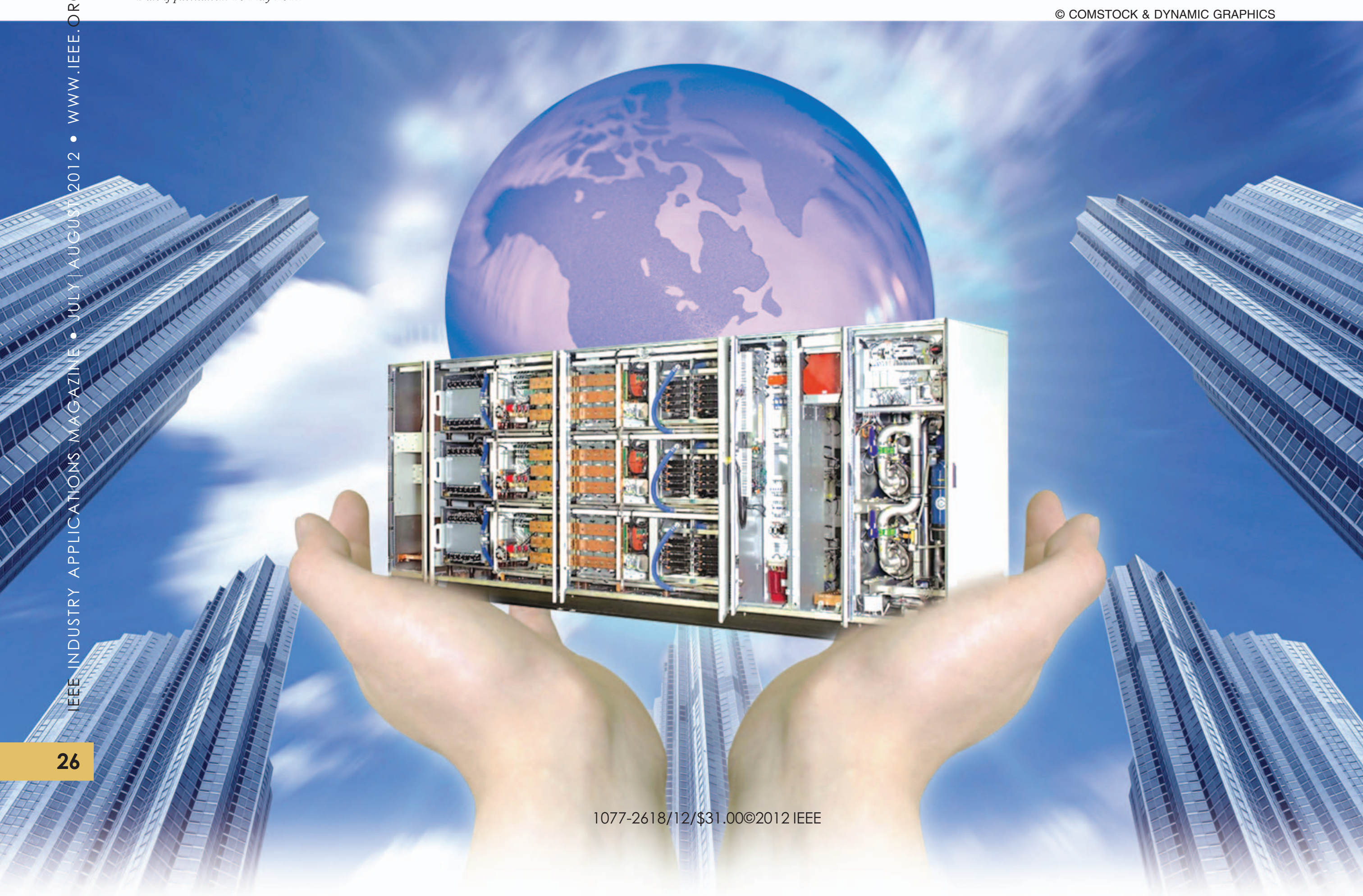
POWERING THE FUTURE OF INDUSTRY

BY SAMIR KOURO,
JOSE RODRIGUEZ,
BIN WU,
STEFFEN BERNET,
& MARCELO PEREZ

High-power adjustable speed drive topologies

THE DEVELOPMENT OF ADVANCED and more cost-effective industrial processes, driven mainly by the economy of scale and higher production rates, has boosted the presence of high-power (HP) drives in several industrial sectors. In addition, efficiency has become a major figure of merit in today's industry because of the economical benefits along with the importance of sustainability. This has led to a higher demand for adjustable speed drives (ASDs), increasing their percentage of share in a market greatly dominated by standard direct grid-connected motor drives (still more than 80% in several industrial sectors). Other factors that have contributed to this recent shift in trend are the developments in power electronics, the increase in

Digital Object Identifier 10.1109/MIAS.2012.2192231
Date of publication: 10 May 2012



1077-2618/12/$31.00©2012 IEEE

reliability of power converters, and the fact that life-cycle costs (initial cost plus cost of operation during the projected life of the drive) have become more important than initial investment in the drive-selection process, especially in HP applications. This article gives an overview of the present state of technology of HP-ASD topologies.

An HP-ASD System Overview

HP-ASDs can be found commercially in single or paralleled units ranging from a power capacity of 0.4 to 200 MVA. Most HP-ASDs operate in the medium-voltage (MV) range (2.3–13.8 kV) [1]. Typical drive voltages are 2.3, 3.3, 4.16, and 6.6 kV. Although less common, some HP-ASDs operate in low voltage, usually at 690 V, and require paralleled converters (or paralleled devices or phase legs) to reach power levels above 0.75 MVA. The operation of HP-ASDs in MV has some benefits such as lower current ratings, smaller cables, smaller dc-link energy storage components, and higher efficiency; therefore, it is the mainstream solution found in HP-ASDs in practice.

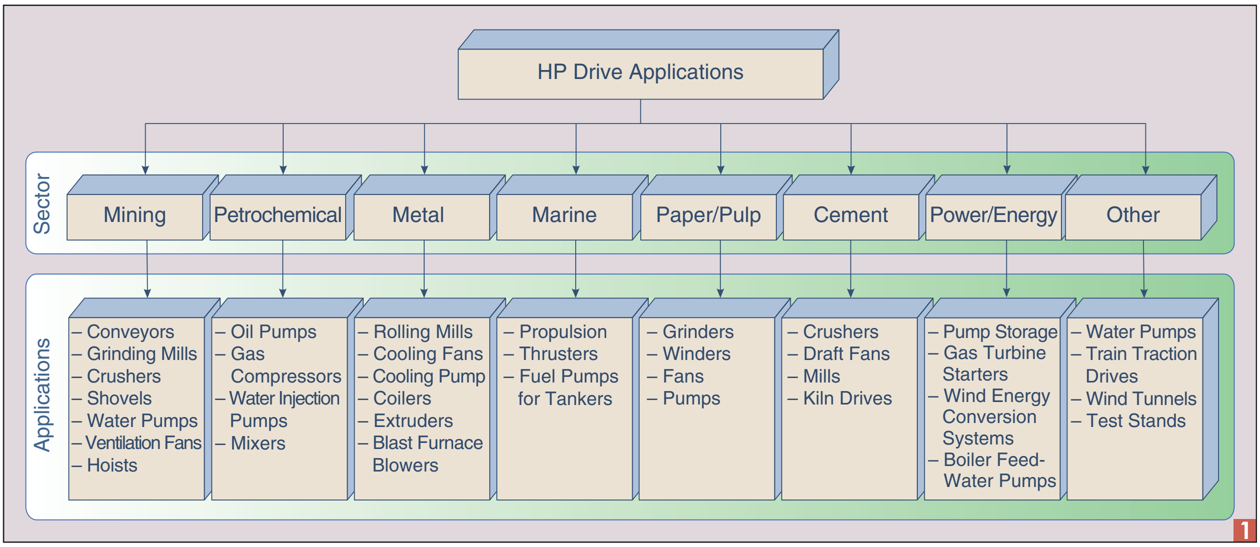
HP-ASDs enable a wide range of industrial processes from simple pumps and fans to high-performance magnetic levitation traction drives and variable-speed wind energy conversion systems (WECSs). The mining, petrochemical, and metal industrial sectors are probably the ones that most depend on HP-ASDs. A list of industrial sectors and their respective applications of HP-ASDs is shown Figure 1.

Variable speed operation has several advantages that may vary depending on the application. For example, pumps, fans, and compressors greatly benefit from variable speed in terms of efficiency, particularly when operating below the rated values. The drive speed can regulate the flow of the liquid or gas to the required value, without losing energy in valves or other mechanical equipment regulating the flow for a fixed-speed pump. In other applications, such as train traction drives and downhill conveyors, ASDs not only regulate the speed but also control the power flow of the system [2], [3]. For example, when the train or conveyor is braking, power can be fed back to the grid, dramatically improving the system efficiency compared with mechanical or electrical resistive braking systems. In WECSs, variable speed operation allows for tracking the maximum power point of the turbine for a given wind speed, maximizing the energy captured by the system [4].

