1 Introduction to Medium- and High-Power Switching Converters

1.1 MARKET FOR MEDIUM- AND HIGH-POWER CONVERTERS

Power electronic converters have been one of the fastest growing market sectors in the electronics industry over the last 25 yrs. Power electronic devices are at the heart of many modern industrial and consumer applications and account for $18 billion per yr in direct sales, with an estimated $570 billion through sales of other products that include power electronic modules.

The main application areas for power electronics are in power quality and protection, switch-mode power conversion, batteries and portable power sources, automotive electronics, solar energy technology, communications power, and motion control (classification similar to a Damell market report). The technology behind the products within these markets is on the saturation side of the S-curve. This means that we cannot expect too many new concepts. On the contrary, the industry's efforts are concentrated in optimization of production and cost efficiency. The Organization of Electronics Manufacturers (OEM) has already shown a clear trend for the power supply sector to stay away from custom-designed products and to optimize standard, modified standard, and modular configurable products.

In power electronics, technology has developed under the pressure of the industry's needs and there are many excellent papers written by both industry and university peers. It is the intention of this book to understand current technology within a business perspective and to present the existing scientific knowledge in an organized manner. This book focuses on medium- and high-power converters and the main applications at this power level are:

- High-voltage DC transmission lines
- Locomotives
- Ship propulsion
- Large- or medium-sized uninterruptible power supply (UPS) systems
- Motor control from horsepower range to multi-MVA
- Propulsion of electric or hybrid vehicles

- Servo-drives, robot or welding machine systems
- Elevator systems
- Distributed generation for renewable energy sources
- Appliances, air conditioners, refrigerators, microwave ovens, washing machines
- Automobile electronics, power steering, power windows, doors or seats
- Switch mode power supply for industrial applications
- Consumer electronics, power supplies for VCR, TV sets, radio
- Distribution systems for computers

Given the global status of power electronics technology, a modern engineer should be aware of market realities and needs. This chapter is a minimal guide to the power electronics industry and seeks to place the scientific content of the book within the context of the industry. The reader will be able to better understand what methods are most useful or sought for by contemporary industry. The numbers given in this chapter are compiled from a series of Internet sources and they may vary slightly from one to another. The main reason they are presented is to get a sense of the size of each activity. Readers not familiar with business numbers may find a good reference in remembering that the total worldwide market of video games (hardware and software) reached $23 billion in 2002. The U.S. video game market was $9.4 billion in 2001, compared to $8.5 billion for the movie box-office and $13.7 billion in music entertainment.

New developments in power electronics are expected along the emerging high-frequency power semiconductor devices (e.g., 1–10 kW switched at 100s kHz). The early adopter segment accounted for about $298 million in power semiconductor sales in 1999 and were projected to grow to at least $765 million in five years, an annual growth rate of 21%. This could be compared with traditional devices that account for a worldwide $4 billion MOSFET market [10–12].

Another dynamic sector is the new motor control integrated circuits sector. The global market for motor control integrated circuits was approximately $910 million in 2000. This market should continue to grow at an average annual rate of 9% through 2005.

The most important application for power-electronic devices lies within the automotive market. The worldwide market for nonentertainment automotive electronics, excluding sensors and commercial vehicles, was estimated at $26.9 billion in 2002 and is forecast to reach $35.4 billion by 2007. OEM forecasts that the use of automotive electronics will advance by 7.1% annually to $100 billion in the year 2007. These are really new divisions for the power electronics market, but they must develop quickly due to the increased demand for human residential efficiency, comfort, and safety. A recent study has counted about 80 small power drives, including two modern cars, in a middle-class American family. This market is expected to double its growth rate in the coming years. The power-electronic products used in home applications are designed for low voltage and low power. Low-power servo-drives are described in this book. Propulsion systems for advanced electric and hybrid vehicles are an emerging application field not included in these statistics.

The largest share of the power converter market is taken by motor drives: a market share that has developed steadily during the last 40 years [1,10–12]. This market opportunity has been followed by a strong R&D effort leading to continuous technology development. However, knowledge in this field allowed complete automation in the production lines, which soon led to excess capacity and which, in turn, resulted in a decrease in the revenue growth rate from 16.6% in 1970 to 5.5% in 2000 [1]. The resulting price erosion has been overcome by introducing new semiconductor devices and improving control algorithms and motor designs to reduce cost, improve efficiency, and increase applicability to a large number of uses. Moreover, the motor drive market will have in time a larger share of the nonindustrial products' market, in contrast to the trends of the last 20 yr, when the end-market has been industrial.

