New Trends and Topologies for High Power Industrial Applications: the Multilevel Converters Solution

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***Abstract*—This paper reviews briefly the current scenarios where power electronics converters are being applied. In the paper, the main focus moves towards the high power applications, reviewing the different alternatives and topologies. The multilevel approach is studied in more depth, showing that is a good solution to the challenges that medium voltage-high power applications pose. Several industry examples are introduced and the most suitable modulation techniques for multilevel high power converters are explained. Among them, the recent selective harmonic mitigation method appears as a good solution to achieve a high performance. Finally the conclusions are addressed.**

I. Introduction

Electronics systems are every day more present in our quotidian life, Power Electronics is a specific discipline clearly differentiated from other electronics disciplines like analog, digital or RF, where the main objective is to represent and process electronically an information. Power Electronics on the other hand, deals with the electric energy conversion, and consequently one of the main concerns is efficiency. Although it is a relatively recent technology, its first developments can be dated in the mid 50's thanks to the commercialization of the SCR, its effects on our lives are everyday more and more important, because of its important reduction in cost, size and increase of performances [1]. The use of advanced control techniques, implemented in modern DSPs or DSP-FPGA combination, has made possible many of the desirable characteristics of modern power systems. Today important markets can be found in areas as diverse as: industrial, commercial, residential, transportation, utility, aerospace, military among others. One possible classification could be in three main scenarios and is summarized in Table I, where the main applications, benefits of applying power electronics and the main requirements are presented.

The power rating for these three scenarios ranges from small consumer applications to the power grid applications where very high power applications are needed. In this last group of high power applications, power electronics plays an important role as enabling technology for the integration of renewable energies to the electrical grid, also improving the efficiency and stability of the grid, by optimally controlling the power flows and from the load side, saving the total energy that loads like large motors are consuming. Another promising application for the stability of the network is the capability of the electronics systems to allow the connection of energy storage systems. The classical structure of a power grid can be seen in Fig. 1, where the different parts where the power electronics systems can be employed are identified. This classical structure presents a low meshed network, a poor integration of renewable energies an and inadequate connection between other grids. The new distribution grid concept solves these problems using power electronic converters. In this way, the renewable energies integration in the power grid has created a wide range of possible high power applications for power electronic converters [2], where the current trend is towards higher power systems, especially in wind energy and storage systems. In addition, FACTS converters are especially designed to improve the quality, the flexibility and the stability of the distribution grid.

II. Solutions for High Power Industrial Applications

A. High Power Semiconductors

To implement very high power electronics systems, high power devices are needed [3]. As mentioned before, the solid state power electronics era started about 50 years ago with the commercialization of the SCR. The evolution of power electronic devices has been constant during these years, but it can be mentioned two important milestones: the insulated gate bipolar transistor (IGBT) in the mid 80's and more recently the integrated gate-commutated thyristor (IGCT). These two devices are currently the workhorses for most of the industrial converters. In Fig. 2, some of the currently commercially available devices are shown. There has been an important evolution of these devices in the last decades, but the market driven applications are growing even faster in terms of the rated power required, this opens a new niche for advanced topologies that can overcome this limitation or will take advantage of a more mature device technology that has been tested for years in industry.

