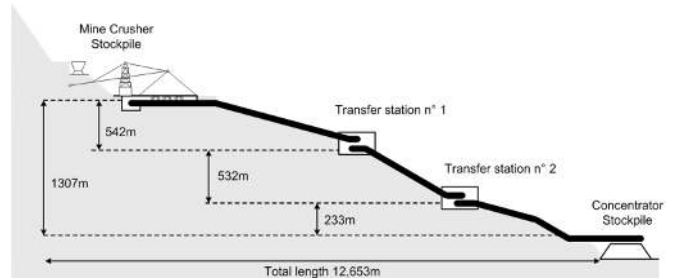


Fig. 44. Downhill conveyor system example.

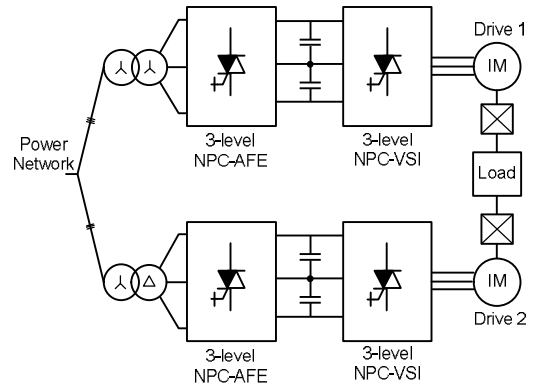


Fig. 45. Conveyor motor drive scheme.

conveyor located in Chilean mining facility [45]. The system operates almost continuously at regenerative requiring a power drive which allows this operating condition in order to improve overall efficiency.

The conveyor is designed to transport 5800 [ton/h] of mineral. The mine stock pile is located at 1307 [m] above the concentrator plant level. The average inclination is 11% and can reach 24% at some places.

The total path is divided in three sections of different lengths: 5905 [m], 5281 [m] and 1467 [m]. Each section has a motor drive in a configuration shown in Fig. 45 where two ac-dc-ac drives feed induction motors that control the conveyor by means of two gearboxes. The delta-delta-why transformer connection achieves 12-pulse operation, improving the input current quality.

Each ac-dc-ac drive is composed by a 3-level active front end NPC rectifier connected in a back to back configuration with a 3-level NPC inverter. Each single drive has a power of 2500 kW. Both sides are implemented using gate turn-off thyristors (GTOs) as power semiconductors. The AFE is modulated using a SHE modulation technique to achieve low switching frequency, allowing to eliminate low order harmonics 11th and 13th not eliminated by the transformer connection [83]. The main features of this drive configuration are [151],[152]:

- fully regenerative operation.
- extremely low input current harmonic content.
- adjustable input power factor.

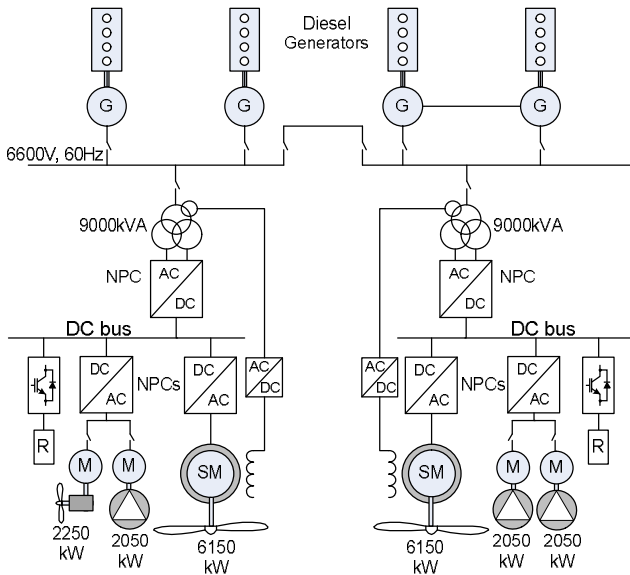


Fig. 46. Tanker propulsion power system.

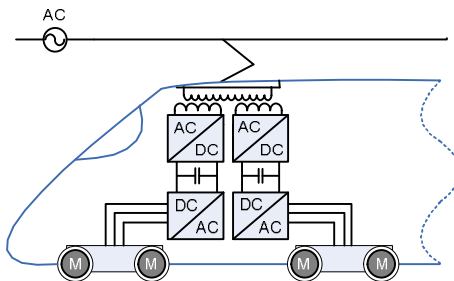


Fig. 47. High speed train traction system using two NPC back to back converters.

C. Transportation

Multilevel converters have important presence in state of the art high power transportation systems such as ship propulsion and high speed train traction. Large ship propulsion, above 25MW, has mainly been dominated by cycloconverters and load commutated inverters. However, in recent years there has been an important market penetration of NPC and CHB topologies for this application. In Fig. 46, the power and propulsion plant for a tanker with twin screw, redundant electrical propulsion system is shown. Two commercial NPC converters drive a 6.15MW motor drive each. The tanker uses a multimotor system in which several motors are fed by the same converter, for example, to drive the pumps for cargo loading and unloading, since cargo pumps and propulsion normally will not be used simultaneously, reducing the overall cost of the system.