The worldwide electronic motor drives' (EMDs) market is projected to increase at a compound annual growth rate (CAGR) of 8.8% per yr from $12.5 billion in 2000 to $19.1 billion in 2005 [1]. CAGR is used as an expression of the growth rate of an investment over a specified period of time. The servo-drives' market grew by nearly 7.8% to about $2.2 billion in 2003. A five-year CAGR of 7.2% is projected between 2001 and 2006, when sales will top $2.9 billion. The low-power AC-drive market in Europe was $1.6 billion in 2001.

Another large business profile for electronic power converters that is estimated to account for $9.2 billion in sales in 2005 is the UPS or grid-related applications [1,2]. In 2001, the total worldwide market for UPS alone was at $5.3 billion, which was expected to grow at a CAGR of 6.1% to reach $7.2 billion by 2006. A derivative from this market is distributed generation, which is probably (since 2002) the most dynamic R&D sector in power electronics in the U.S.A. The combination of a grid power supply and a nonconventional power source such as a diesel generator, a fuel-cell, or a wind turbine requires power electronics conditioning and protection. The appropriate power converters do not really bring anything new in their structure or packaging but their control is a challenge yet to be solved.

Other consumer markets include the AC/DC power supply, the PC and Workstation power supply markets, and the communication power market. The total merchant AC/DC power supply market is projected to grow from $7.7 billion in 2002 to $9.6 billion in 2007, a CAGR of 4.6%. The total worldwide external power supply market is expected to increase from $2.7 billion in 2000 to $4.6 billion in 2005, a CAGR of 11.4%. The worldwide PC and Workstation power supply merchant market is projected to grow from $3.5 billion in 1997 to $6.8 billion in 2002, a CAGR of 13.8%. Communication power is a very dynamic sector. The worldwide communications power systems market will grow from $4.4 billion in 2003 to $5.7 billion in 2008, a CAGR of 5.5%. As these markets use only low-voltage systems, and are, therefore, not the focus of this book.

A final remark about outsourcing. Because power electronics technology is mature, all market participants have established corporate structures that focus more on context rather than core functions (G. Moore, *Living on the Fault Line*).

This favors a certain level of bureaucracy and makes difficult development of new technologies or implementation of new business concepts. On the other hand, corporate participation in a competitive environment implies effort to reduce costs and improve quality of end products. As implementation and development of disruptive technologies is difficult due to the current status of technology and the business structure of these corporations, the cost reduction is achieved through outsourcing more and more of the context functions while maintaining ownership and control of the core function [2].

The power electronics industry is facing a paradigm shift. This shift reflects the acceleration of outsourcing and a migration to subcontract manufacturing in Asia. The worldwide shipments of power supply and power management integrated circuits from Asia were over $5.0 billion in 2003 and are expected to increase at an annual growth rate of 8.8%, reaching close to $7.0 billion by 2006. For example, average prices for power supplies have dropped from about $1 per watt to about 50 ¢ over the past five years.

Another new market segment deals with medium-voltage motor drives up to 3300 V and 2000 A. High-voltage insular gate bipolar transistors (IGBTs) have been introduced recently and they take more and more of the gate turn-off thyristors' (GTOs') traditional market. The picture here is filled with new devices, such as the integrated gate commutated thyristor (IGCT), a traditional IGBT device with the gate driver co-located with the power semiconductor. Motor drives delivering 19,000 HP are nowadays built by companies such as the Robicon Corporation.

An emerging application for medium-voltage motor drives consists of propulsion systems in the multi-MW range. The development, especially in Europe and Japan, of power electronics used in locomotive propulsion has encouraged replacement of GTO switches by their modern IGBT counterparts. Traditional GTO solutions [4,5] are already in use in the 6.4 MW EuroSprinter locomotive built by Krauss-Maffei and Siemens. Other examples are the locomotives RENFE8252 in Spain and CPLE5600 in Portugal.

Electric propulsion has redeemed itself as the proper choice for large cruise ships and is accepted more and more for warships. Unfortunately, simple operating profiles of some low-power vessels or commercial pressures make the all-electric solution not generally attractive. There exist many types of ships between these two extremes in which an all-electric solution can be successful. This solution provides potential for safer, more flexible, and sustainable vessels in the future as well as increased effectiveness in war and reduced life-cycle cost within the warship fleet.

Recent efforts in the U.S. Navy to procure all-electric ship-propulsion systems for warships and submarines are remarkable. Since the late 1990s, Eaton NCD (currently DRS Technologies) has already delivered a 2.2 MW brushless DC motor drive for submarine propulsion [8] and such efforts are continuing within the defense industry around the world.