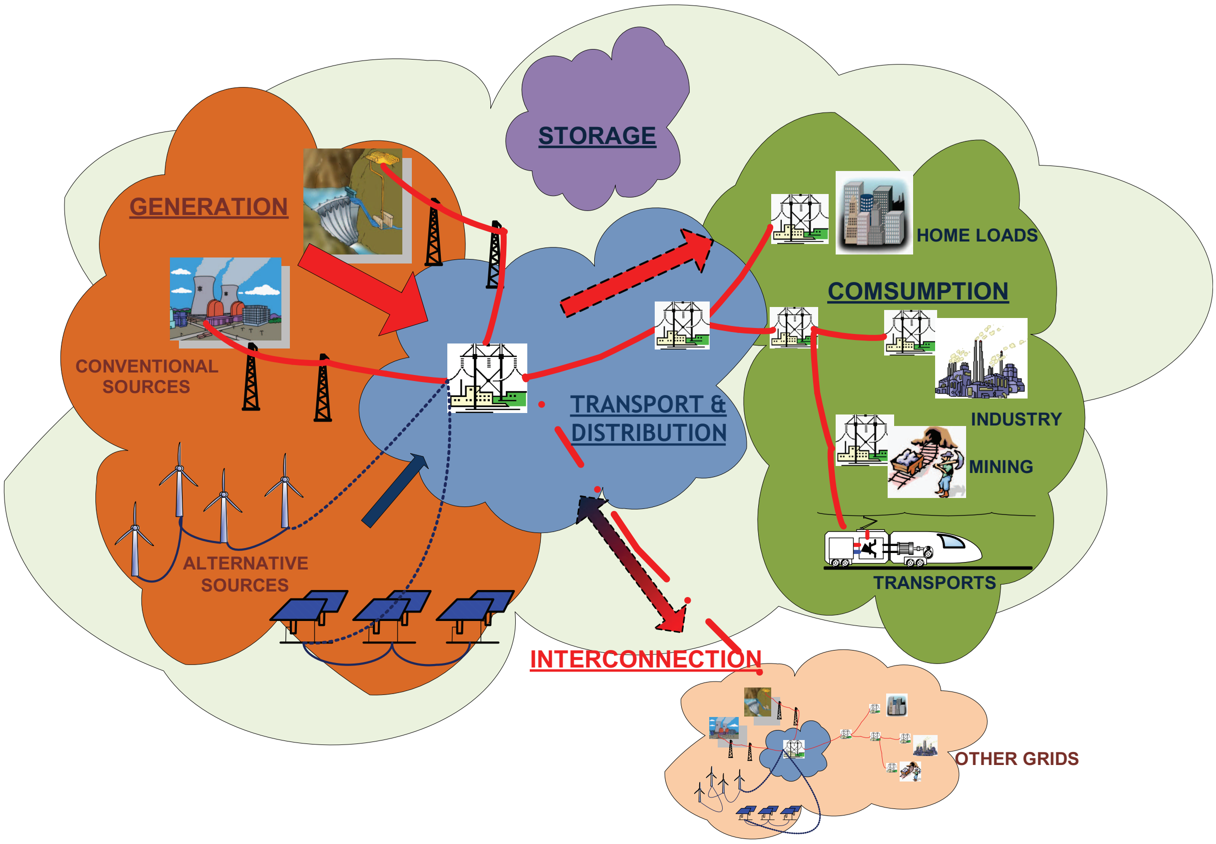

Fig. 1. Current scenario of the electrical grid

B. High Power Converters Topologies. The Multilevel Solution

A power converter for high power applications can be built based on high power semiconductors (several kV IGCTs) but the best option is to use multilevel converters due to their advantages in terms of high nominal power and high quality of the output waveforms [4], [5]. In fact, multilevel converters are becoming the solution to integrate new renewable energy sources to the distribution grid [2]. As it is affirmed in [4], the age of multilevel converters has arrived. Among the multilevel converter topologies, the diode-clamped converter, also usually called neutral-point-clamped converter (NPC), the

TABLE I
MAIN APPLICATIONS, BENEFITS AND REQUIREMENTS OF POWER ELECTRONICS

	Consumer Electronics	Automotive and Transport	Power grids and Industry
Applications	Battery chargers Switched power supplies Portable Devices Household appliances	Trains Automotive Aerospace	Generation (conventional and alternative) Distribution Load side Storage
Benefits	More efficient systems Energy savings Stability Decrease size and weight Integration into portable devices	More electrical vehicles More efficiency and availability New power and traction systems Low maintenance costs Storage and regenerative systems	More efficiency and stability More integration of alternative energies More grid flexibility Increase reliability and robustness
Challenges and Requirements	Decrease losses Decrease production costs High reliability Noise reduction	Decrease losses, weight and size Increase of power managed Increase reliability	More complexity Decrease losses Larger power generators Larger industrial motors

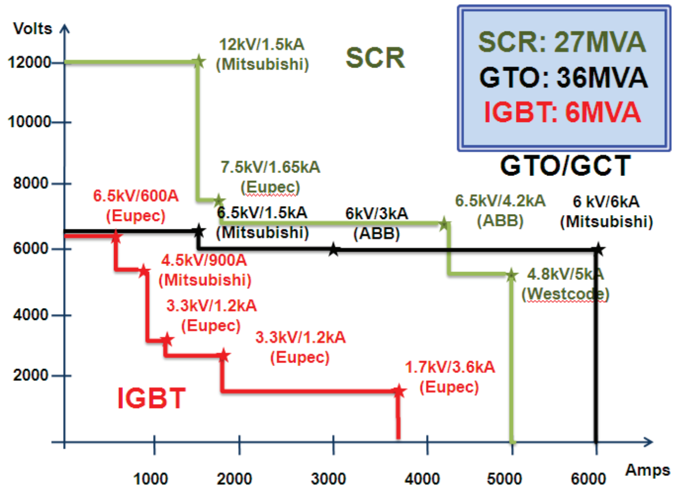

Fig. 2. Classification of the most common power semiconductors

flying capacitor converter (FCC) and the cascaded H-bridge converter (CHB) are the most common ones. A single-phase diagram of these topologies is represented in Fig. 3.

