Chapter 1
Power Semiconductor Devices—Key Components for Efficient Electrical Energy Conversion Systems

1.1 Systems, Power Converters and Power Semiconductor Devices

In a competitive market, technical systems rely on automation and process control to improve their productivity. Initially, these productivity gains were focused on attaining higher production volumes or less (human) labor-intensive processes to save costs. Today, attention is paid towards energy efficiency because of a global awareness of climate change and, above all, questions related to increasing energy prices, as well as security of energy and increasing urbanization. Consequently, it is expected that the trend towards more electrical systems will continue and accelerate over the next decades. As a result, the need to efficiently process electrical energy will dramatically increase.

Devices that are capable of converting electrical energy from one form into another, i.e. transforming electrical energy, have been a major breakthrough technology since the beginning of electrical power systems and are considered key enabling technologies. For example, without transformers, large-scale power generation, transmission and distribution of electrical power would not have been possible. Interestingly, very few people today are aware that without this invention, initially called secondary generator [Jon04], we would not have been able to create such an efficient, safe and (locally) environmentally clean power supply system. Of course, as transformers, or generally speaking electro-magnetic devices, can only transform voltage or control reactances, their use in automation systems remained limited. At the beginning of electrification, frequency and phase control could only be realized using electro-mechanical conversion devices (i.e. motors, generators). However, these machines were bulky, required maintenance, had high losses and remained expensive. Furthermore, these electro-mechanical devices had rather low control bandwidth. Therefore, they operated mostly at fixed set points. Today, most automation and process control systems require more

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flexible energy conversion means to vary dynamically voltage or to regulate current, frequency, phase angle, etc.

At present, power electronics is the most advanced electrical energy conversion technology that attains both high flexibility and efficiency. As an engineering field, power electronics came into existence about 50 years ago, with the development and the market introduction of the so-called silicon controlled rectifier, known today as the thyristor [Hol01, Owe07]. Clearly, power electronics and power semiconductor devices are closely intertwined fields. Indeed, in its Operations Handbook, the IEEE Power Electronics Society defines the field of power electronics as *"This technology encompasses the effective use of electronic components, the application of circuit theory and design techniques, and the development of analytical tools toward efficient electronic conversion, control, and conditioning of electric power"* [PEL05].

Simply stated, **a power electronics system is an efficient energy conversion means using power semiconductor devices**. A power electronics system can be illustrated with the block diagram shown in Fig. 1.1.

A special class of power electronic systems are electrical drives. A block diagram of an electrical drive is illustrated in Fig. 1.2. Electrical drives are used in propulsion systems, power generation (wind turbines), industrial and commercial drives, for example in heating ventilation and air conditioning systems, and in motion control. In an electrical drive, the control of the electro-mechanical energy converter, the latter being a highly sophisticated load from a control perspective, is

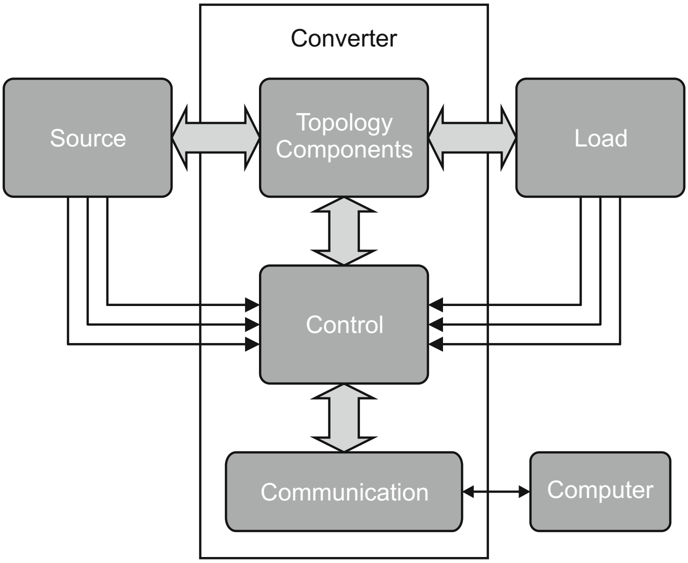


Fig. 1.1 Power electronic systems convert and control electrical energy in an efficient manner between a source and a load. Sensor interfaces to the source and load, as well as information and communication links, are often integrated

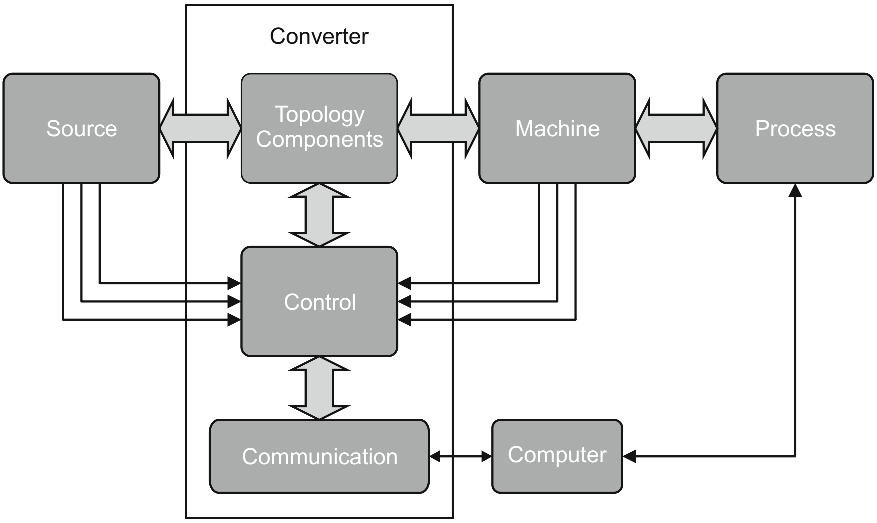


Fig. 1.2 Highly dynamic electrical drives systems comprise power electronic converters and electrical machines or actuators with dedicated control to convert electrical energy into mechanical motion