Different solutions for multi-level inverters are of interest for medium- and high-voltage applications allowing operation of up to 25 kV. A special approach consists of a stack of connected single-phase inverters, which is being extensively analyzed in the ABB and Daimler laboratories [5].

Harmonic performance is limited, however, due to limited switching frequency. New device materials, such as silicon-carbide (SiC) may make the dream of high-frequency switching come true for medium- or high-voltage applications.

The modern R&D engineer is increasingly faced with the problems of improving detail in the product. This requires a great deal of knowledge of the existing methods and their suitability to one application or another. Extension of knowledge from traditional textbooks is usually accomplished through papers or emerging tutorials within conferences. This book tries to fill this gap and provide an advanced manual of solutions as they are applied by industry or have a great potential to be used in production lines.

The biggest difference from the other fields of electronics is the *power* coordinate. If students learn about a circuit or method for one class of applications of electronics, they can easily manage to debug or put into service versions of that circuit from different manufacturers or within different applications. Power electronic circuits and their applications, however, are very different. The topology of a three-phase rectifier equipped with thyristors can be used for a 500 MVA HVDC transmission line or for a 1 kW welding machine. We can understand the basic operation of the three-phase phase-controlled rectifier from a college textbook, but the two systems are extremely different in reality. Each *thyristor* circuit explained in the textbook has a different implementation in practice, ranging from a half-inch TO-220 package to a building of six floors. The protection circuits are also very different, and range from no protection at all to sets of computer-controlled panels and automatic hot-swap replacement units. Finally, the cooling system could range from environmental air to complex systems of pumps or fans that by themselves have large installed power.

Given this diversity of power levels and applications, different power semiconductor switches are more suitable for each case. Figure 1.1 stretches over the whole range of possible switching frequencies and installed power achievable with a single device. For larger power levels, multiple converters can be hardware connected in parallel. Modern power semiconductor devices, especially those of high power, require a good knowledge and control of their $\mathrm{d}v/\mathrm{d}t$ and $\mathrm{d}i/\mathrm{d}t$ variations. These can be achieved through gate control as well as through circuit design, as shown in Chapter 2, which is dedicated to understanding the operation and parameters of diverse power semiconductor devices.

For a better understanding of the industry's requirements of power converters, let us first take a look at several industrial systems comprising power converters. The explanation provided here goes beyond that found in standard power electronic textbooks; large amounts of detail have been given regarding protection and building of the actual system.

Requirements for the following several applications well represented on the market are presented in this introductory chapter:

- Motor drives: from horsepower to MW
- Grid interfaces or distributed generation
- Multi-converter power electronic systems

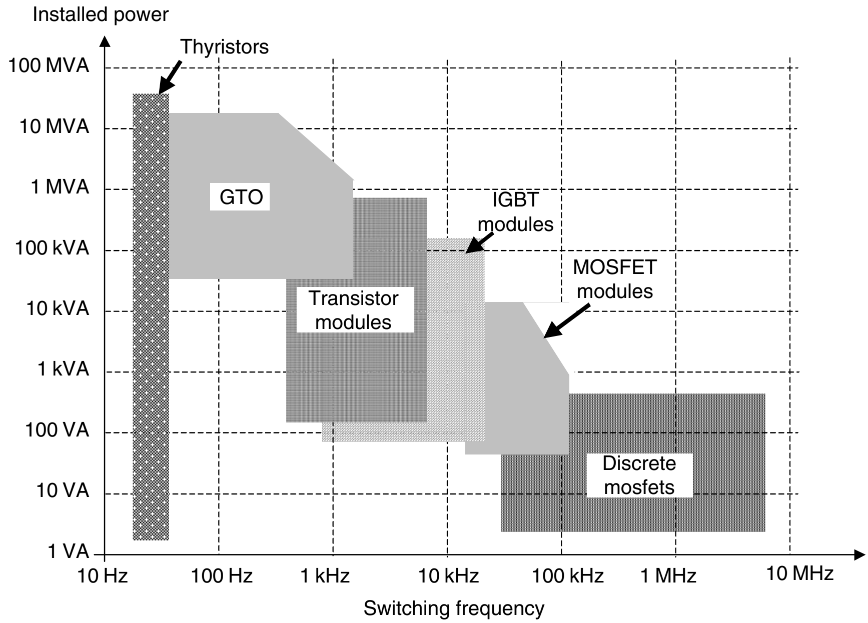

FIGURE 1.1 Power switches availability.