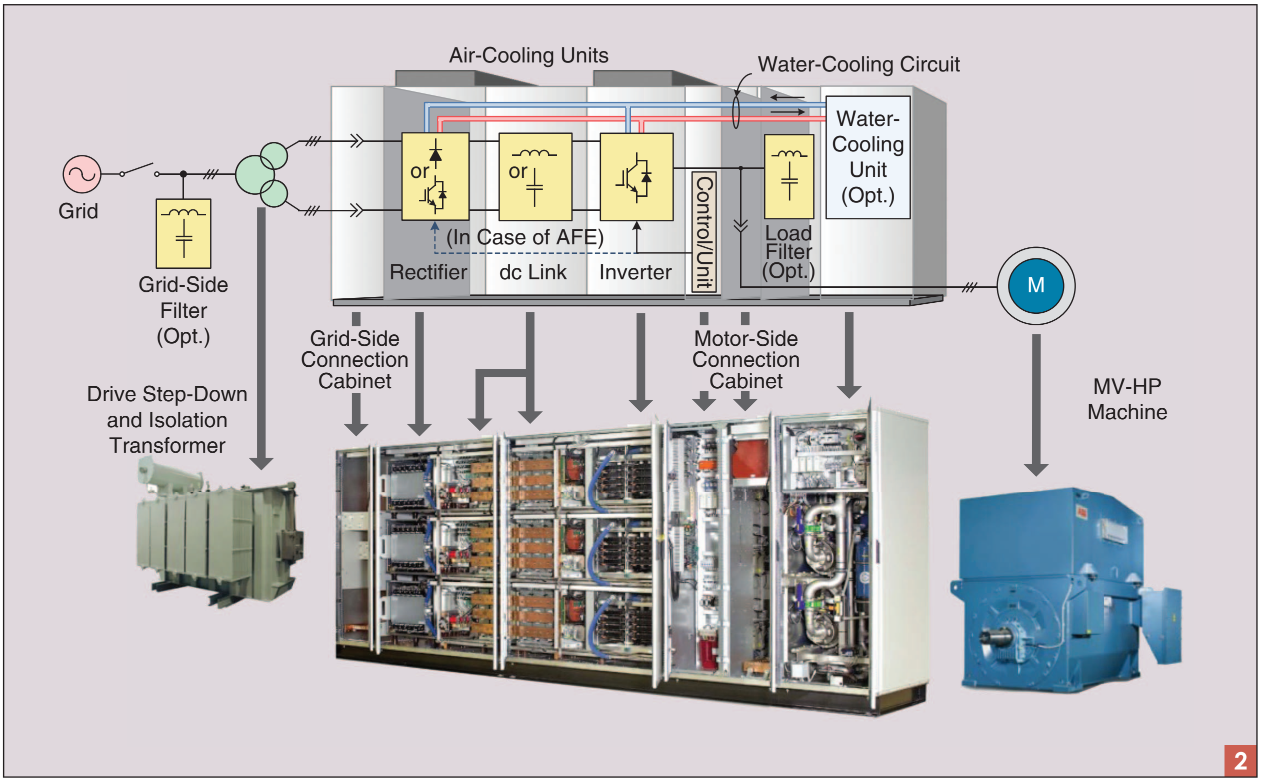
An HP-ASD is not just a single piece of equipment. In fact, it is a system of multidisciplinary nature that involves power electronics, electromechanical systems, control systems, digital signal processing, finite element analysis, thermodynamics, and even economics. Figure 2 shows an example of a typical HP-ASD. The system consists of a circuit breaker that is used to connect/disconnect the drive to the grid. The transformer steps down the grid voltage to the system's operating voltage and provides galvanic isolation. Some drive configurations that are discussed later do not require a transformer. In addition, depending on the topology and power levels, some systems require grid-side filters to comply with power quality standards.

Between the transformer and machine is the power converter. The power converter is the heart of the variable-speed property of the drive since it is in charge of regulating the power (voltages and currents) delivered to the machine terminals. An HP converter consists of a series of cabinets that host the following components and functions:

- *Grid connection cabinet*: connection point of MV ac line.
- *Rectifier*: converts ac to dc power. It is made of noncontrolled components such as diodes (passive front end) or controllable components made of power switches [active front end (AFE)]. In the case of AFE, the active and reactive power can be controlled, which provides regenerative capability for electric braking or generation applications.
- *DC link*: energy storage stage of the power converter. It may be of a capacitive or inductive nature for voltage source converters (VSCs) and current source converters (CSCs), respectively. The dc link decouples the rectifier from the inverter stage.
- *Inverter*: converts the dc power of the dc link into variable frequency, variable amplitude, and adjustable phase angle of the ac voltages and currents delivered to the machine. In this way, the inverter



HP-ASD applications.



An HP-ASD system description. (Photos in figure are courtesy of ABB.)

is responsible for controlling the torque, flux, and speed of the machine. The inverter converts the dc voltage into ac voltage (for VSCs) or the dc current into ac current (for CSCs) by connecting/disconnecting the machine terminals to different voltage (or current) potentials of the dc link. These connections are possible through power switches that are arranged in different ways with the dc-link capacitors (or inductors) depending on the topology that will be discussed later. The successive alternation between different levels of voltage (or current) results in a time-average voltage in VSCs (or current in CSCs) that can be controlled according to a desired reference. This process of performing the switching between levels over time is known as modulation.

- *Control system*: responsible for achieving the desired dynamic and steady-state behavior of the machine variables (and grid in case of AFE). The controller uses measured and estimated machine variables for feedback to compute the necessary control action(s) to be performed by the power converter. The controller's outputs are usually the control signals resulting from the modulation stage. They are used to control the power switches of the inverter (and rectifier if AFE is used).
- *Load filter*: as the generated voltage (current in CSCs) by the converter is a switched waveform with an ac time-average component (known as fundamental component), the voltage (current in CSCs) waveform may need to be filtered to eliminate the switching harmonics that may cause losses, electromagnetic interference, torque ripple, or other undesirable effects in the machine. Since the machine itself is a low-pass filter of inductive nature, the use of filters may not be necessary, depending on the voltage quality given by a particular topology, the robustness of the machine design, and the application's power quality requirements.
- *Load connection cabinet*: connection point for machine terminals.
- *Air/water cooling units*: power electronic devices have conduction and switching losses produced during the transmission of power and commutation process, respectively. These losses are due to the equivalent electric resistance of the power device during conduction or commutation. Although these losses are small in percentage for megawatt drives (<3%), there is a significant amount of energy that needs to be dissipated to keep the converter running at appropriate temperatures. Heat dissipation is performed by the air-cooling fans at the top of the rectifier and inverter cabinets or by a water-cooling circuit. The use of one or the other depends on the power capacity of the converter and switching frequency. Usually, HP converters are water cooled.
- *Machine*: most commonly used machines in HP-ASDs are squirrel cage induction machines and wound rotor synchronous machines (WRSMs). Nevertheless, wound rotor induction machines and permanent magnet synchronous machines are also used. The term machine includes both motor and generator applications.

The efficiency of the whole systems varies depending on the configuration, topology, machine, control/modulation, and manufacturer. In HP-ASDs, commonly reported efficiencies are >98% for the transformer, >96% for the converter, and approximately 85–95% for the machine.

HP Semiconductors for HP-ASDs

Power Switches

As explained earlier, the core of the ASDs is the converter and the power electronics behind it. The evolution of the power converter topologies, such as power ratings, efficiency, reliability, cost, and performance, is directly related to the evolution in power semiconductor devices [5].

Table 1 lists the power devices currently used in HP-ASDs along with their ratings and most distinctive features. The most common semiconductor device is the power diode, which is widely used for uncontrolled line-frequency rectifiers (regular diodes) and as freewheeling device in antiparallel connection (fast-recovery diodes) with power switches to enable a current path for some switching states of VSCs. Diodes can reach the highest ratings among the different devices. The most common presentation used in HP-ASDs is the press pack shown in Table 1. The press pack leads to a compact design, particularly if series-connected diodes are required, and enables double-sided cooling [1].

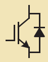
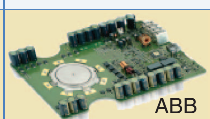
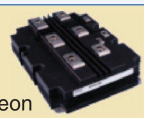
The thyristor, or silicon-controlled rectifier (SCR), is the earliest HP device with control capability. The turn on is achieved by applying a pulse of positive gate current of shorter duration, provided that it is forward biased. It is well proven in practice, very reliable, and efficient and reaches the highest ratings among the active devices and has overload capability. On the weak side, it has a slow commutation, and it is a line-commutated device, which means that the turn off will depend on the load (or grid for the rectifier) operating point and type. This degrades the dynamic performance and power quality. Nevertheless, because it is line commutated, it switches at fundamental switching frequency and, therefore, has a higher efficiency. In addition, the SCR has very low conduction losses when compared with other devices.