integrated in the power electronics converter control. Most research institutions that deal with power electronic converter technology also work on electrical drive technology, because this field still represents one of the largest application areas (expressed in installed apparent power) of power electronic converters [Ded06]. In the near future, despite the increased use of power converters in photovoltaic systems and computer power supplies, it is expected that this dominance of drives will remain. Most experts predict that the existing industrial markets for drives will continue to grow and will be complemented by newly developed markets, such as wind turbines, more electric ships and aircrafts and electric mobility, i.e. trains, trams, trolley busses, automobiles, scooters and bikes.

1.1.1 Basic Principles of Power Converters

Looking into the generic power electronic converter block diagram of Fig. 1.1, more details can be revealed when considering the operating principles and the topology of a modern power electronic converter. Basically, to make power electronic converters work, three types of components are needed:

- Active components, i.e. the power semiconductor components, that turn on and off the power flow within the converter. The devices are either in the off-state (forward or reverse blocking) or in the on-state (conducting).

- Passive components, i.e. transformers, inductors and capacitors, which temporarily store energy within the converter system. Based on the operating frequency, voltage, cooling method and level of integration, different magnetic, dielectric and insulation materials are used. For a given power rating of the converter, higher operating (switching) frequencies enable smaller passive components.
- Control unit, i.e. analog and digital electronics, signal converters, processors and sensors to control the energy flow within the converter such that the internal variables (voltage, current) follow computed reference signals that guarantee proper behavior of the converter according to the external commands (that are obtained via a digital communication link). Today, most control units also provide status and system level diagnostics.

As power electronic converters ought to convert electrical energy efficiently (efficiencies above 95%), linear operation of power devices is no option. Rather, the devices are operated in a switching mode. Hence, in the power supply area, to make this distinction, power converters are called “switched-mode power supplies”. The basic idea behind all power converters to control and convert the electrical energy flowing through the converter is to break down this continuous flow of energy in small packets of energy, process these packets and deliver the energy in another, but again a continuous, format at the output. Hence, power converters are true power processors! In doing so, all converter topologies must respect fundamental circuit theory principles. Most importantly, the principle that electrical energy can only be exchanged efficiently via a switching network when energy is exchanged between dual components, i.e. energy stored in capacitors or voltage sources should be transferred to inductors or current sources.

As described in guidelines and standards, for example IEEE 519-1992 [IEE92] and IEC 61000 -3-6 [IEC08], and to protect sources and loads, the energy flow at the input and at the output of the converter has to be continuous, substantially free from harmonics and electromagnetic noise. To make the energy flow continuous, filter components are necessary. Note that in many applications these filter components can be part of the source or the load. To minimize cost of filter components, to comply with international standards and to improve efficiency, the control units of inverters, DC-to-DC converters and rectifiers tend to switch the power devices at constant switching frequency, using pulse width modulation (PWM) techniques, sometimes called duty-cycle control. Basic circuit theory and component design proves that higher switching frequencies will lead to smaller passive elements and filter components. Hence, all converter designs strive to increase switching frequencies to minimize overall converter costs. However, as will be discussed in the next sections, higher switching frequencies impact converter efficiency. As a result, a balance has to be found between investment material and production costs and efficiency. Note that efficiency also determines the energy costs of the conversion process over the entire life span of the converter.

1.1.2 Types of Power Converters and Selection of Power Devices

Power electronic converters can be categorized in various ways. Today, with power electronics it is possible to convert electrical energy from AC to DC (rectifier), from DC to DC (DC-to-DC converter) and from DC back to AC (inverter).

Although some converters can convert AC directly to AC (matrix- and cyclo-converters), most AC-to-AC conversion is done using a series connection of a rectifier and an inverter. Hence, as shown in Fig. 1.3, most converters possess at least one DC-link, where the energy is temporarily stored between the different conversion stages. Based on the type of DC-link used, the converters can be divided in current source and voltage source converters. Current source converters use an inductor to store the energy magnetically and operate with near constant current in the DC-link. Their dual, i.e. the voltage source converter, uses a capacitor to keep the DC voltage constant.