1.2 ADJUSTABLE SPEED DRIVES

A three-phase Adjustable Speed Drive (ASD) comprises not just the power converter; it is a whole system that includes the power converter.

Figure 1.2 shows a complete ASD system consisting of:

- A three-phase rectifier system able to convert the grid three-phase system into a DC voltage
- An intermediate DC circuit usually composed of a large capacitor bank
- A three-phase inverter able to generate variable frequency, and variable voltage in the three-phase system
- A control circuit built with a Digital Signal Processor (DSP), microcontroller, or Programmable Logic Circuit (PLC) device
- Sensors and analog-signal preprocessing
- Connect/disconnect power switches, fuses, or protection circuitry
- Thermal-management system based on heatsinks or coldplates and a cooling system
- Start-up circuit with charging of the DC bus capacitor
- Braking resistor circuit

1.2.1 AC/DC Converter

The input stage, called the three-phase rectifier, is built in many applications with rectifier diodes. The DC bus voltage is therefore quasi-constant at 1.35 times

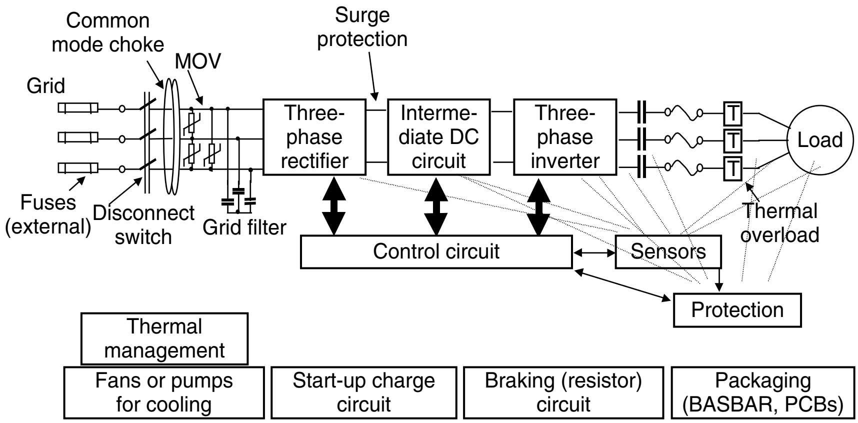

FIGURE 1.2 Global view of a three-phase ASD system.

the line-to-line voltage (VLL). For a system with a VLL of 460 V, the DC voltage equals 620 V. Rarely, this power converter is made with SCR devices in order to control the DC voltage with a method called phase control. Both solutions introduce very large harmonics of the current on the grid. These can become bothersome at large power levels, pollute the grid, and create problems for other users. In order to minimize these harmonics, parallel connection of several rectifier stages is used after the input voltages are phase-shifted with transformers (Figure 3.15).

Another solution used often during the last few years consists of active front-end rectifiers built with controllable devices such as IGBTs or MOSFETs. Such three-phase power converters can process power directly, or they can be used as active filters to deliver the difference between the square-wave current produced by the diode rectifier and an ideal sinusoidal waveform. Thus, they result rated at a lower power level. If a direct three-phase active converter is used, the DC bus voltage can be higher due to the boost operation of that converter. This is advantageous, as it is easier to manipulate high-power levels from a high-voltage source.

1.2.2 Intermediate Circuit

The intermediate circuit is also called the *DC Link*, as it really is a DC link between the input rectifier and the output inverter. It serves as a power storage device. It is composed of a reactor inductor and a capacitor bank. Inductors filter the current through the capacitor in order to limit losses and heating. These two components are the bulkiest parts in the converter system panel (Figure 1.3).

Many manufacturers of ASD use a very large capacitance on the bus in order to ensure a power ride by enabling the motor to continue to operate when grid power is interrupted. Because of this large capacitance, however, it takes a longer time for these capacitors to discharge once power is turned off.

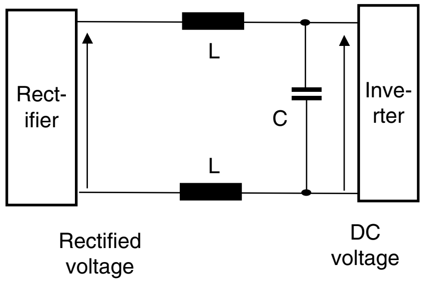

FIGURE 1.3 Intermediate DC circuit.

1.2.3 DC Capacitor Bank

The main functions of the DC capacitor bank are:

- Filter the harmonic ripple produced by the switching devices to produce clean sine-in, sine-out waveforms;
- Provide a stable voltage to ensure the control system's stability;
- Store energy useful for quick transients in the output;
- Work together with the brake resistor to limit DC voltage during regeneration of the "inverter" power stage;
- Limit overvoltages (clamp) before the system protection takes over and shutdown the power devices or start other auxiliary protection.