One of the applications where multilevel technology is considered as the state of the art power conversion systems is high speed railway traction. The main reason is that high speed trains are driven by higher fundamental frequencies (up to 400Hz) and demand high dynamic performance and efficiency. To generate voltages of such frequencies with traditional two-level converters, and keeping good dynamic performance, will necessarily signify very high switching frequencies, hence losses (including expensive and bulky cooling systems). Multilevel converter not only can reduce the transformer by operating at higher voltages, but also deliver good power quality for the catenaries and motors (less need of filters) and operation with lower switching frequencies while keeping dynamic performance. The use of back-to-back configurations also permits bidirectional power flow, enabling regenerative braking so the energy can be fed back to the catenaries. Because of the back-to-back necessity, and the fact that the transformer for CHB is too bulky, the preferred multilevel topology used for this applications are the FC [153] and NPC [29], [154]. Figure 47, shows simplified schematic of a state of the art locomotive powered by two NPC in back-to-back configuration in which each one powers one bogey containing 4 motors each.

Another very attractive application of multilevel converters in transportation is magnetic levitation, or maglev. An example is the Transrapid system [155]-[158],[23]. Maglev systems do not have traditional rotating motors as regular trains, instead they use linear motors, specifically long stator linear synchronous motors. The system is composed of a propulsion system (rather than traction in this case) and a levitation system. The purpose of the first one is to produce horizontal movement of the train, and is composed of the stator placed on the guideway and the "rotor", which consists of magnets on the vehicle, and is placed on the vehicle. The rotor magnets have also lateral part called guidance magnet that is in charge of keeping the train on the guideway. On the other hand, the levitation system is also performed by the stator attracting the rotor magnets and is charge of suspending the rotor in the air, eliminating friction that is present in traditional rotating machine. Thus, when the long stator windings are supplied with three-phase current, a traveling electromagnetic field is created instead of the rotating magnetic field of a conventional electric motor. This traveling

field interacts with the support magnets of the rotor producing the horizontal thrust. The speed can be controlled in the same way as in rotational machines by adjusting the frequency and amplitude of the stator voltage which acts accordingly on the travelling magnetic field. By shifting the phase angle of this field the motor can accelerate or brake. Since there is no friction, a very high percentage of the energy can be fed back to the grid, improving overall efficiency of the system.

The levitation system is fed by on-board batteries which are recharged through linear generators integrated into the support magnets while travelling.

The high dynamic performance needed by this application, the need of regenerative braking, and the power level of the application makes multilevel back to back converters an attractive solution. In fact the Transrapid uses NPC back to back converters to control the propulsion system as shown in the simplified diagram of Fig. 48. The only difference with the topology shown in Fig. 3, is that it includes asymmetric snubber circuits [155]. It should be noticed that only one segment of the linear stator where the train is crossing is

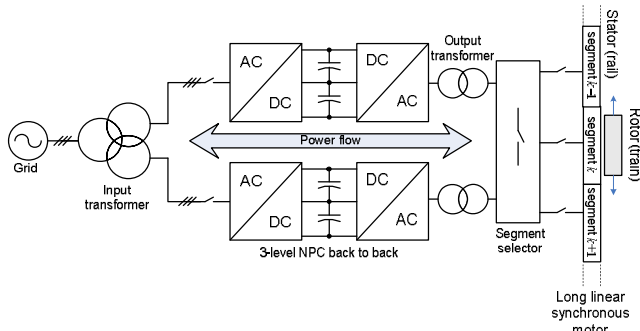


Fig. 48. Maglev train long linear synchronous motor multilevel drive system.

energized, therefore an additional segment selector is needed.

Initially the Transrapid used GTO devices, which are nowadays replaced by IGCT power semiconductors. Because of the high speeds achieved by the train (430km/h), higher fundamental frequencies are necessary, which independently of the modulation method that is used, will require a water-cooled refrigerating system for the power semiconductors due to the high switching frequency and nominal power rating of the drive.

There are currently two Transrapid systems operating in the world: the 31.5 km long test facilities in Emsland, TVE, Germany; and a commercial 30km segment connecting the Long Yang Road subway station with the Pudong International Airport in Shanghai, China. The last one features 12 converter units of 15.6MVA each.

VIII. CONCLUSION

Multilevel converters have matured from being an emerging technology to a well established and attractive solution for medium-voltage high-power applications. Three topologies and several modulation methods have found industrial application. Initially, the higher power rates together with the improved power quality have been the major market drive and trigger for research and development of multilevel converters. However, the continuous development of technology and the evolution of industrial applications will

open new challenges and opportunities that could motivate further improvements to multilevel converter technology.

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