The NPC was introduced in 1981 in [6] and it is the multilevel converter topology with most current industrial application. A diagram of a phase of a three-level NPC is represented in Fig. 3a. The NPC topology has become a mature solution for high power applications due to its high performance in terms of harmonic spectrum quality, low switching losses and acceptable economical cost. Issues as the voltage balance control were overcome for three-level NPC and some three-level industrial products such as ACS6000 (3 MVA–27 MVA, 4.5 kV IGCT based) by ABB [7] or the SINAMICS GM150 (up to 28 MVA, 3.3 or 6.5 kV HV-IGBT for a minimum number of components, 4.5 kV IGCT in the power range above 8 MVA) by Siemens are currently available [8] with applications as pumps and fans, compressors, mine hoists, conveyors, crushers and mills, wind tunnels and marine drives. A laboratory prototype of a 50 kVA three-level diode-clamped converter is shown in Fig. 4.

On the other hand, the modularity is an important feature of the FCC which is formed by the series connection of basic power cells composed by a capacitor and two semiconductors with opposite gating signals [9]. A N-level FCC is formed by N-1 power cells. A single-phase diagram of a three-level FCC is represented in Fig. 3b. In addition, the voltage balance control of the floating capacitors of the power cells can be naturally achieved by using the phase-shifted PWM modulation technique [10]. The FCC topology is especially well designed for applications where the number of levels has to be high. Some industrial products are present in the market as the VDM 6000 (up to 2240 kW, IGBT based) by ALSTOM [11]. It can be applied to fans and pumps, compressors, conveyors and mills, mine winding machines, propulsion drives in marine applications, as well as all sectors of the metal industry.

Finally, the multilevel CHB topology introduced in [12] also presents high modularity because it is composed by several full H-bridges connected in series. A single-phase diagram of a five-level CHB is represented in Fig. 3c. A possible disadvantage of the CHB topology is that independent dc sources are needed for of each H-bridge. For this purpose, a transformer with different secondaries can be used in order to build an ac-ac converter. Other possible solution is to use different dc sources to provide energy to the converter, i. e., connecting different PV strings to each H-bridge or building a hybrid power system with fuel cells, solar panels and batteries [13]. In this way, the CHB topology has good features when several dc sources are present in the power system. Some industrial products are present in the market as the MVD Perfect Harmony by Siemens-Robicon (up to 22 MW, IGBT based) [14]. It can be applied to retrofit, power generation, power water/wastewater, oil and gas and pulp/paper. A laboratory prototype of a 50 kVA two-cell CHB converter is shown in Fig. 5.

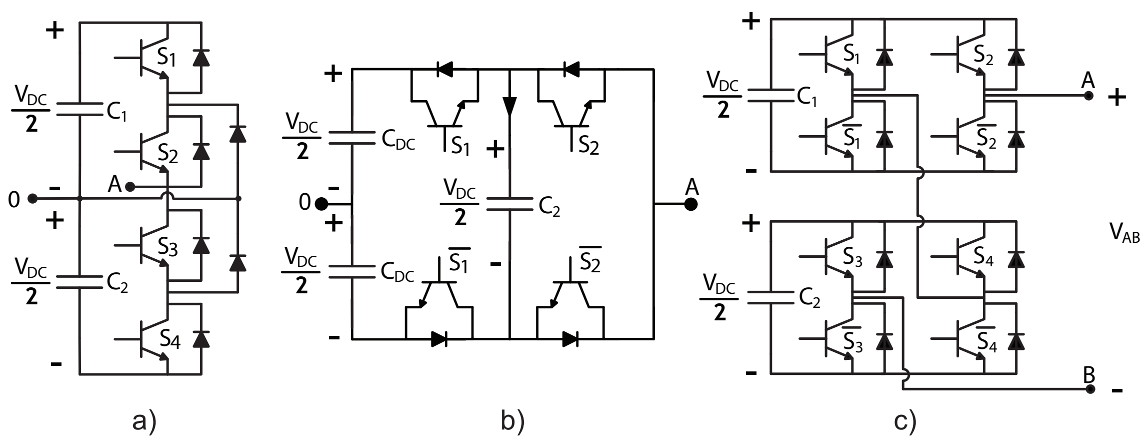

Fig. 3. Most common multilevel converter topologies. a) Three-level diode-clamped converter also called neutral-point-clamped converter (NPC) b) Three-level flying capacitor converter (FCC) c) Five-level cascaded H-bridge converter (CHB)