If the load is unbalanced or nonlinear, an alternative current circulates through the DC bus at twice the fundamental frequency. Depending on the value of the DC capacitor, this current can produce an oscillation of the DC bus voltage. Additional capacitive kVA in the DC link seems mandatory for inverters that feed unbalanced or nonlinear loads. This implies:

- Increased weight, volume, cost
- Selection of DC link to satisfy the maximum expected imbalance or worst-case nonlinear
- Increased losses and reduced reliability of the DC link components

Different active filtering solutions are considered to solve this problem.

1.2.4 Soft-Charge Circuit

ASDs at power levels above 30 HP (22.5 kW) use a soft-charge circuit for powering up the drive. Without this circuit, the in-rush current will be very large at power-on due to the extremely small impedance of the discharged DC bus capacitor. This large in-rush current would blow the grid fuses if not damage the rectifier semiconductors.

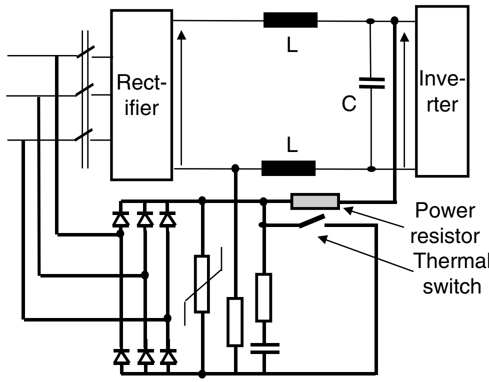

FIGURE 1.4 Principle of a soft-charge circuit.

Figure 1.4 presents a possible soft-charge circuit. It basically adds a power resistor in the path of capacitor charging. This power resistor is also protected with a thermal switch able to disconnect above a certain temperature. After the voltage on the capacitor is larger than a minimum value, the power converter is disconnected through the grid disconnect switch. Due to the cooling requirements for the power resistor, the ASD can start only after one or two minutes.

1.2.5 DC Reactor

The other important part of the intermediate circuit consists of the DC reactor. This is also called *choke* or *DC coils*. It has two basic functions:

- Reduce the harmonics of the current by about 40%, with advantages in the power source or grid current
- Help reduce power interruptions to avoid numerous nuisance shut-downs

1.2.6 Brake Circuit

The intermediate circuit may also contain a brake circuit that takes the power from the DC bus when the drive is decelerating or stopping (Figure 1.5). Its operation is very simple: when the voltage across the capacitor bank increases above a certain level, the IGBT is turned-on and the power resistor is connected across the DC bus, at the inverter input. The inverter current now feeds a parallel R–C circuit. A large part of this current circulates through the resistor along with the discharge current from the capacitor. Usually, the brake circuit is part of the ASD, and the brake resistor is something the user adds depending on his requirements for a specific application.

One alternative to using the brake circuit is to transfer the excess power back to the grid through a power converter. This is called *regeneration* due to its efficiency advantages. However, one drawback is that it produces harmonics on the grid

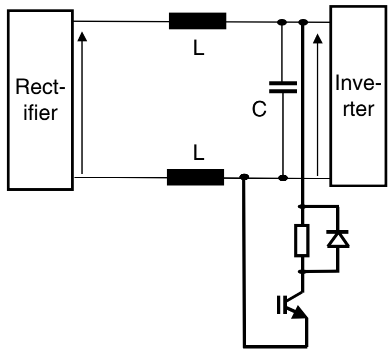

FIGURE 1.5 Brake circuit.

voltage affecting the incoming power to the converter. Finally, another option is to transfer the power excess to another drive's DC bus capacitor. This is sometimes called *load sharing*.

1.2.7 Three-Phase Inverter

The third major component of the system is the three-phase inverter. This is used for conversion of energy from DC voltage in an AC three-phase system with variable frequency and variable voltage. Typically, the topology is based on six IGBTs connected in a bridge; this will be discussed later in Chapter 3. Control of the three-phase inverter for this purpose is called pulse width modulation (PWM). Different PWM methods will be introduced in Chapter 4 and Chapter 5. Other topologies for DC/AC conversion are also presented in this book in Chapter 6 and Chapter 7.

1.2.8 Protection Circuits

A very important function for the whole ASD system is represented by the protection circuitry. We have protection for each power semiconductor device at overvoltage, overcurrent, overtemperature, or at problems within the gate drivers. The appropriate protection circuits will be presented in Chapter 3. More protection at the system level includes input or output fuses.