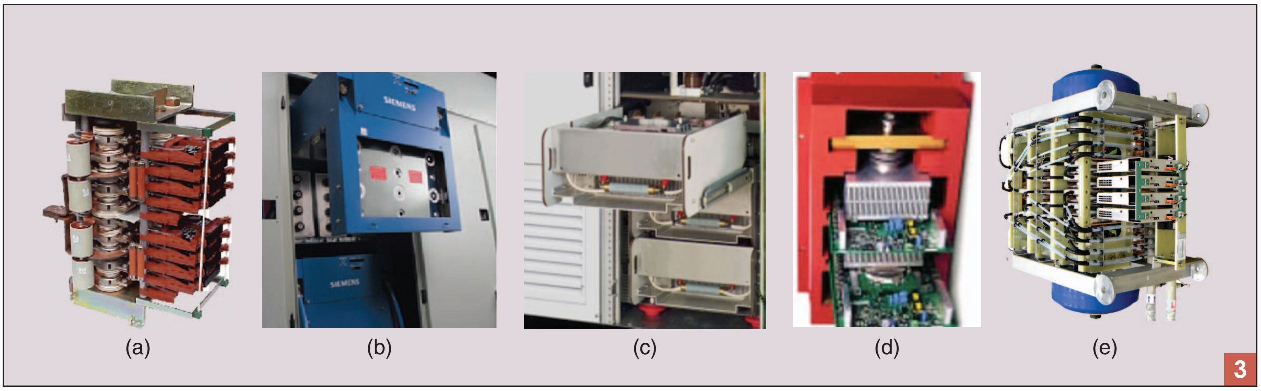
The gate turn-off (GTO) thyristor is a self-commutated variant of the thyristor. The GTO is self-extinguishable since it can be turned off by a negative gate current. GTOs normally have a press-pack design, as shown in Table 1. It has a bulky and expensive turn-off snubber circuit with high snubber losses and a complex gate driver. The GTO is currently obsolete; however, several drives commissioned in the 1990s with GTOs are still operating.

The gate-commutated thyristor [also known as integrated gate-commutated thyristor (IGCT)] is the successor of the GTO. The IGCT has a thinner wafer and smaller gate inductance leading to lower on-state losses. Manufacturers provide proprietary gate drives resulting in a more reliable device. Variants of the IGCT include the asymmetrical, reverse-conducting, and symmetrical types. Asymmetrical IGCTs are used in VSCs with antiparallel diodes. Reverse-conducting IGCTs include the freewheeling diode in the package. Finally, the symmetric gate commutated thyristor (SGCT) is used in CSCs.

The insulated gate bipolar transistor (IGBT) is the dominant technology in low-power and low-voltage applications. Nevertheless, there are a couple of topologies that can arrange these devices to reach an MV operation. It is a voltage-controlled self-commutated device. The module presentation shown in Table 1 is the most common one. The IGBT device features simple gate driver, snubberless operation, and high switching speed. Recent developments have resulted in IGBTs with higher-voltage blocking capability closer to the IGCT, also known as MV-IGBT, high-voltage IGBT (HV-IGBT), and injection-enhanced

TABLE 1. POWER SEMICONDUCTOR DEVICES USED IN HP-ASDS.

	Diode	Thyristor	GTO	IGCT/GCT/SGCT	IGBT/HV-IGBT/IEGT
Symbol					
Max. voltage	8.5 kV at 1.2 kA	12 kV at 1.5 kA	6 kV at 6 kA	10 kV at 1.7 kA	6.5 kV at 0.75 kA
Max. current	9.6 kA at 1.8 kV	5 kA at 0.4 kV	6 kA at 6 kV	5 kA at 4.5 kV	2.4 kA at 1.7 kV
Features	• Very high power • Reliable (proven) • Conduction losses • Reverse recovery current	• Very high power • Very low losses • High overload • Line commutated • Slow	• High power • Self commutated • Less reliable • Currently obsolete	• High power • Low losses • Self-commutated • Expensive	• Reliable (proven) • Fast • Self-commutated • Medium power
Example	 Westcode 3.6 kV at 1.4 kA	 Semikron 2.8 kV at 1 kA	 ABB 4.5 kV at 4 kA	 ABB 5.5 kV at 0.9 kA	 Infineon 6.5 kV at 0.75 kA
Typical HP converter	– Freewheel diode in MV converters – Multipulse rectifiers	– Cycloconverter – LCI – Rectifiers for MV drives	– 3L-NPC – PWM-CSC	– 3L-NPC – 3L-ANPC – PWM-CSC (SGCT) – 5L-HNPC	– CHB – 2L-VSC (series) – 5L-HNPC – 3L-NPC



Examples of PEBBs: (a) IGCT phase leg for 3L-NPC (photo courtesy of ABB), (b) H-bridge power cell for CHB (photo courtesy of Siemens), (c) Series IGBT-based phase drawer leg for 5L-HANPC (photo courtesy of ABB), (d) SGCT phase leg for PWM-CSC (photo courtesy of Rockwell Automation), and (e) IGCT phase leg for 3L-NPC (photo courtesy of Siemens).

gate transistor (IEGT). Currently, the SGCT dominates the CSC market, whereas the IGBT and IGCT share the VSC market.

Power Electronics Building Block

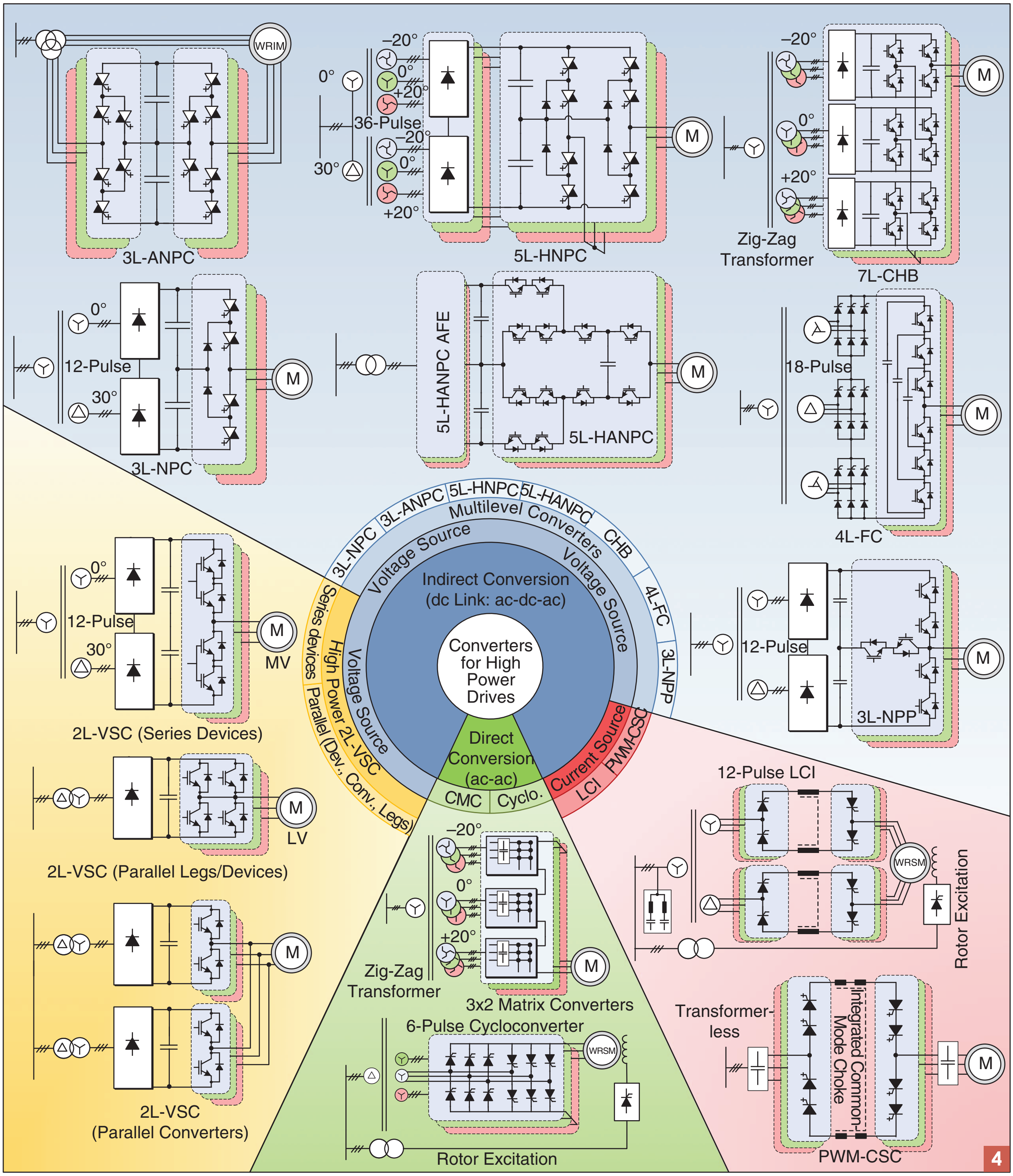
The power electronics building block (PEBB) concept has gained increased attention over time for HP converter design [19], [20]. The definition of PEBB is somewhat ambiguous in the sense that many contributions have adopted the PEBB name to refer to different power electronics assemblies with different levels of integration such as semiconductors with integrated gate drive, integrated power modules with various switch and converter arrangements, a complete phase leg of a converter, or even a whole power cell of a converter. Nevertheless, there is a consensus that a PEBB has a higher level of integration of power electronic components that together form a greater part of the power converter. In the MV market, PEBBs are usually referred to as phase leg assemblies of the power converter. This enables easier scaling of the converter to different power levels by just paralleling PEBBs. The purpose of the PEBB is to increase design flexibility, modularity, and reliability while reducing maintenance and replacement times. PEBBs reduce the development time of new converter topologies and facilitate customization of tailored drives. Different examples of commercially available PEBBs and the corresponding topology in which they are used are given in Figure 3.