In case of AC supplies and loads, the converter could take advantage of the fact that the fundamental component of the line current or the load current crosses zero. These converters are called line-commutated or load-commutated converters and are still common in controlled rectifiers and high-power resonant converters as well as synchronous machine drives, using thyristors. A three-phase bridge rectifier is shown in Fig. 1.4. Detailed analysis shows that these converters produce line side harmonics and cause considerable lagging reactive power [Moh02]. Consequently, large filters and reactive power (so-called VAR-) compensation circuits are needed to maintain high power quality. As these filters cause losses and represent a

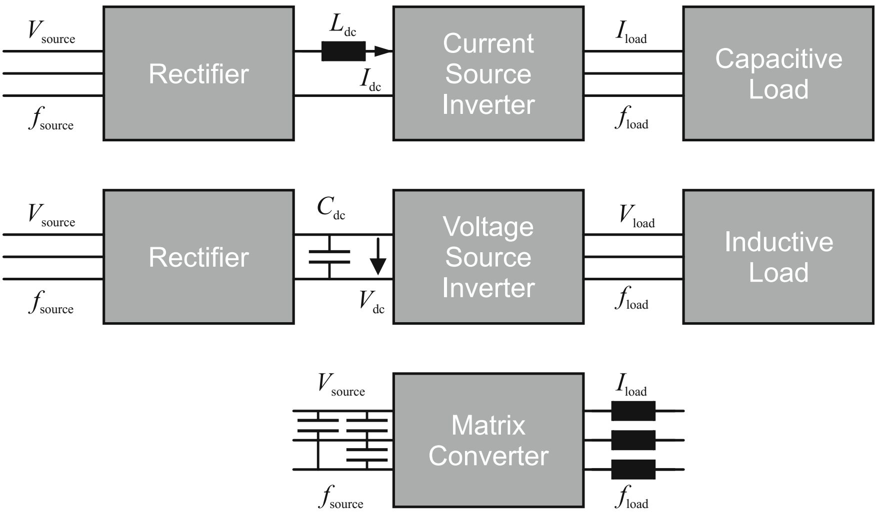


Fig. 1.3 DC-link converters and matrix converters can convert electrical power between (three-phase) AC supplies and loads. Most converters use a combination of rectifier and inverter

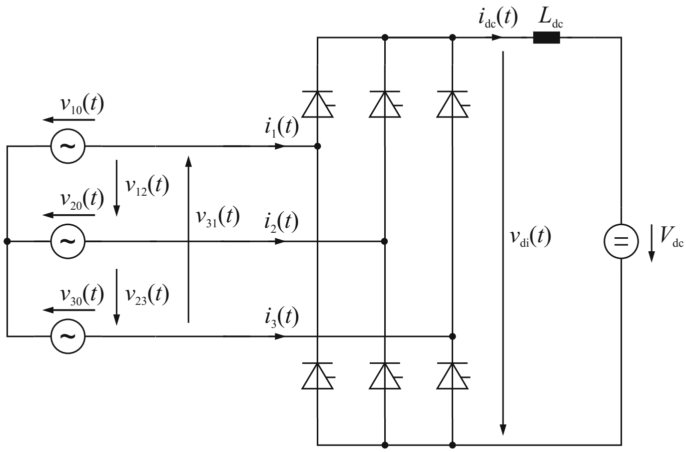


Fig. 1.4 Elementary diagram of line-commutated rectifier circuit, based on thyristors

substantial investment cost, line commutated (rectifier) circuits are slowly phased out in favor of forced commutated circuits that use active turn-off power semiconductor devices, i.e. power transistors (MOSFET, IGBT) or turn-off thyristors (GTO, IGCT). Active rectifier circuits (actually inverters operating in rectifying mode) can eliminate the need for VAR compensators and reduce or eliminate harmonic filter components.

However, not only the type of converter (rectifier, inverter or DC-to-DC converter), but also the type of topology selected (voltage source or current source) has a profound impact on the characteristics and the type of semiconductor devices that are required. A three-phase current source inverter and a three-phase voltage source inverter are illustrated in Fig. 1.5 to point out the operating differences of the devices.

In current source converters, the devices need to have forward and reverse blocking capability. These devices are called symmetrical voltage blocking devices. Although symmetrical blocking turn-off devices do exist, in practice, the reverse blocking capability is often realized by connecting or integrating a diode in series with the active turn-off semiconductor switch (transistor or turn-off thyristor). Hence, in this case, higher conduction losses must be tolerated as compared to asymmetric blocking devices. As will be shown in this book, the physics of power semiconductor switches leads to the fact that the design of symmetrical blocking turn-off devices (with integrated reverse blocking pn-junction) somehow relates to thyristor-based structures (see Chaps. 8 and 10.7). As these devices are more suitable for high power applications (voltages above 2.5 kV), some high-power converter manufacturers still use symmetrical (GCT) devices in high-power (above 10 MVA) current source converters [Zar01]. The main advantage of such converters is the fact that a current source converter is fault-tolerant against internal and external short circuits.

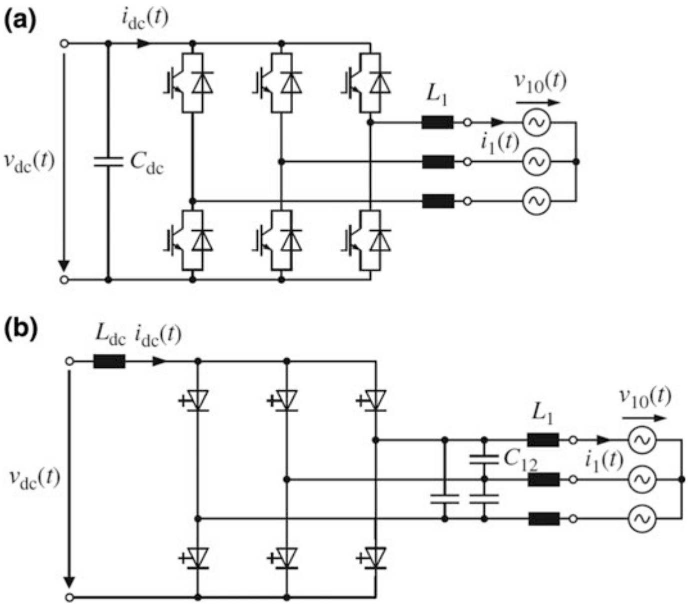


Fig. 1.5 Elementary diagrams of **a** voltage source inverter (VSI) and **b** current source inverter (CSI) circuits