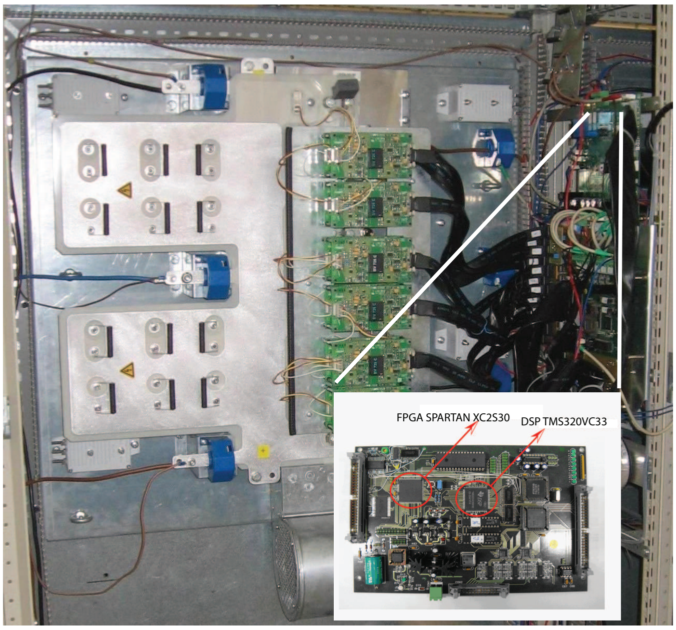

Fig. 4. Laboratory prototype of a medium-voltage 50 kVA three-level diode-clamped converter. The control hardware system is based on a DSP-FPGA platform.

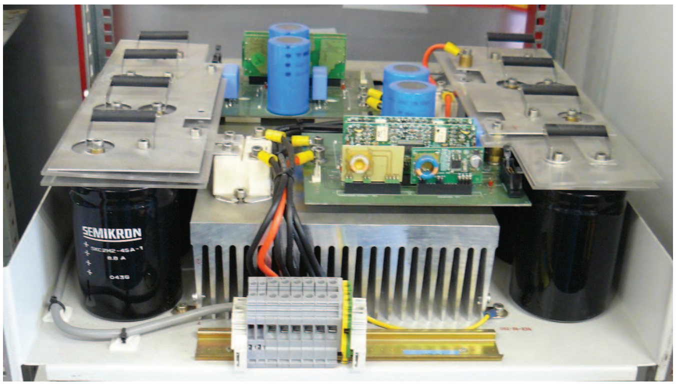

Fig. 5. Laboratory prototype of a medium-voltage 50 kVA two-cell cascaded multilevel converter.

III. Modulation Techniques for High Power Converters

A very important feature of the multilevel converters operation is the modulation technique to be applied. In Fig. 6, a classification of the most common modulation techniques for multilevel converters is introduced [4]. In general, all the modulation techniques can be classified in three main groups: high switching frequency PWM, mixed switching frequency and fundamental switching frequency. The high power applications need low switching frequencies to limit the losses below acceptable values and therefore only mixed and fundamental switching frequency modulation methods can be applied.

The mixed switching frequency techniques are based on a combination of very low switching frequency techniques and medium frequency PWM techniques. It is specifically designed for asymmetrical multilevel CHB converters where each H-bridge provides different amount of power. The high power cells are modulated using simple comparisons with a voltage value achieving very low switching losses. The low power cells are modulated using a classical unipolar PWM technique finally generating the output waveform with low harmonic distortion and low losses [15].

If the power losses are still high or the multilevel converter is not an asymmetrical CHB, a fundamental switching frequency modulation method has to be used. Two different modulation techniques are the most important methods using fundamental switching frequency: space vector control and selective harmonic control. The space vector control (SVC) is based on the space vector modulation concept but only using one switching state of the converter to generate the desired reference voltage [16]. However, it can be noticed that the SVC technique only achieves good results if the switching frequency is above 2.5 kHz or when the number of levels of the converter is at least eleven. Therefore, only multilevel converters with a very high number of levels can use SVC for high power applications.