HP-ASDs Converter Topologies

Probably, one of the areas where ASD technology has experienced a major leap in the last decade is the appearance of several new commercial power converter topologies [6]. Until the early 2000s, the major players in the HP-ASDs arena were the load-commutated inverter (LCI) and cycloconverter (CCV) for very HP applications, such as marine propulsion and gearless grinding mills, whereas the pulse-width modulation-CSC (PWM-CSC) and three-level neutral-point-clamped converter (3L-NPC) dominated most megawatt applications such as pumps, fans, compressors, and conveyors. These topologies were offered by a handful of manufacturers.

Currently, several companies have entered the MV converter market and offer a wide range of topologies. The converter topologies can be divided into two main groups: direct and indirect conversion. Direct converters are those topologies in which a direct ac-ac conversion is performed between the grid and machine side without energy storage elements. Indirect conversion is shown in Figure 2, in which a rectifying stage is followed by an inversion stage with an energy storage link between them. As mentioned earlier, the indirect approach can be further divided into CSCs and VSCs, depending on the nature of the dc link (inductive and capacitive, respectively). In addition, VSCs can also be classified into two-level and multilevel converters depending on the number of voltage levels generated at the output. This classification, along with the different power circuits of converter topologies, used in practice are illustrated in Figure 4.

The development of so many new MV converter topologies reflects how active this R&D area has been over the past few years. The reasons are as follows: an increase of industrial processes demanding higher power, MV operation, and variable speed capability. Some industries like wind energy are facing new technical challenges and requirements, such as more demanding grid codes and higher power ratings (in megawatt range), which demand more sophisticated drive topologies and control. HP applications, such as ship propulsion, hydro-pumped storage, mineral grinding mills, and downhill conveyors, have also become more demanding in performance, power quality, and efficiency. This has forced the industry to look at newer technology and consider it over well-proven topologies such as CCVs and LCI drives. Another reason for the increase of converter topologies is that what used to be a sophisticated drive technology, engineered and tailored for a specific industrial process, has become a mature technology that can be transferred quickly to a standard off-the-shelf product. The PEBB concept described earlier has greatly contributed to this extent by providing manufacturers with valuable modularity and flexibility to arrange new drive configurations without extensive design and testing before becoming a standard product. Other reasons for the appearance of new topologies are not strictly related to technical matters and may include commercial strategies, marketing, and development of proprietary technology to remain competitive in this fast-growing market.



Classification and power circuits of HP converters used in ASDs. Only one phase is shown in detail for all converters.

Two-Level VSC

The IGBT-based two-level VSC (2L-VSC) is the workhorse in the low-power, low-voltage motor drive industry. Two approaches are available for HP drives: 1) low-voltage 2L-VSC (690 V) with high current to reach megawatt level, in which paralleled devices or paralleled converter-phase-legs or whole paralleled converters are required and 2) MV operation (>2.3 kV) with lower current, which requires a series connection of devices [7]. All these options are shown in Figure 4. The case of low voltage with paralleled converters has been widely adopted in multimegawatt WECSs [4]. The main reason is that standard generators used in WECSs are of low voltage (690 V). However, this alternative is not mainstream in more traditional and industrial HP motor drive applications. In this case, the MV option makes more sense and has been commercialized for pumps, fans, and applications alike. This topology has been discontinued (although some drives commissioned in the last decade are still operative), mainly because the series connection of devices does not introduce any additional benefit in terms of *dv/dt* reduction and power quality. In addition, losses and voltage blocking may be uneven among series devices.

Three-Level Neutral-Point-Clamped Converter

The earliest development of this technology dates to the late 1970s, where the diode clamped concept was introduced [8]. This evolved into the 3L-NPC known today [9], [10] and later became the first multilevel converter that made it into industrial application. The 3L-NPC uses an arrangement of four power switches per leg, clamped with diodes to a midpoint of the dc link, as shown in Figure 4. In this way, each switch blocks half of the total dc-link voltage, enabling MV operation with IGCT and HV-IGBT devices. In addition, the converter can clamp the phase output to the neutral point, generating an extra voltage level compared with 2L-VSC (hence, 3L-NPC). This results in a reduction of *dv/dt* and improved power quality, which made 3L-NPC interesting for MV HP drives. Ratings and other characteristics of the NPC can be found in Table 2. One of the disadvantages of 3L-NPC is that the power switches do not have symmetric losses, forcing a derating of the devices [11]. The converter also requires voltage balancing of the dc-link capacitor voltages [12]. This converter family, although scalable for higher voltages and more levels, requires a series connection of diodes and auxiliary balance circuits to balance the capacitor voltages over the whole operating range for configurations above three levels. Therefore, the diode-clamped converter is commercially available only in three-level configurations. This converter is usually controlled with direct torque control (DTC) and field-oriented control (FOC, also known as vector control). For FOC, a modulation stage is necessary, which is usually level-shifted PWM with added zero sequence and offset to the reference to shift the neutral and balance the dc-link capacitors [13]. The main applications are pumps, fans and conveyors, and traction drive for the magnetic levitation train [36].

Cascaded H-Bridge Converter

The cascaded H-bridge (CHB) converter was the first multilevel concept introduced in the late 1960s [14] but found its industrial application in the 1990s [15]. This topology consists of the series connection of three-level H-bridge power cells, as shown in Figure 4. The series connection allows a natural increase in the converter voltage, hence, the capacity of the converter. The number of levels of the output voltage is $2k + 1$, where k is the number of cells. Thanks to the modularity of this topology, commercial CHBs can be found up to 17 levels and 13.8 kV with low-voltage IGBT technology, as described in Table 2. The most common configurations are the seven level at 3.3 kV and 13 level at 6.6 kV. This converter is usually controlled with FOC using phase-shifted PWM (PS-PWM) [16]. It operates with low device switching frequencies (below 500 Hz), although the output voltage harmonic content (apparent switching frequency) is shifted k times to higher frequencies. Because of the high amount of output voltage levels, this converter does not require an output filter for most applications. The main drawback of this topology is the need of isolated dc sources to power each H-bridge, which requires a complicated phase-shifting transformer. However, this transformer together with diode rectifiers forms a multipulse configuration with very low input current distortion and eliminates the need to balance capacitor voltages. Because of the complicated front end, it is uncommon to see this converter in highly regenerative applications, and the great majority feature diode front ends. The main applications of the CHB are pumps in the water industry and fans in the cement industry.

A variant of CHBs recently introduced in industry is the cascaded half-bridge or modular multilevel converter (MMC, also known as M2C). The MMC is composed of single-phase 2L-VSC legs or half bridges connected in series [6]. The topology has found practical application for HV dc systems [32]. Although it has been proposed for train traction drives [33], it has not yet been commercialized for ASD motor applications, and therefore it is not discussed further in this article.

Four-Level Flying Capacitor Converter

The flying capacitor (FC) concept was introduced in the early 1970s [17] but became practical and was developed for MV drives in the 1990s [18]. The converter generates additional voltage levels, while reducing the voltage stress on the power switches, by clamping an FC between two devices, as illustrated in Figure 4. Each pair of switches with one FC forms a power cell. Additional cells can be connected, increasing the number of voltage levels of the converter, and is therefore considered a modular structure. The four-level configuration found practical application but is currently not under production. The four-level FC converter (4L-FC) can be controlled with FOC and PS-PWM [16]. This modulation naturally balances the capacitor voltage to the desired value. The FCs need initialization, and, therefore, this topology uses a semicontrolled multipulse rectifier as seen in Figure 4. The additional capacitors are considered a drawback since capacitors are more prone to failure than other components of the converter. In addition, higher switching frequencies are required to properly balance FCs and are suitable for higher speed applications. The main applications of the FC are train traction drives and pumps in the water industry.

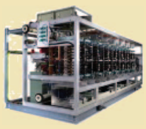
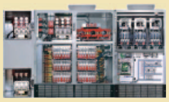
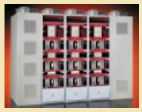
Three-Level Active NPC

The three-level active NPC (3L-ANPC) tackles the main drawback of the NPC by adding one active switch inverse to the clamping diodes, as shown in Figure 4. This enables a controllable path for the neutral current, which allows distributing losses evenly among devices [11]. As a consequence, higher power ratings or switching frequencies are possible. This converter family is offered by one major manufacturer and has been used to successfully control the rotor currents of a 200-MVA doubly fed induction machine for a hydropumped storage system. The machine operates as a generator driving a turbine, when lowering water from the reservoir, and reverses to change the turbine to a pump to store water uphill. The converter is made of two parallel back-to-back (BTB) 3L-NPCs, reaching 30% of the total rating of the system. This enables a 60% adjustable speed range of the drive.