Voltage source converters require a reverse conducting device because they inevitably drive inductive loads at their AC terminals. Hence, to avoid voltage spikes, when a device turns off current, a freewheeling path is needed. This reverse conduction or freewheeling capability of semiconductor switches can be realized by connecting or integrating a diode anti-parallel to the turn-off device. As this additional junction is not in series with the main turn-off device, no additional voltage drop occurs in the current path of the converter. Hence, with the present state of device technology, voltage source converters tend to be more efficient than current source converters, especially at partial load conditions [Wun03]. Indeed, at partial load the current source converter still has a high circulating current in the DC-link of the converter, while the voltage source operates at reduced current, even when the DC-link capacitor carries full voltage.

In practice, due to the lower losses in the DC-link capacitor as compared to the DC-link inductor, the size of a voltage source converter can become considerably smaller than that of a current source converter. In addition, most loads and sources behave inductively (at the switching frequency). Hence, voltage source converters may not require additional impedances or filters, while a current source converter requires capacitors at its output terminals. Taking all these engineering considerations into account, one can understand the growing importance of voltage source converters as compared to current source converters. The device manufacturers have responded to this growing market by optimizing far better asymmetric transistors and thyristors with respect to conduction and switching losses, which led to considerable efficiency improvements and less cooling costs. Furthermore, most voltage source converter topologies use the two-level phase leg configuration that was shown in Fig. 1.5a. This phase leg topology has become so universal that device manufacturers offer complete phase legs integrated in single modules as elementary building blocks, called *power electronic building blocks* (PEBBs), thereby reducing manufacturing cost and improving reliability (see Chap. 14). As power electronics is becoming a mature technology, one can state that in the near future most new converter designs (with ratings from few mVA to several GVA) will be voltage source type converters.

1.2 Operating and Selecting Power Semiconductors

When designing a power converter, many details need to be considered to achieve the design goals. Typical design specifications are low cost, high efficiency or high power density (low weight, small size). Ultimately, thermal considerations, i.e. device losses, cooling and maximum operating temperature, determine the physical limits of a converter design. When devices are operated within their (electrical) safe operation area (SOA), conduction and switching losses dominate device losses. The underlying physics of these losses are described and analyzed in this book. However, it should be noted that the converter designer can substantially minimize these losses by making proper design decisions. In general, the outcome of the design depends greatly on the selection of:

- device type (unipolar, bipolar, transistor, thyristor) and rating (voltage and current margins, frequency range)
- switching frequency
- converter layout (minimizing parasitic stray inductances, capacitances and skin-effects)
- topology (two-level, multi-level, hard-switching or soft-switching)
- gate control (switching slew rate)
- control (switching functions, minimizing filters, EMI)

Furthermore, as losses cannot be avoided, the design of the cooling system (liquid cooling, air cooling) has a strong impact on the selection of the type of packaging. Several types of packaging technologies are currently available on the market: discrete, module and press-type packages. Whereas, the discrete and module packages can be electrically insulated, which allows all devices of a converter to be mounted on one heat sink, the press-type packages can be cooled on both sides. Typically, discrete devices are used in switched mode power supplies (up to 10 kW). Higher power levels, up to 1 MW, require parallel connection of multiple semiconductor chips and make use of the module type package, while double-sided cooled packages (single wafer disk type designs or multiple-chip press-packs) are used at the highest power levels up to several Gigawatts. Details of system architecture are discussed in Chap. 11.

As already stated, the device switching power (product of maximum blocking voltage and repetitive turn-off current) and its maximum switching frequency are important criteria for a first selection of a power semiconductor in many applications. Next to this theoretical application limit, the practical application range of silicon devices depends also on cooling limits and economical factors.

At present several device structures have been developed, each offering specific advantages. The structures of today's most important power semiconductor devices are shown in Fig. 1.6. However, it is worth mentioning that in modern applications classical bipolar transistors have been superseded by IGBTs (Insulated Gate Bipolar Transistors), being basically a MOS-controlled bipolar device. Details on each of the devices in Fig. 1.6 will be given in Chaps. 5–10.

As production of silicon devices has made great progress over the past 50 years, the application range of silicon devices has expanded and became better understood. Fig. 1.7 illustrates the practical application range of each type of silicon device in classical power converters (rectifiers and hard-switching power converters).