1.2.9 Sensors

Voltage on the DC bus and of the output currents is monitored through sensors. Some manufacturers use two current sensors at the output of the inverter while others use three sensors, one for each phase.

1.2.10 Motor Connection

Large-power ASDs include motor coils that allow the operation of the motor far from the ASD system. For instance, the standard distance for a Danfoss drive is up to 300 m (1000 ft) for unshielded (unscreened) cable and 150 m (500 ft) for shielded (screened) cable [6]. If these coils are not used, the standard distance from the drive to the motor is as low as 50 m (160 ft) [6].

1.2.11 Controller

All of these blocks are supervised, monitored, and controlled from a central controller module. This is usually implemented on a digital circuit built around a microcontroller, DSP, PLC, or Field Programmable Gate Array (FPGA), Application-Specific Integrated Circuits (ASIC).

There are several functions that mandatorily must be included in the system:

- System command
  - System initialization
  - Run auto-test program
  - Define start/stop functions and check their operation
  - Define acceleration/deceleration of the system
  - Define sense of rotation or direction of displacement
  - Interfaces
    - Display data
    - User-interface
    - Communication with upper hierarchical level
- Control and regulation
  - Control algorithm
  - Data acquisition and digital processing
  - Regulation
  - Limits of control variables
  - Nonlinear characteristics
- Rectifier control when it is not built with only diodes
  - Synchronization
  - Command angle generation
  - Harmonic control
  - Power factor control
  - Gate control
- Inverter control
  - Three-phase system generation
  - PWM generation
  - Minimum pulse control
  - Change of voltage and frequency
  - Limit of the operation range
- Supervision
  - Protection
  - Diagnosis
  - Data storage
  - Report to upper level through communication interface

Chapter 8 and Chapter 11 will provide details about the experimental aspects of implementing these functions in modern microcontrollers.

Power converters used for ASD applications generally need to satisfy some requirements or standards. Typical requirements are next presented.

1.3 GRID INTERFACES OR DISTRIBUTED GENERATION

Power electronics has been used for controlling and monitoring power transfer through HVDC links, especially in countries such as Canada and Brazil with isolated or local power systems. The back-to-back connection of controlled rectifier bridges on both ends of a DC transmission line allows control of up to 150 MW after the AC/DC/AC conversion [8]. However, these systems are rather rare, and the extensive use of power electronics in power systems is increasing as either active filters or grid interfaces. Many utility companies are providing solutions for power quality at the facility level on the utility side of the power meter. This multi-MW equipment is expensive and not likely to find success in the market [5].

A separate class of applications deals with nonconventional power sources, such as fuel cells, solar power, micro-turbines or wind power. These projects with distributed energy sources manage local power generation in the range of 1 kW to 1 MW. For instance, one of the largest fuel-cell-based equipment is installed in Anchorage, Alaska, and accounts for 1 MW [7,9].

Special features are included in power converter controls in order to transfer energy from any of these energy sources or conventional batteries to grid [3]. At higher power levels, this energy is exchanged on three-phase systems. Two operation modes are typical for these applications:

- Grid parallel: power converters that synchronize with the grid while exchanging energy from or to the grid;
- Stand-alone: that maintain three-phase voltage generation while the grid is disconnected.

Definitely, the control system must be able to switch between these modes any time the grid is lost or re-appears suddenly. Such requirements are also present in a conventional UPS system. The distributed generation system can also combine power delivery from the grid and the alternate source of energy.

The power electronic system maintains many of the protection and connection features presented for the ASD case. Let us take a closer look at the requirements of the grid interface.

The switching nature of operating power converters has led to various concerns about the quality of the grid at the point where the power converter is connected. Many standards have been elaborated in this respect. Some of these follow general requirements for inverters, some are specific for the grid connection. Any new power electronic equipment dedicated to a grid interface must obey regulations. Unfortunately, there are different grid voltage systems in the world and grid requirements are different from country to country. Constraints to low-voltage grid applications around the world are presented next. Appropriate standards are next quoted and they can be consulted for larger grid voltage systems:

- Nominal voltage ratings and operating tolerances for 60 Hz electric power systems from 100 V through 230 kV [14]
- Voltage sags analysis and methods of reporting sag characteristic graphically and statistically [15]
- Guidelines and limits for current and voltage distortion levels on transmission and distribution circuits [16]
- Powering and Grounding Sensitive Electronic Equipment [17]
- Monitoring of single-phase and polyphase AC power systems [18]
- Incompatibility of modern electronic equipment with a normal power system [19]
- Distributed Resources Interconnected with Electric Power Systems [3]

1.3.1 Grid Harmonics

Most European countries require compliance with EN61000-3-2. It lays down absolute limits for each individual harmonics. Japan's regulations are also derived from EN61000-3-2. Australia, U.S.A., and U.K. set relative limits with a Total Harmonic Distortion (THD) of the current of 5% maximum and maximum values for each individual harmonic. Methods for minimizing those grid harmonics are presented in Chapter 9.