Five-Level H-Bridge NPC

The five-level H-bridge NPC (5L-HNPC) is composed of two 3L-NPC legs forming an H-bridge per phase, as shown in Figure 4. This generates a five-level voltage

TABLE 2. HP CONVERTER RATINGS AND MAIN CHARACTERISTICS (PART 1).

	3L-NPC	3L-ANPC	5L-HNPC	5L-HANPC	4L-FC	CHB
P	0.4–40 MVA	6–100 MVA	2–120 MVA	0.2–1.6 MVA	0.3–8 MVA	0.2–132 MVA
V	1.25–6.6 kV	6–220 kV	6–7.2 kV	4–6.9 kV	2.4–4.16 kV	2.3–13.8 kV
Device	IGCT/HV-IGBT/ IEGT/GCT	IGCT	IGCT/GCT	HV-IGB (two in Series)	MV-IGBT	LV-IGBT
Front end	T n 12/24-pulse diode T n AFE	T n AFE	T n 36 pulse diode	T n Transformerless AFE/Transformer AFE	18-pulse semicontrolled (diode+thyristor) T n	8/24/30/36/48/54-pulse diode Z-transformer T n
Machine	SCIM/WRIM/WRSM	WRIM	SCIM/WRIM/WRSM	SCIM	SCIM/WRIM/WRSM	SCIM/WRIM/WRSM
Control	V/F FOC TC	FOC	V/F FOC DTC	DTC	V/F FOC	V/F FOC
Modulation	LS-PWM α 3L-SHE 3L-SVM	LS-PWM α 3L-SHE 3L-SVM	LS-PWM	DTC (no modulation)	PS-PWM	PS-PWM
Features	• 3L-waveform • Simple front end • Well-proven technology • Clamping diodes • Up to 3L in practice • Uneven heat distribution • Voltage unbalance	• 3L-waveform • Even heat distribution • High capacity • Voltage unbalance • More switches • Up to 3L in practice	• 5L-waveform • Low switching frequency • High capacity • Three separate supplies • No regeneration • Voltage unbalance	• 5L-waveform • Small footprint • Higher voltage • Flying capacitors • Low power • Series devices	• 4L-waveform • Self-balancing voltage • Modular • Flying capacitors • Initialization • Higher switching frequency • Discontinued	• 7L to 17L waveform • Low switching frequency • Higher capacity • Modular • Complex transformer • Large footprint
Ind. drive	 Converteam MV7000	 ABB PCS 8000	 TMEIC-GE Dura-Bilt5i MV	 ABB ACS 2000	 Alstom Alspa VDM 6000	 Siemens Perfect Harmony

output waveform while significantly increasing the capacity of the converter [21]. It is an adapted version of the CHB with only one cell per phase but composed of NPC legs instead of 2L-VSC legs. Like the CHB, it requires isolated dc sources for each H-bridge and, hence, uses a more complicated transformer. However, like the CHB, this comes with significant improvement in the grid-side currents. The converter picture shown in Figure 2 corresponds to a commercial 5L-HNPC converter. The main applications of the 5L-HNPC are compressors, extruders, and conveyors.

Five-Level Hybrid ANPC

The five-level hybrid ANPC (5L-HANPC) is a hybrid topology composed of a 3L-ANPC and an FC power cell connected at the output [22]. This results in a five-level voltage waveform. The FC cell does not increase the power rating of the converter and acts more as an active filter reducing the dv/dt and the total harmonic distortion (THD) of the output waveform. This topology features series-connected IGBTs as shown in Figure 4. The use of HV-IGBTs enables the converter to reach higher voltages up to 6.9 kV, as listed in Table 2. However, the current rating of the devices is lower, and, therefore, this topology is in the lower end of the HP converters with a maximum capacity of 1 MVA. This converter is available exclusively with AFE and is aimed at regenerative braking drives or generators in MV and medium power range. The advantages are improved waveform quality, the ANPC switches operating at fundamental frequency, small footprint, and regenerative capability. The disadvantages are series-connected devices, the use of FCs, and a more complex circuit structure.

Three-Level Neutral Point Piloted

This is the newest addition to the multilevel VSC family for MV drives. It is based on the transistor-clamped concept [23]. The topology is basically a 2L-VSC in which the output phase nodes are connected through a bidirectional switch to a midpoint in the dc link, as shown in Figure 4 [24]. This enables the generation of an additional voltage level, such as with the 3L-NPC. To reach MV operation, series-connected IGBTs are used in the converter leg. The bidirectional switch allows for controlling the neutral current much like the ANPC. Some previous versions of this concept were introduced with different bidirectional switches [23] and extended for more levels. The main advantages are simple converter structure, controllable neutral current, and HP capacity. The disadvantages are the series-connected devices that require a snubber and the use of a bidirectional switch that require a special commutation sequence. The prime application of the three-level neutral point piloted (3L-NPP) is train traction drives.

THE PWM-CSC WAS THE FIRST TRANSFORMERLESS MV DRIVE ON THE MARKET.

PWM-Current Source Converter

The PWM-CSC has found widespread use in heavy-duty MV drives and has been a major player in this area. Compared with VSCs, CSCs modulate an ac current waveform instead of voltage. Instead of a capacitor, CSCs have an inductor choke as a dc link, whose current is controlled by the current source rectifier. The current version of this topology also features an integrated common mode dc choke [31] that enables transformerless operation [1], [25]. In fact, the PWM-CSC was the first transformerless MV drive on the market. Modern PWM-CSCs use SGCT technology and are controlled with FOC and modulated using selective harmonic elimination, trapezoidal PWM, and current space vector modulation. The PWM-CSC delivers sinusoidal voltages to machine and grid side. The switched current waveform is filtered with capacitor filters, as shown in Figure 4, much like the voltage waveform filtered in their counterpart VSCs. This filter also assists commutation, thereby providing a current path for the CSCs. The main advantages of this topology are the absence of dv/dt, no wave reflection, simple converter structure (low switch count), transformerless topology, and inherent overcurrent and short-circuit protection. The main disadvantage is the lower dynamic performance because of the large dc choke, whose current needs to be controlled for dynamic changes. This topology is well suited for HP low dynamic requirements applications, such as pumps, fans, and compressors. A summary of ratings and characteristics is given in Table 3.

Load-Commutated Inverter

The LCI is the first power converter used in HP-ASDs and is composed of a phase-controlled rectifier and an SCR inverter. One of the most common topologies found in practice consists of two units connected in a 12-pulse configuration feeding a six-phase WRSM, as shown in Figure 4. The rectifiers provide an adjustable dc current smoothed by a dc inductor, which then feeds the inverters [25]. WRSMs are normally used in LCI drives since the thyristor switches in the converter do not have self-turn-off capability and their commutation is assisted by the WRSM operating at a leading power factor. The LCI is suitable for very large drives with a power rating of tens of megawatts, as shown in Table 3. This is due to the use of thyristor devices that lead to a low manufacturing cost and high energy efficiency when compared with IGBT or IGCT devices used in other types of drives. A key example of an LCI drive is the 100-MW WRSM drive installed in NASA's wind tunnel test facility [26], the largest full-scale converter-fed drive to date. LCIs are also still popular in marine propulsion drives. The main disadvantages are the grid-side current harmonics, which require additional filters, as shown in Figure 4, and the low dynamic performance.

Cycloconverters

CCVs are based on the antiparallel connection of thyristor bridges without a dc link and are therefore part of the direct conversion family (ac–ac). They are controlled through natural commutation, as described in [27]. A typical six-pulse configuration with one stator winding is shown in Figure 4, although configurations with higher number of pulses are more common. Motors with two separated stator windings are also employed. The main advantages of drives based on thyristors are the low switching losses, therefore, their high efficiency, and the inherent bidirectional power flow capability through the complete speed range. CCVs also can operate under high overload conditions (200% during 1 min or 100% during 5 min). The drawbacks are the limited frequency range (maximum 24 Hz for 50 Hz supply and 28 Hz for 60 Hz supply) and the low power factor at low motor speed. This reliability and efficiency have enabled the use of CCV for the development of HP drive systems for control in low speed range and high torque applications such as cement mills, ore grinding mills, ship propulsion, and mine winders.