Note that for these applications the operation ranges are within a hyperboloid. In other words, the product of switching power (product of max. voltage and current) and switching frequency that can be attained per device in practical conversion

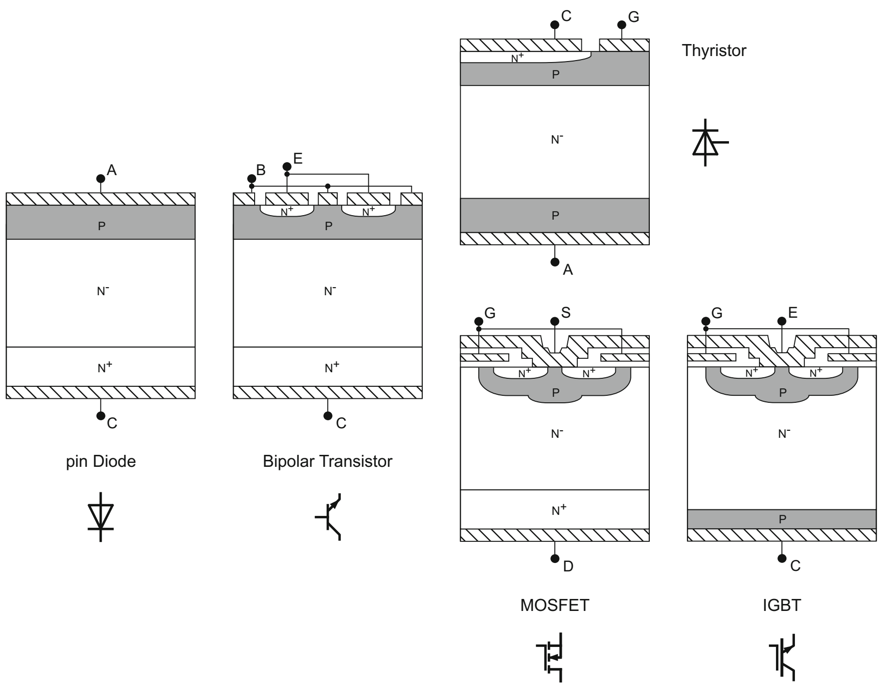


Fig. 1.6 Basic structures of common power semiconductor devices

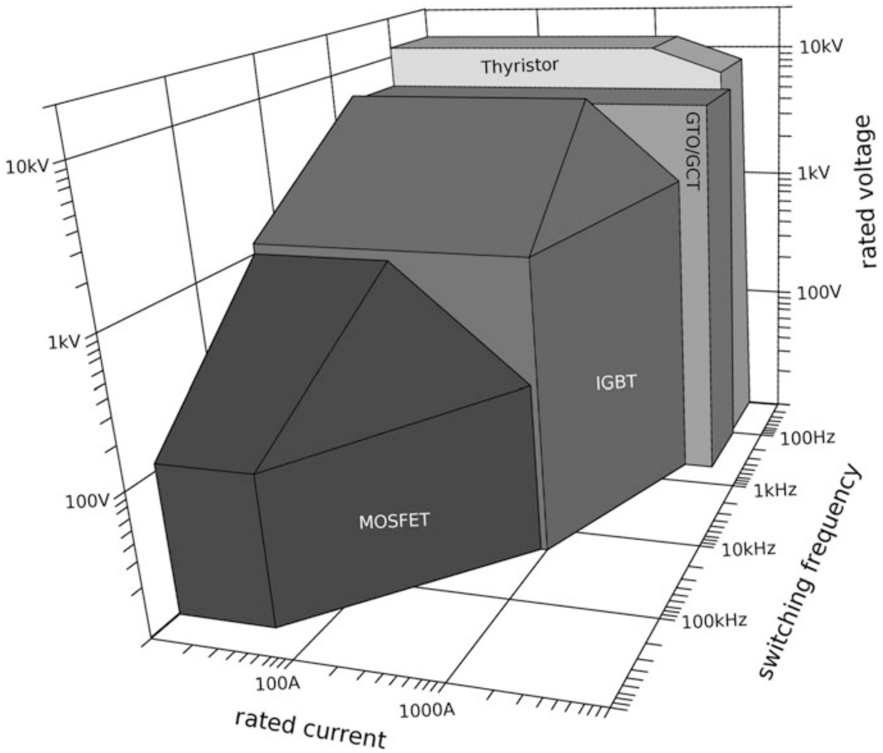


Fig. 1.7 Operating range of silicon power semiconductor devices

systems using silicon devices, assuming classical hard-switching converter configurations and similar type of cooling, appears to be fairly constant:

$$P_{sw-hard} \cdot f_{sw} = V_{max-hard} \cdot I_{max-hard} \cdot f_{sw} \approx 10^9 \text{ VA/s}$$

This frequency-power product is a good performance indicator for how well the designer was able to maximize utilization of the power semiconductors and to improve the power density of the converter. Indeed, as pointed out earlier, increasing switching frequency also reduces size of transformers, machines and filter components (at constant apparent power). Actually, if passive components of the same type (electromagnetic or electrostatic) are being considered, for example inductors, transformers and machines, they also experience a similar frequency-power product barrier as they use the same materials (copper, silicon-steel and insulation materials), operating at same maximum temperatures.