Finally, the selective harmonic control methods appear as the best solution to modulate a multilevel converter for high power applications. Among the selective harmonic control methods, the well known selective harmonic elimination technique (SHEPWM) is a pre-programmed PWM technique where the switching angles to apply to the converter are determined in order to make zero some harmonic order in the harmonic spectrum of the output waveforms [17]. For instance, if three switching angles α_1, α_2 and α_3 are considered and a symmetrical waveform is assumed, three conditions can be applied. The modulation index can be fixed generating the desired RMS voltage and two harmonic orders can be eliminated (usually 5^{th} and 7^{th} which are the lowest non-triplen harmonic orders). The SHEPWM technique has been successfully extended to different multilevel converter topologies being applied to several high power applications.

However, current regulations all over the world do not force to make zero the harmonic content of some harmonic orders. All the grid codes which are currently coming into effect only fix maximum values for each harmonic order up to 49^{th}. SHEPWM technique was not originally designed taking into account these grid codes. SHEPWM achieves the elimination of several low order harmonics avoiding the necessary passive filters to reduce their contribution. However, the other harmonic orders are not considered and usually bulky and expensive filters are needed to reduce these harmonics up to acceptable levels. In order to improve the SHEPWM technique taking into account the current regulations, the selective harmonic mitigation technique (SHMPWM) was introduced in [18]. The SHMPWM is a flexible pre-programmed PWM technique where the objective is to maintain all the harmonics as much as possible below the maximum allowed values imposed by the grid codes. Therefore, is an extension of the SHEPWM technique considering the actual scenario of the regulations. In the SHMPWM technique, the switching angles

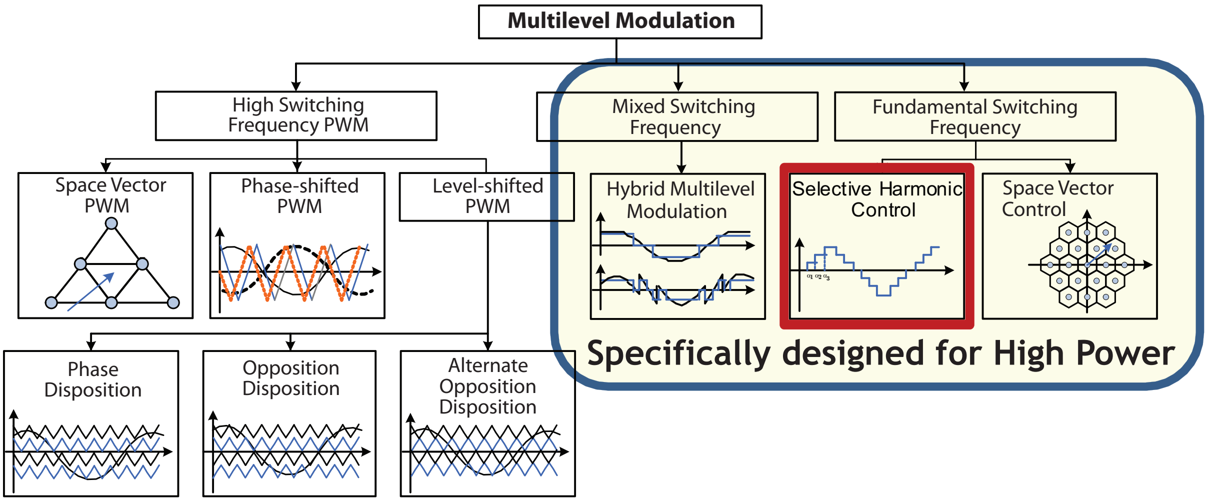

Fig. 6. Classification of the most common modulation of multilevel converters

α_i are determined using optimization methods where the cost function is related to the distortion that has to be reduced comparing with the grid code. The difficulty of the SHMPWM technique lies in the design of the best cost function to achieve the best results. Usually, the cost function is defined using factors c_1 and E_1 to fix the fundamental harmonic. In addition, the weighting factors c_i (i=5,7,...,49) and the harmonic distortion errors E_i are used which are equal to the necessary distortion to be reduced for each harmonic order i. Factors H_i are the distortion of harmonic order i achieved by the SHMPWM technique and L_i is the maximum value allowed by the applied grid code for the harmonic order i. In addition, usually grid codes also fix the maximum value of the total harmonic distortion (THD) by factor L_{THD} so additional variables H_{THD}, c_{THD} and E_{THD} have to be introduced. The final switching angles α_i are those optimizing the value of the cost function OF.