Cascaded Matrix Converter

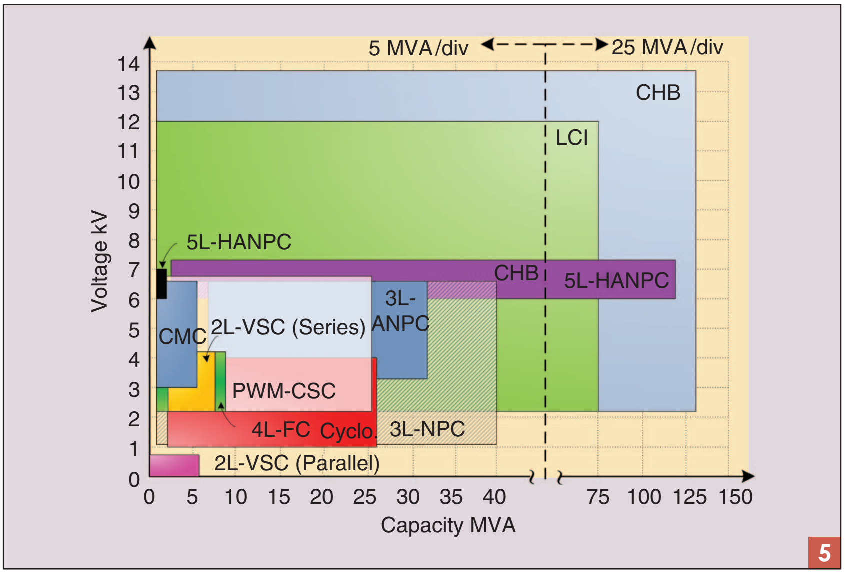
Another direct-conversion HP topology found in industry is the cascaded matrix converter (CMC) [28], which consists of a series connection of several 3×2 matrix converters, similar to the CHB, to reach MV operation. The matrix converter cells directly connect the input ac lines to the output ac lines through bidirectional switches without need of energy storage devices. The additional voltage levels are produced by introducing a phase-shifting power transformer that provides isolated and phase-shifted three-phase secondary ac sources connected to the load side by a matrix converter power cell. This topology can be found with three and six cells per phase to reach from 3- to 6.6-kV operation. The main advantages are the lack of energy storage devices and smaller footprint. Therefore, this topology is useful for HP drives where limited space is available, such as pumps in ships and rigs. Among the disadvantages are the great number of semiconductors needed, the complicated transformer, and special consideration for modulation to avoid forbidden switching states.

TABLE 3. HP CONVERTER RATINGS AND MAIN CHARACTERISTICS (PART 2).

	2L-VSC (Parallel)	2L-VDC (Series)	PWM-CSC	LCI	CCV	CMC
P	<=5.6 kVA	1.4–7.2 MVA	0.15–25.4 MVA	2.8–75 MVA	1–27 MVA	0.2–6 MVA
V	<=690 V	2.3–4.16 kV	2.4–6.9 kV	2.3–12 kV	1–4 kV	3–6.6 kV
Device	IGBT	HV-IGBT (>2 in series)	SGCT/Thyristor	Thyristor	Thyristor	Bidirectional IGBT
Front end	6,12- pulse diode/ Diode + boost	6,12, 18- pulse diode	Transformer less AFE/Transformer AFE 18-pulse SCR	6, 12- pulse SCR	Direct ac-ac	Direct ac-ac + z transformer
Machine	SCIM/WRIM/WRSM	SCIM/WRIM/WRSM	SCIM/WRSM	WRSM	WRSM	SCIM/WRIM
Control	V/F FOC TC	FOC	FOC	FOC	FOC	FOC
Modulation	PWM SHE SVM	PWM SHE SVM	TPWM Current SHE Current SVM	Phase controlled voltage at rectifier side and line commutation at inverter side	Natural commutation technology	Indirect SVM = Voltage SVM + Current SVM
Features	• Known topology • Standard design easy to escalate • 2L-waveform • Parallel devices or converters • High switch frequency • Large dc-link caps	• Known topology • MV operation • 2L waveform • Series devices • High *dv*/*dt*	• Sinusoidal voltage • No wave reflection • No isolation transformer • Low switch count • Lower dynamic performance • Large dc choke • Need of capacitive filters	• Reliable and efficient • Fundamental switching frequency • Low initial cost • Widely proven • Line commutated • Poor dynamic performance	• Good for low speed and high torque • Reliable and efficient • Low initial cost • No storage dc-link • Harmonics • Maximum $f_o = 24$ Hz • Poor dynamic performance	• No storage dc link • Inherent 4Q • Small footprint • Complicated transformer • High device count • Difficult modulation
Example	 TMEIC-GE Tmdrive-10	 Converteam VDM5000	 Rockwell PF7000	 Siemens Sinamics GL150	 Siemens Simovert D	 Yaskawa FSDrive MX1S

All the converter topologies presented previously and shown in Figure 4 have advantages and drawbacks, some of which are listed in Tables 2 and 3. Although each one has some interesting features in which they excel over the others, no power converter topology outperforms another in every technical requirement; they cater the needs of different applications. This can be further seen in Figure 5, where a graphic summary of the power and voltage ratings of the different converter topologies have been illustrated. Note that the power axis has been divided in two different scales to provide more detail between 0 and 40 MVA. From Figure 5, it is clear that some converter topologies are not aimed at the same target voltage or power level. For example, many topologies cannot compete with the CHB in applications above 6.9 kV. Other topologies are aimed at specific applications such as 5L-HANPC, which is available from 6 to 6.9 kV but with a narrower power range offer. From Figure 5, it is also clear that the largest area of overlap (or competition) between topologies is concentrated; hence, the competition is concentrated between 2.3 and 6.6 kV and 0.7 and 25 MVA. This is in direct correlation with the concentration of HP drive applications and their ratings found in industry (such as pumps, fans, and compressors).

Efficiency is one of the key features of MV-HP converters. However, an assessment comparing the classic and newer converter topologies in relation to switching and conduction losses is still pending and is a challenging task to undertake. The fact that many converters use different semiconductors, cover different power ratings and voltage levels, and are aimed at different applications makes it exceptionally difficult to find a common and fair frame of comparison to establish such analysis. Some attempts have been made comparing losses in classic multilevel converter topologies [34], [35].



HP converter operating ranges.

Rectifiers for HP-ASDs

The rectifier side of indirect power conversion systems has two important tasks: providing a steady dc source for the inverter side (or multiple sources) and providing an efficient and high power-quality interface to the grid. The latter is particularly challenging, considering that grid code requirements and standards are very demanding, particularly for HP systems.

There are two types of rectifiers: regenerative and nonregenerative, depending on their ability to have bidirectional power flow or not. Nonregenerative rectifiers are usually based on three-phase diode bridges and are also known as passive rectifiers since there is no control on the ac-side currents and dc-side voltage. Regenerative rectifiers are made of controlled switch device converters and are also known as AFE rectifiers.

Nonregenerative Rectifiers

Most HP applications operate the majority of the time in steady state close to rated values with few dynamic transitions. Moreover, they also operate mainly in two quadrants of the torque–speed curve: positive torque with positive speed and negative torque with negative speed (both in motoring mode). Hence, the power flow is mainly from grid to load, and there is no need for regeneration capability in the grid-side rectifier. This is why passive front ends based on diode three-phase bridges are the most commonly used rectifiers in the megawatt range. A resistive braking chopper is usually connected in parallel to the dc link to dissipate power in case of regenerative operation when braking or during speed reversal.

Diode rectifiers are simple in structure, compact, reliable, and efficient, but do not allow regeneration. However, they deliver pulsating power to the dc link, generating highly distorted input currents with large low-order harmonics. In the megawatt range, most of these harmonics are outside the limits of the grid codes and standards, which would require several passive filters. To mitigate these harmonics and reach MV ratings while reducing series-connected devices, multipulse rectifier configurations are used [1].

A multipulse rectifier is composed of a special transformer with a three-phase primary winding and two or more secondary windings with each one feeding a separate diode-bridge rectifier. By introducing proper phase shifts between the secondary windings, the input current harmonics can be mitigated since the pulsating power between the diode rectifiers are also shifted and combined in the core of the transformer. As a general rule, the phase shift between secondary windings is $60°/n$, where n is the number of secondary windings or diode rectifiers. For a two-secondary winding transformer with a wye connection in the primary, a simple possibility is to use another wye connection in one of the secondary windings (0° phase shift) and a delta connection in the second one (30° phase shift).

A single three-phase diode bridge rectifier produces six power pulses in the dc side (six pulses of voltage charging of the capacitor). Because of the phase shift in the transformer, a two-secondary winding transformer will produce 12 pulses, reducing not only the input current harmonics but also the voltage ripple in the dc link. This multiplicative effect on the pulses gives to this kind of rectifiers their name as multipulse rectifiers. Commonly used configurations are 12-pulse (two rectifiers) and 18-pulse (three rectifiers) configurations. Table 4 shows the rectifier power circuit, the input current waveform (considering capacitive and inductive dc-links), and the input current harmonics eliminated by several multipulse configurations. The six-pulse rectifier is also shown for comparison purposes. Note that, by increasing the rectifier configuration in six pulses, two dominant low-order harmonics are eliminated. Rectifiers of 18 pulses and above comply with IEEE Standard 519. The 12-pulse configuration still requires filtering of some harmonics under certain operating conditions.

Regenerative Rectifiers

In high-performance ASDs where dynamic changes are frequent, such as traction drives, or in highly regenerative applications such as downhill conveyors and large shovels [3], [29], the use of regenerative rectifiers is recommended. In these applications, the higher initial investment of an AFE, compared to diode front end, is paid back in time due to energy savings and greater efficiency. In addition, AFEs have the capability to control the grid currents at will, which enables the elimination of low-order harmonics compared to diode rectifiers. Instead, the AFE introduces switching harmonics that depend on the modulation method and grid interface filter (usually an inductor or inductive-capacitive LCL filters). The only drawbacks of AFEs compared with diode rectifiers are the more complex converter system (additional measurements, control system, and more active devices), higher initial cost, and

TABLE 4. MULTIPULSE RECTIFIER CONFIGURATIONS.