To reduce switching losses, soft-switching converters or wide bandgap materials, such as Silicon Carbide (SiC) devices, can break this technology barrier. For example, soft-switching resonant converters are being applied successfully in switched-mode power supplies and DC-to-DC converters. In soft-switching converters, not only the switching losses of the turn-off devices are being reduced, but also the reverse recovery losses of the power diodes are mostly eliminated. As will be shown in this book, reverse recovery effects in power diodes not only increase switching losses, but also are a root cause for high HF noise (EMI) in converters. To limit these EMI effects, designers are forced to slow down switching transients, which leads to higher switching losses in hard-switching converters. As soft-switching converters utilize resonant snubber techniques, these losses do not occur and the switching frequency can be increased or, alternatively, the output power of the converter may be augmented. Soft-switching (resonant or transition-resonant) converters typically improve the frequency-power product by a factor of up to five:

$$P_{sw-soft} \cdot f_{sw} \approx 5 \times 10^9 \text{ VA/s}$$

As was stated, yet another approach to increase power density of converters is the use of SiC diodes. SiC diodes have near zero reverse recovery current. Hence, the silicon turn-off devices can be operated with higher turn-on and turn-off slew rates. These hybrid silicon-SiC designs are currently under investigation as SiC diodes are becoming available at higher power levels. Combining this hybrid concept with high-frequency soft-switching principles, i.e. using the parasitic elements of the devices (capacitances) and packages (inductances) as resonant components, the highest power densities can be attained. These concepts already find their implementation in ultra compact power supplies. Also, high-power DC-to-DC converters start to make use of these principles. One can estimate that the frequency-power product of the silicon switches in these hybrid converters can become as high as 10^{10} VA/s.

1.3 Applications of Power Semiconductors

One can conclude that the field of power electronics and of power semiconductors is still evolving at a rapid pace. Soon, all electric power will pass, not only through copper, dielectric or magnetic materials but also through semiconductors, often several times, because most applications require energy conversions or because increased efficiency is required in these energy conversion processes.

As was mentioned above, converters are being used over a wide power range, with ratings from milli-Watts or mVA (technically speaking, it is more correct to use apparent power) up to Gigawatts. Depending on the required voltage and current ratings of the power semiconductors, different types of power semiconductors are being used. At the low power end (1 VA up to 1 kVA), switched-mode power supplies for battery chargers, mostly for portable communication devices and power tools, as well as for electronic systems (audio, video and controllers) and personal computer systems form a major global market. Pushed by legislation, these power supplies have steadily augmented efficiency by improving control and developing better power devices and passive components. Modern power supplies also have reduced standby losses. The trend is towards higher switching frequencies because less material is needed for filter components. Hence, most power supplies in this power range are using power MOSFET devices to convert electrical energy.

Another major market for power electronic systems are electronic ballasts in lighting systems. New energy efficient light sources (fluorescent, gas discharge lamps, LED, OLED) require control and conversion of the electrical power to operate. The main challenge is to develop power electronic circuits that are cheap and that can be mass-produced. Moreover, the overall life-cycle assessment (to assess impact on environment) of light sources seems to favor more efficient lighting systems [Ste02]. New legislation in the EU will phase out incandescent light bulbs.

Drive applications span a power range from few 10 VA up to 100 MVA. In automotive applications, many small drives (100 VA up to 1 kVA) are fed from the on-board power source, nominally 12 or 24 V. Hence, MOSFET devices are most common in these applications. On the other hand, grid connected drives have to cope with the different grid standard voltage levels. For example, single-phase systems for households in North America and power systems in the aircraft industry, have 115 V (rms) phase-voltage at 60 Hz or 400 Hz, respectively. Higher power single-phase systems offer 230 V line-to-line. In Europe, single-phase systems are 230 V, while three-phase line-to-line voltages equal 400 V. Canada and the US also have 460 V three-phase power systems. Typically, the highest low-voltage power systems have 660 V line voltage (IEC 60038 defines low-voltage systems up to 1000 V). To cope with all standards and to lower production costs, device manufacturers have settled on few voltage levels that cover most grid connected applications (rectifiers and inverters). Consequently, power devices with a breakdown voltage of 600, 1200 and 1700 V have been developed. As transistor type devices offer short circuit protection at low cost, IGBTs are predominantly being used in drives fed from power grids. Medium voltage drives (grid voltage from 1000 V up to 36 kV) use, depending on drive rating, transistor (IGBTs) and turn-off thyristor (GTO or GCT) type devices. Above 3 kV, i.e. at higher voltage and power ratings (above 5 MW), three-level converters [Nab81] based on GCTs seem to dominate the market. However, at very high power levels above 15 MW, load commutated inverters (LCIs) using thyristors are still produced by some manufacturers, for example in rolling mills and compressor drives [Wu08].

Drives in traction applications such as locomotives, trains and trams also face many different voltage standards. In Europe, several DC (600, 1500 and 3000 V) and AC (16.7 and 50 Hz) systems are used. Older converter designs used thyristors to control torque of various types of machines (DC, synchronous and asynchronous machines). Typically, one converter would drive multiple motors (multi-axle design). More and more, IGBT based converters are being used and single-axle designs are preferred. Hence, the required rating of the converters in traction systems has gone down, which favors designs based on transistor type devices. Most importantly, the load-cycle capacity of the converter is essential for the required reliability, especially in traction applications. In this area, research is on-going to improve device package and cooling system reliability to reduce converter life-cycle costs (more details can be found in Chap. 14).