Power converters are also subject to harmonics from grid. The harmonics of the mains (grid) voltage a converter can cope with are given in the European standard EN60146-1-1 [13,14].

1.3.2 Power Factor

A power factor of 1.00 is considered the best case, while anything higher than 0.8 is acceptable. If these levels cannot be achieved with the power system itself, additional units are used for power factor correction. This is the case of large inductive loads on the grid or on silicon-controlled rectifiers.

The high-frequency components of the input currents can be further reduced with chokes on the mains or on the DC link. DC link chokes also prevent resonance with the grid impedance. The incorporation of DC chokes on the power converter structure reduces the harmonic currents by up to 40% [13,14].

1.3.3 DC Current Injection

It is very important to not inject DC components on the grid. Many countries avoid transformerless connection of switching converters to the grid. The operation of the power-switching converter must be symmetrical, so as not to produce DC components. The amount of DC current accepted by different countries is very different.

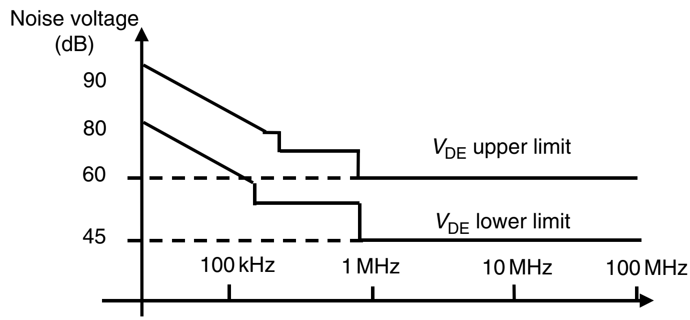

FIGURE 1.6 Example of EMI standard requirements.

A maximum of 0.5 mA is allowed in the U.K.; Australia's regulations allow a maximum of 0.5% of the power converter's rated current or 5 mA, whichever is greater; U.S. regulations limit DC to a maximum of 0.5% of rated current; Japan allows a maximum 1% of rated current; and Germany a maximum 1 A per power converter connected to grid [13,14].

1.3.4 Electro-Magnetic Compatibility and Electro-Magnetic Inference

Step-switching waveforms of up to 15 V/nsec or 5 A/nsec generate electro-magnetic inference (EMI) in both conducted and radiated forms. The conducted EMI is generated in differential (symmetrical) mode or common (asymmetrical) mode. Symmetrical mode EMI is generated when currents flow into the connection lines due to the power semiconductor variation of current (di/dt). The common mode EMI is produced due to the high (dv/dt) and parasitic capacitances to ground or connecting lines.

The radio or EMI interference produced by power converters depends on a number of factors:

- Switching frequency of the converter
- Slope of current and voltage at switching
- Impedance of the mains power supply
- Length of cables from grid and to the motor

Standards have been defined for previous applications of power converters and they are reapplied to these grid interfaces. The most used standards for EMI are the German standard VDE or the Europe standard EN55011 (Figure 1.6). Appliances are covered by Europe standard EN55014, while power converter products are covered by EN61800-3.

The interference conducted to grid is usually reduced with a filter composed of coils and capacitors. If the power converter is not built with this filter, it can be purchased separately: "class A" for industrial applications and "class B" for household

TABLE 1.1
Voltage and Frequency Variations

	Voltage			Frequency		
Country	**Max V**	**Min V**	**Run-On Time (Sec)**	**Max HZ**	**Min HZ**	**Run-On Time (Sec)**
Australia	270	200	2	50–52	48–50	2
Austria	253	195	0.2	50.2	49.8	0.2
Denmark	253	195	0.2	50.5	49.5	0.2
Germany	253	195	0.2	50.2	49.8	0.2
Italy	264	184	0.1 (@ 264 V) 0.15 (@ 184 V)	50.3	49.7	0.1
Japan	120	80	0.5–2	51.5	48.5	0.5–2
Mexico	132	108	2	61	59	—
Netherlands	244	207	0.1	52	48	2
Portugal	264	195	0.1–1	50.25	49.75	0.1
Switzerland	264	195	0.2	51	49	0.2
UK	253	207	Disconnect	50.5	47	Disconnect
USA	164	64	0.022–0.100	60.6	59.3	0.1

Source: Data compiled from Panhuber C, Raport IEA-PVPS, T5, April 2001, with permission, and other internet sources.

applications. Moreover, using screened or armored cables limits the interference generated from power converter to the switching motor.