	Multipulse Rectifier	Grid Current (Inductive dc Link)	Grid Current (Capacitive dc Link)	Eliminated Harmonics
6 pulse	i_s, 0°	THD = 28.3%	THD = 98.5%	No harmonics eliminated. Does not comply with IEEE 519 requirements
12 pulse	i_s, 0°, +30°	THD = 12.4%	THD = 21.5%	5, 7th eliminated. Needs filter to comply IEEE 519 requirements
18 pulse	i_s, +20°, 0°, –20°	THD = 7.2%	THD = 7.3%	5, 7,11, 13th eliminated. Complies with IEEE 519 requirements
24 pulse	i_s, –15°, 0°, +15°, +30°	THD = 4.9%	THD = 2.3%	Under 23rd eliminated. Complies with IEEE 519 requirements

lower reliability (switches and gate drives are more prompt to failure than diodes).

In relation to the available configurations, AFEs are usually of the same topology as the one used for the inverter stage. Hence, regenerative rectifier/inverter topologies are also known as BTB converters. Most of the topologies illustrated in Figure 4 are available in BTB configuration, which can be identified in Tables 2 and 3 by the four-quadrant available option. The MV 2L-VSC and the 4L-FC appear without regenerative option found in the market, although BTB configuration is straightforward and reported in literature [16]. The CHB cannot be used in BTB configuration with the same topology because it needs isolation between cells to avoid short circuits. Nevertheless, regenerative versions for the CHB are made possible by replacing the diode front ends of each power cell by a single-phase H-bridge rectifier or a three-phase VSC. This solution dramatically increases the number of switching devices and is therefore not common in practice, although it is offered by one manufacturer [6].

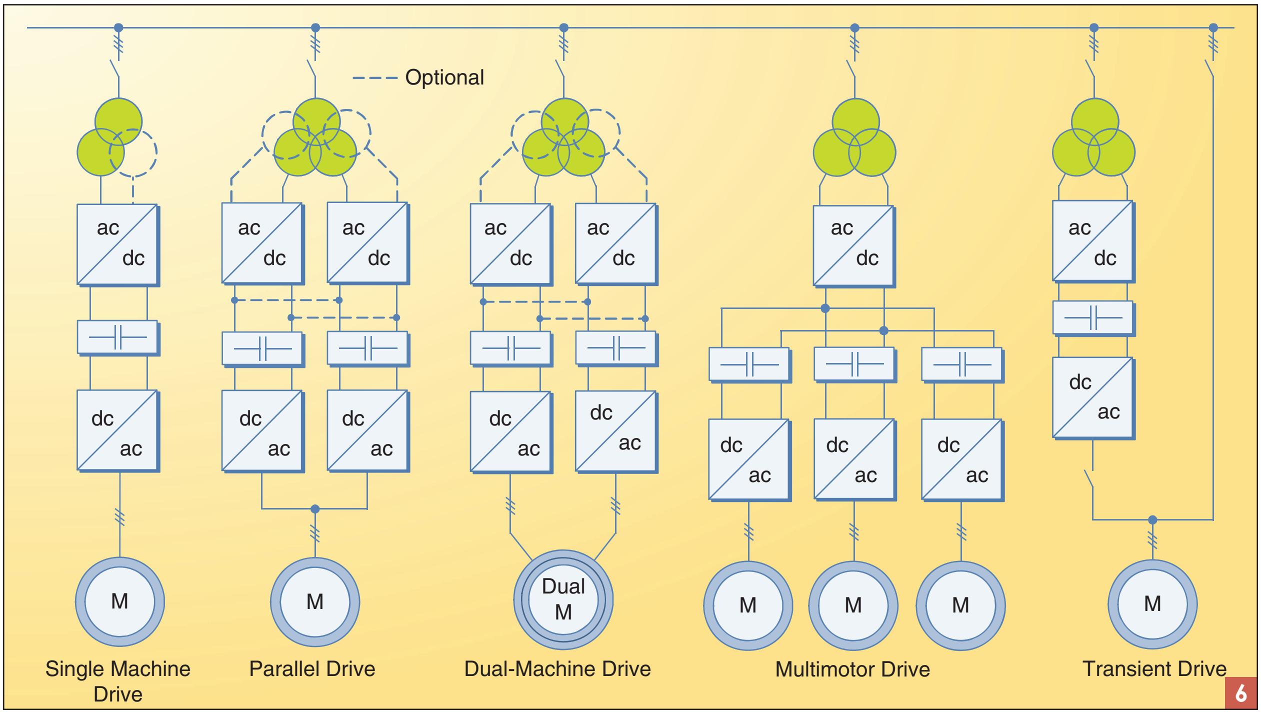
Usually the AFE converter is modulated using the same method employed for the inverter. The same occurs for the control method, where an analogy of FOC and DTC for grid side is used, namely, voltage-oriented control (VOC) and direct power control (DPC), respectively. Instead of controlling torque, flux, and speed as the inverter does, the AFE controls the dc-link voltage (current, in case of CSCs), grid currents, and active and reactive power.

It is worth noticing that HP motors are designed to tolerate switching harmonics and operate with relatively low stator frequencies (<30 Hz, depending on the number of poles), facilitating the job of modulation at the inverter side. Instead, the grid side has more demanding harmonic and power quality requirements and operates with reference frequencies of 50 or 60 Hz, which represents a greater challenge for the modulation stage.

Drive Configurations

The drive topologies shown in Figure 4 consider only single converter and single machine configurations. However, many applications are in a power range where two or more power converters are needed to reach the necessary power capacity. In fact, many of the maximum power ratings given for the different converter topologies in Tables 2 and 3 are obtained by parallel connection of up to four converters in some cases. In addition, many industrial applications such as steel rolling mills, conveyors, and traction drives have more than one machine powering the same process.

Figure 6 shows some of the most common drive configurations used in industry. The parallel drive configuration doubles the total capacity of the converter to power larger loads. It helps to improve the input current waveform by using a multipulse rectifier system. In addition, it provides redundancy in such a way that, if one converter fails, the system can still operate at half the capacity.



HP-ASD configurations.

The dual-machine drive configuration is aimed at dual three-phase winding stator machines, six-phase machines, and open-end windings machines. In this case, the converters are not in parallel. They form a so-called dual channel to power the motor. This configuration has the same advantages as the parallel drive configuration but with the added benefit that power quality can be greatly improved at the machine side as well. Depending on the angle displacement between the two set of three-phase windings, the fifth and seventh harmonics can be eliminated.

The multimotor drive configuration, as mentioned earlier, is useful in cases where several machines are used in the same process. In this scheme, a centralized rectifier (which can be more than one if required) powers a dc bus that feeds all the machines. These machines can work at a same speed with same control, have independent control, belong to different processes, and be of different types. For example, an oil tanker may use the rectifier and dc bus to power the WRSM propulsion motor during transportation while the drives to pump oil in and out of the ship are not in use. Then, on site, the pumps are activated to load/unload the oil with the same rectifier while the propulsion drive is not in use. This saves space and expense since one or more rectifiers can be spared.

Some HP applications do not require high dynamic performance and are operated always in open loop at rated values. This is the case for large fans and large ship propulsion drives, for example. To provide a controlled and soft start for such applications, a transient drive configuration may be used. During the start-up, the machine is powered through the converter, and the direct connection switch to the grid is open. When the system has reached steady state and is operating at rated condition, the converter synchronizes its operation with the grid. After that, the grid switch is closed and the motor is powered through both channels. Finally, the converter switch is opened and the machine is powered solely by the grid. Since the converter is used for short times (only for start-up and short transients), it may be rated at partial capacity.

Reliability and Redundancy in HP-ASDs

Reliability is a very important factor in HP-ASDs. As they power key equipment, downtimes represent huge economic losses. In some applications, failure condition can even lead to hazardous situation for equipment and workers.

To incorporate fault-tolerant capability to the drive, power converters have used the concept of redundant hardware to step in during failure operation. The first solution of this kind was used in thyristor-based converters (LCI and CCV), where an additional thyristor was connected in parallel to each device to provide an extra path in case of a failure. This concept is known as $N + 1$ redundancy. The $N + 1$ concept has also been used in CHB converters by adding a redundant power cell that can replace a faulty one. Both the faulty and redundant cells are disconnected and connected, respectively, by a solid-state bypass switch. These solutions increase the cost and size of the converter. Currently, other approaches of fault-tolerant operation based on using the existing hardware or with minor additions have been reported particularly for multilevel converters [30]. Multilevel converters could be seen as less reliable because of the higher component count, but at the same time, they have more internal redundancies and modular structures that favor fault-tolerant operation. It could be interpreted that they have redundant hardware built in that is in use in normal conditions but can serve for fault-tolerant operation. Perhaps, the greater challenges at the present state of technology are related to fault detection and diagnosis to make fault-tolerant operation feasible in practice.

Conclusions

The HP-ASD technology has experienced a huge development in the last decade. This can be appreciated by the large number of recently introduced drive configurations on the market. In addition, many industrial applications are reaching MV operation and megawatt range or have experienced changes in requirements on efficiency, performance, and power quality, making the use of HP-ASDs more attractive. It can be concluded that, today, more than ever, HP-ASDs is an enabling technology ready to continue powering the future of industry for the decades to come.