Yet another modern drive application at the lower power spectrum (10 W) is the electronic toothbrush. This household appliance is a true power electronics marvel. A switched-mode power supply transforms the power of the AC line (115 V or 230 V phase voltage) to medium frequency (50 kHz) AC power to allow a contactless energy transfer (via a split transformer core) to the hand-held battery fed toothbrush. A rectifier converts the medium frequency to DC. A step-down converter regulates the charging current to the battery and the electronics. An electronic commutated brushless PM machine drives the mechanical gears that move the brush in a rocking motion. Note that the complexity of this toothbrush approaches that of an electric vehicle. At these power levels, control and power devices are highly integrated to make mass production possible at reasonable cost. However, often these low power applications are precursors of what can be achieved with high-level integration at higher power levels in the future.

Power electronics is used in generator systems whenever constant speed operation of a turbine or an engine cannot be guaranteed. A typical application is maximum power point tracking of generators driven by combustion engines (10 to 1000 kW range). More recently, power generation with wind turbines is inverter driven. Power levels of wind turbines have grown from 50 kW in 1985 to 5.0 MW in 2004 [Ack05]. Wind turbine manufacturers expect off-shore wind turbines to reach 10 MW per unit in the future. These large units will be "full converter" units in contrast to the doubly-fed generators systems, that are currently mostly used in on-shore applications. Doubly-fed generators (also called rotating transformers) use AC-to-AC converters that are rated typically lower than 60% of the turbine power. This solution tends to be economically advantageous when using low-voltage (400 V or 690 V) generators, up to 5.0 MW. Note that worldwide approximately 120 GVA of inverter apparent peak power has been installed in the last decade to satisfy the demand for wind power [Wea09].

Another high-power application is transport of electrical energy over long distances using high-voltage DC (HVDC) transmission. Classical HVDC systems use three-phase bridge type rectifiers based on thyristors. Some variants use direct light triggered thyristors, although the requirement of diagnostic status feedback (via a glass-fiber, due to the high-voltage basic insulation level requirements) often favors separate light-triggered thyristors or thyristors triggered using a classical gate driver (both methods use energy stored in the snubber capacitor to trigger the thyristor via a glass fiber). The first HVDC systems date from 1977 and are still in use. However, increasing power demand over long distances (mostly hydro-power), for example in the so-called BRIC countries (Brazil, Russia, India and China) has given HVDC a new boost. HVDC technology is now operating with ±500 kV, delivering 3 GW of power, while new systems will operate at ±800 kV, transmitting 6 GW [Ast05]. These transmission systems are current source type converters and are designed to deliver power from point-to-point. Voltage source type transmission systems are being implemented in those areas, where more decentralized power generation takes place. These systems (called HVDC Light or HVDC Plus) currently use press-pack IGBTs or IGBT modules. The functional advantages of voltage source systems, i.e. independent active and reactive power control, PWM voltage control, lower harmonics and smaller filter requirements, have enabled voltage source converter technology to compete economically against classical HVDC at power levels up to 1 GW [Asp97]. Currently, off-shore wind power plants are under construction using voltage source systems to transmit power via undersea cables.

Electrolysers for electrowinning and electroplating are yet another high power application in power electronics. Contrary to HVDC, very high DC currents at modest voltage (200 V to 500 V) have to be controlled [Wie00]. Units delivering more than 100 kA have been constructed based on thyristor rectifiers. In the future, electrolysers may play a growing role when energy from renewable power sources is converted and stored in hydrogen [Bir06].

A growing market for power electronics are converters for photovoltaic (PV) systems, especially grid connected PV systems. High efficiency, also at partial load, drives the design of PV converters. Units from 150 W (module converters), 5 kW (string converters) up to 1 MW (central converters) are being produced [Qin02]. Most designs use IGBT devices. Depending on geographical latitude, most road maps of PV cell manufacturers foresee PV at parity with electrical energy cost by 2015 (southern Europe) and 2020 (central Europe). Large-scale PV systems as well as solar thermal systems are envisaged in the near future around the Equator. To transport the electrical energy, HVDC transmission systems will be needed that span entire continents. These super-grids are under study and can be realized with today's state-of-the-art power electronics [Zha08].

The more the energy demand of the world will rely on renewable power sources, the more electrical storage capacity will be needed. High power battery storage systems are being demonstrated for over a decade in Japan using high-temperature sodium-sulfur batteries [Bit05]. Lithium-ion battery technology will further increase power density and energy density [Sau08]. Furthermore, if electric vehicles, all driven by power electronic converters, are used on a massive scale, it is anticipated that these vehicles can provide sufficient storage capacity to substantially load-level renewable power sources.

1.4 Power Electronics for Carbon Emission Reduction

Power electronics is significant for society's future. Power semiconductor components are drivers and enablers to the technological advancements that reduce carbon emissions. In Japan, it is discussed that, in the future, our way of life and practices will be an "intelligent electrified society". Power components will be responsible for the increased efficiency of the individual applications. They will serve as the key components in a variety of fields.

In 2010 Mutsuhiro Mori from Hitachi published a study called "Power Semiconductor Devices Creating Comfortable Low Carbon Society" [Mor10] with the estimation that the market volume for power semiconductors will grow 10-fold by 2050. It contains long time technical trends. These trends, extended by further European studies like [Pop12] and other material, are briefly addressed in the following sections.