A new trend in EMI protection is the use of converter methods to reduce the common mode voltages; this will be analyzed in detail in Chapter 6.

1.3.5 Frequency and Voltage Variations

It is accepted that power converters connected to grid can operate only within certain voltage and frequency windows. The system is considered stable within these windows. Along with voltage or frequency limits, a maximum allowable run-on time is also defined and it varies considerably from country to country. Table 1.1 shows these limits [10].

1.3.6 Maximum Power Connected at Low-Voltage Grid

The maximum power installed in a power converter used as a grid interface is not always regulated by standards. Single-phase converters can be connected to low-voltage systems if their power is below 4.6 kW in Germany or Austria, 5 kW in U.K. or Italy, and 10 kW in Australia. Three-phase converters can be connected to a low-voltage grid if their power is below 25 kW in Mexico, 30 kW in Australia, and 100 kW in Portugal. Obviously, higher power converters can be connected to three-phase systems with higher voltages.

1.4 MULTI-CONVERTER POWER ELECTRONIC SYSTEMS

The advent of power electronic applications in industry changed the focus from issues related to building the power converter to issues related to system development and interaction between different power converters. Many modern industrial systems are composed of several ASDs connected to the same DC bus in *multi-drive or multi-module* configurations. Modular design in multi-converter applications is based on the knowledge gained by individual analysis of each power converter. Power quality, efficiency, and system stability are affected by the interdependency between power stages.

Examples of multi-converter applications are:

- Industrial multi-drive systems
- Parallel operation achieving higher power levels
- Electric or hybrid electric vehicles
- Aircraft power electronic systems
- Ship power electronic systems
- Space electronic systems

Figure 1.7 shows a schematic of a modern power electronic system. The power source can be the industrial AC grid followed by an AC/DC power conversion, or the main power source can be a nonconventional power source, such as solar, wind, or thermal energy. After the appropriate conversion, the whole power resides on the DC bus. This bus supplies several motor drives. Some of them can dynamically be on the motoring mode, some on regeneration. The important thing is to manage the power on the DC bus so that the voltage is kept within two certain limits. This raises new problems, such as the stability of the DC bus at different loads. If one of the ASDs is working at constant torque with its speed regulated, its power can be considered constant. A load with constant power presents negative dynamic impedance that is a source of instability on the bus. Chapter 9 makes an extensive analysis of multi-converter power electronic systems.

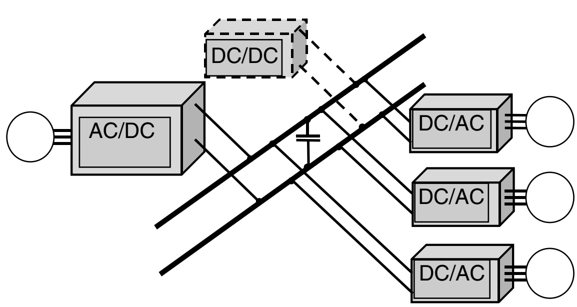

FIGURE 1.7 Complex power electronics system composed of several drives.

Multi-drive or multi-converter systems have several advantages:

- Modularity: quick and easy to integrate in panels and cabinets
- Scalability
- Redundancy
- Reliability: easy to replace a faulty module with a new one (*hot-swap* possible)
- Electronic gearing
- Flexibility: modules can be customized to any application
- Use of the same control cards and software for a large number of applications
- The same personnel training requirements across a wide power range
- Reduced-size library of *AutoCad* drawings, easy to integrate in a new design
- Lead-time reduction and money savings by minimizing spare requirements
- Same packaging and power density across the whole power range
- Technical advantages of using a single, high-power DC bus structure
- Optimized cooling system

1.5 CONCLUSION

Power electronics has emerged as a well-established technology with a broad range of applications. This chapter has shown the application spectrum for power converters and it has focused on adjustable speed drives and grid interfaces. Constraints and standards to be met by different power converters within these applications are briefly listed. Equipment involving power converters are being increasingly used in all domains of our lives. Most of this energy is processed at medium and high power through power converters. The following chapters take an in-depth look at the theory of three-phase power converters, giving details of their problems and providing many solutions that can be implemented.

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