$$
\begin{gathered}
E_i = H_i - L_i \\
E_{THD} = H_{THD} - L_{THD} \\
OF = c_1 E_1 + \sum_i c_i E_i + c_{THD} E_{THD}
\end{gathered}
\tag{1}
$$

The SHMPWM technique has been successfully applied to three-level converters demonstrating that it can be designed for any multilevel converter topology. In Fig. 7, a comparison of the experimental results obtained using the classical SHEPWM and the SHMPWM methods is represented. In this case, 15 switching angles are considered and the modulation index is equal to 1.07. Under these conditions, from Fig. 7a, it is clear that the SHEPWM technique is able to fix the fundamental harmonic and it eliminates harmonics up to 45^{th} as expected. However, harmonics 47^{th} and 49^{th} are above the grid code that is also represented in the same figure (red line). In addition, the distortion to be reduced in harmonics 47^{th} and 49^{th} is very high so bulky and expensive filters are needed. On the

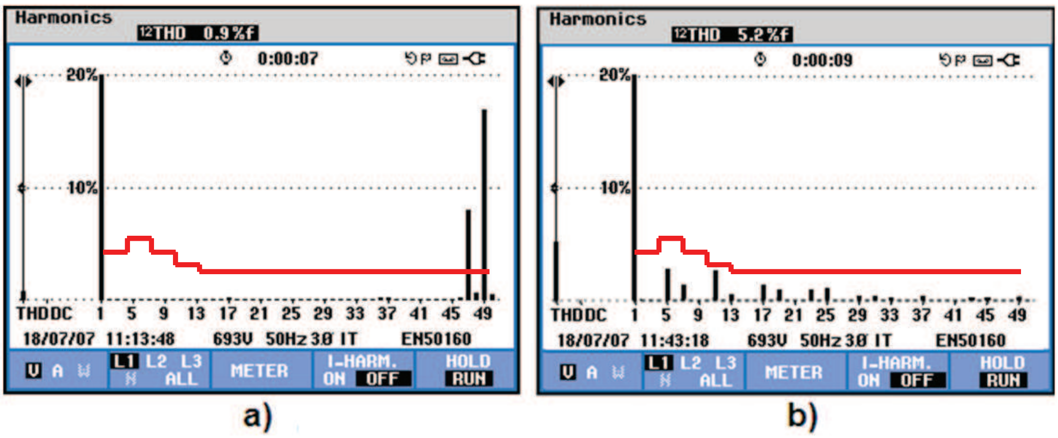

Fig. 7. Comparison between the obtained results using: a) Selective Harmonic Elimination technique b) Selective Harmonic Mitigation Technique. The maximum allowed by the applied grid code (EN 50160 requirements + quality grid code CIGRE WG 36-05) is also represented in red.

other hand, in Fig. 7b the same conditions are considered applying the SHMPWM technique. In this case, harmonics 47^{th} and 49^{th} are below the limit imposed by the grid code avoiding the use of filters. This is achieved at the expense of increasing the value of all the harmonics but all of them are below the limits acceptable for the grid code. It can be noticed that the SHMPWM technique is suitable to be applied to any multilevel converter topology and can be extended to be used when the number of levels of the converter is higher. Therefore, SHMPWM technique presents the best performance for current high power applications. It only presents problems when a high dynamic response of the system is needed what is not usually required in very high power applications. However, some recent works deal with this concern [19].

IV. Conclusions

Power applications are step by step increasing their nominal power because of the continuous power demand growth. In this paper, it is claimed that multilevel converters are the most convenient way to provide power conversion for medium-voltage high-power applications. Challenges such as optimized modulation and control techniques, necessary hardware/software platforms and other technological issues have been overcome in the last years [4]. In fact, the multilevel converters are currently being adopted by the industry as a mature technology and several industrial products are already present in the market.

There are still some issues to be improved such as the dissemination of the results to more industries (fundamental to achieve a widespread use), the reliability and the fault tolerant operation where the researchers all over the world are currently focused. However, it can be affirmed that the multilevel converters are experiencing a fast growing expansion with a brilliant future for a high number of applications as the renewable energies integration, storage systems, FACTS, motor drives and electric vehicles.

Acknowledgment

The authors gratefully acknowledge the financial support provided by the Spanish Ministry of Science and Technology under the project TEC2006-03863 and by the Andalusian Government Research Council under the project EXC/2005/TIC-1172.

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