Acknowledgment

The authors gratefully acknowledge support by CCTVal (FB0821) and Fondecyt 1110783.

References

[1] B. Wu, *High-Power Converters and AC Drives*. New York: Wiley-IEEE Press, Mar. 2006.

[2] S. Dieckerhoff, S. Bernet, and D. Krug, "Power loss-oriented evaluation of high voltage IGBTs and multilevel converters in transformerless traction applications," *IEEE Trans. Power Electron.*, vol. 20, no. 6, pp. 1328–1336, Nov. 2005.

[3] J. R. Rodriguez, J. Pontt, R. Huerta, G. Alzamora, N. Becker, S. Kouro, P. Cortes, and P. Lezana, "Resonances in a high-power active-front-end rectifier system," *IEEE Trans. Ind. Electron.*, vol. 52, no. 2, pp. 482–488, Apr. 2005.

[4] B. Wu, Y. Lang, N. Zargari, and S. Kouro, *Power Conversion and Control of Wind Energy Systems*. New York: Wiley-IEEE Press, June 2011.

[5] B. K. Bose, "Power electronics and motor drives recent progress and perspective," *IEEE Trans. Ind. Electron.*, vol. 56, no. 2, pp. 581–588, Feb. 2009.

[6] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L. G. Franquelo, B. Wu, J. Rodriguez, M. Perez, and J. I. Leon, "Recent advances and industrial applications of multilevel converters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2553–2580, Aug. 2010.

[7] J. Rodriguez, S. Bernet, B. Wu, J. O. Pontt, and S. Kouro, "Multilevel voltage-source-converter topologies for industrial medium-voltage drives," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 2930–2945, Dec. 2007.

[8] R. H. Baker, "High-voltage converter circuit," U.S. Patent 4 203 151, May 13, 1980.

[9] R. H. Baker, "Bridge converter circuit," U.S. Patent 4 270 163, May 26, 1981.

[10] A. Nabae, I. Takahashi, and H. Akagi, "A neutral-point-clamped PWM inverter," in *Conf. Rec. IAS Annu. Meeting*, Cincinnati, OH, Sep. 28–Oct. 3, 1980, vol. 3, pp. 761–766.

[11] T. Bruckner, S. Bernet, and H. Guldner, "The active NPC converter and its loss-balancing control," *IEEE Trans. Ind. Electron.*, vol. 52, no. 3, pp. 855–868, June 2005.

[12] S. Busquets-Monge, S. Alepuz, J. Bordonau, and J. Peracaula, "Voltage balancing control of diode-clamped multilevel converters with passive front-ends," *IEEE Trans. Power Electron.*, vol. 23, no. 4, pp. 1751–1758, July 2008.

[13] D. G. Holmes and T. Lipo, *Pulse Width Modulation for Power Converters: Principles and Practice*, 1st ed. New York: Wiley-IEEE Press, Sept. 2003.

[14] W. McMurray, "Fast response stepped-wave switching power converter circuit," U.S. Patent 3 581 212, May 25, 1971.

[15] P. W. Hammond, "A new approach to enhance power quality for medium voltage drives," in *Proc. IAS 42nd Annu. Petroleum Chem. Ind. Conf.*, Sept. 11–13, 1995, pp. 231–235.

[16] J. Rodriguez, L. G. Franquelo, S. Kouro, J. I. Leon, R. C. Portillo, M. A. M. Prats, and M. A. Perez, "Multilevel converters: An enabling technology for high-power applications," *Proc. IEEE*, vol. 97, no. 11, pp. 1786–1817, Nov. 2009.

[17] J. A. Dickerson and G. H. Ottaway, "Transformerless power supply with line to load isolation," U.S. Patent 3 596 369, Aug. 3, 1971.

[18] T. Meynard and H. Foch, "Dispositif électronique de conversion d'énergie électrique," French Patent 267 971 5B1, Jan. 29, 1993.

[19] T. Ericsen, N. Hingorani, and Y. Khersonsky, "PEBB—power electronics building blocks from concept to reality," in *Proc. IEEE Industry Applications Society 53rd Annual Petroleum and Chemical Industry Conf., (PCIC)*, Sept. 11–15, 2006, pp. 1–7.

[20] O. Apeldoorn, B. Odegard, P. Steimer, and S. Bernet, "A 16 MVA ANPC-PEBB with 6 ka IGCTs," in *Conf. Rec. 40th IAS Annu. Meeting*, Oct. 2–6, 2005, vol. 2, pp. 818–824.

[21] C. M. Wu, W. H. Lau, and H. Chung, "A five-level neutral-point-clamped H-bridge PWM inverter with superior harmonics suppression: A theoretical analysis," in *Proc. IEEE Int. Symp. Circuits Syst.*, Orlando, FL, May 30–June 2, 1999, vol. 5, pp. 198–201.

[22] P. Barbosa, P. Steimer, J. Steinke, L. Meysenc, M. Winkelnkemper, and N. Celanovic, "Active neutral-point-clamped multilevel converters," in *Proc. IEEE 36th Power Electron. Spec. Conf.*, June 16, 2005, pp. 2296–2301.

[23] J. Dixon and L. Morán, "High-level multistep inverter optimization using a minimum number of power transistors," *IEEE Trans. Power Electron.*, vol. 21, no. 2, pp. 330–337, Mar. 2006.

[24] V. Guennegues, B. Gollentz, F. Meibody-Tabar, S. Rael, and L. Leclere, "A converter topology for high speed motor drive applications," in *Proc. 13th EPE*, Oct. 2009, p. 8.

[25] B. Wu, J. Pontt, J. Rodriguez, S. Bernet, and S. Kouro, "Current-source converter and cycloconverter topologies for industrial medium-voltage drives," *IEEE Trans. Ind. Electron.*, vol. 55, no. 7, pp. 2786–2797, July 2008.

[26] R. Bhatia, H. U. Krattiger, A. Bonanini, et al., "Adjustable speed drive with a single 100-MW synchronous motor," *ABB Rev.*, no. 6, pp. 14–20, 1998.

[27] L. Gyugi and B. R. Pelly, *Static Power Frequency Changers*. New York: Wiley, 1976.

[28] J. Wang, B. Wu, and N. R. Zargari, "High-power multi-modular matrix converters with sinusoidal input/output waveforms," in *Proc. 35th IEEE IECON*, Nov. 3–5, 2009, pp. 547–552.

[29] J. Rodriguez, L. Moran, J. Pontt, J. Espinoza, R. Diaz, and E. Silva, "Operating experience of shovel drives for mining applications," *IEEE Trans. Ind. Applicat.*, vol. 40, no. 2, pp. 664–671, Mar.–Apr. 2004.

[30] P. Lezana, J. Pou, T. Meynard, J. Rodriguez, S. Ceballos, and F. Richardeau, "Survey on fault operation on multilevel inverters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 7, pp. 2207–2218, July 2010.

[31] B. Wu, S. Rizzo, N. Zargari, and Y. Xiao, "An integrated DC link choke for elimination of motor common-mode voltage in medium voltage drives," in *Conf. Rec. 36th IAS Annu. Meeting*, 2001, vol. 3, pp. 2022–2027.

[32] B. Gemmell, J. Dorn, D. Retzmann, and D. Soerangr, "Prospects of multilevel VSC technologies for power transmission," in *Proc. IEEE/PES T&D Conf. Expo.*, Apr. 21–24, 2008, pp. 1–16.

[33] M. Glinka and R. Marquardt, "A new AC/AC multilevel converter family," *IEEE Trans. Ind. Electron.*, vol. 52, no. 3, pp. 662–669, June 2005.

[34] D. Krug, S. Bernet, S. S. Fazel, K. Jalili, and M. Malinowski, "Comparison of 2.3-kV medium-voltage multilevel converters for industrial medium-voltage drives," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 2979–2992, Dec. 2007.

[35] S. S. Fazel, S. Bernet, D. Krug, and K. Jalili, "Design and comparison of 4-kV neutral-point-clamped, flying-capacitor, and series-connected H-bridge multilevel converters," *IEEE Trans. Ind. Applicat.*, vol. 43, no. 4, pp. 1032–1040, July/Aug. 2007.

[36] U. Henning, R. Hoffmann, and J. Hochleitner, "Advanced static power converter and control components for TRANSRAPID maglev system," in *Proc. PCC Osaka*, Apr. 2–5, 2002, vol. 3, pp. 1045–1049.

Samir Kouro (samir.kouro@usm.cl), Jose Rodriguez, and Marcelo Perez are with the Universidad Tecnica Federico Santa Maria in Valparaiso, Chile. Bin Wu is with Ryerson University, Toronto, Ontario, Canada. Steffen Bernet is with Dresden University of Technology in Dresden, Germany. Kouro, Bernet, and Perez are Members of the IEEE. Rodriguez and Wu are Fellows of the IEEE. *This article first appeared as "High-Power Adjustable Speed Drive Topologies Powering the Future of Industry" presented at the 2010 IEEE Energy Conversion Congress and Exposition.*