Energy Efficiency

At the opening session of APEC 2013, B.J. Baliga stated that IGBT-based power electronics has saved "75 Trillion pounds" CO_2-emission in the last 20 years. This is about 33.4 Billion tons CO_2, which is equivalent to the emissions of 390 large power plants of 1 GW each over a period of 20 years, assuming the 2013 emission factor (1 kWh = 0.596 kg CO_2) and an average load factor of 84%. Hence, power semiconductor devices are enablers for higher efficiency, leading to the fact that 390 central power plants have become expendable. However, this notion is not reflected in society. The "greenest" electricity is the one that does not need be produced.

Around 50% of the total electricity consumption occurs in electric motors in the industry and other applications. Between 40 to 50% of the applications show efficiency gains by using power electronic variable speed motor drives. Today, 80–85% of all drives are already power electronic controlled. Combining all these factors, the total electric energy savings potential with further variable speed drives is about 5–6% of the total electrical power consumption in Europe, by application of existing power devices [Pop12]. The next step is to equip motor drives with power devices that show significantly reduced losses.

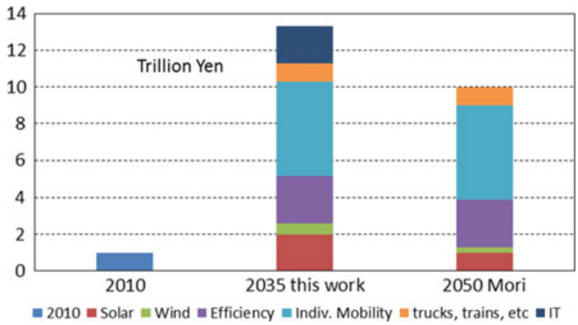
About 21% of electricity is consumed for lighting [EPE07]. Replacing traditional fluorescent sources by high-efficiency ones using electronic ballast reduces the energy consumption by 61% [Pop12]. Further savings are related to new technologies based on solid-state lighting (LED) requiring effective digital controlled power converters. All this makes application of power devices necessary. A large ecological potential and strong growth area for power electronics exists in energy efficiency.

Electromobility

Mobility and traffic must be sustainable, i.e. without excessive CO_2, particle and noise emissions. Here, power electronic inverters are essential sub-systems for all transport systems of the future, whether it is e-vehicles, hybrids, rail vehicles or vehicles powered by fuel cells. At the moment, the view on future transport is too narrowly limited to electric cars. Individual mobility is an important factor in our standard of living. It is compatible with ecology if we ensure that different modes of transport—railway transport, public traffic, individual traffic complement each other.

In this scenario, the future driver will be mobile but possibly car-less. He or she uses a car when need arises. Hence, car sharing organizations are only the beginning of an alternative use of vehicles. In addition, a good railway system is a crucial factor as well. Future traffic requires a high amount of power devices. In the forecast given in [Mor10], individual mobility is seen as the largest growth volume for power devices (Fig.1.8).

Fig. 1.8 Expected market volume of power semiconductors. Forecast 2050 by M. Mori [Mor10], forecast with higher engagement for sustainability 2035 this work: [Lut17]



Information Technology

In 2006, already 10% of the world's electricity was consumed by information technology (IT) [EPE07], while forecasts point to a strong increase, thus regarding 2017 we better assume 15%. The Kitakyushu Research Group for Sustainability estimates: until 2025 the data traffic will increase by a factor of 200, the required electricity consumption by a factor of five. From a sustainability point-of-view, this would be a disaster.

Electric energy demanded by data centers and servers in Europe was 56 TWh in 2007 and was predicted to have an increment to 104 TWh in 2020. In a typical data center, less than half of this power is delivered to the computing units, which includes microprocessors, memory and disk drives. The rest of the power is lost in power conversion, distribution and cooling [Pop12]. Conventional AC-distributed architectures suffer from low efficiency due to many conversion steps. Using high-voltage DC distribution at 400 V and high-efficiency DC-DC converters, the overall efficiency can be increased from 50 to 70%. There are further strong activities necessary to reduce energy consumptions of microprocessors etc.

Wireless communication is highly electricity consuming, mainly due to the poor efficiency of base stations. A typical base station (2007) was equipped for an input power of 2 kW, with an average power consumption of 1.3 kW. The radiation output power was 20 W, a comparatively high power for usual short transmission distances. A typical telecom radio base station with an output power of 120 W has a power consumption of more than 10 kW. This translates into a system efficiency of 1.2% [Pop12], which is quite low.

The efficiency of the power transmitter is barely 6% [Pop12]. Innovative solutions like the use of multilevel converters and a linear regulator allow the use of a switching frequency equal to the bandwidth of the envelope signal [Vas10]. For RF devices, progress with the GaN HEMT has shown that it is possible to realize highly efficient switch-mode amplifiers at microwave frequencies [Pop12].

A wide extension of IT applications is intended in every day life and the industrial production with the slogan "Internet of Things (IoT)" and "Industry 4.0", even the term "next industrial revolution" is used. Unfortunately, energy efficiency is rarely considered in the IoT and Industry 4.0 communicated outlines and roadmaps. Without energy and energy efficiency considerations these "revolutions" will conflict with ecological constraints. Moreover, the next industrial revolution must consider sustainability: From linear economy (natural resource—production—consumption—waste) to a global circular economy [Vol15].

Renewable Energy and Smart Electricity Distribution

Wind energy and solar energy need power electronic inverters. The sales of wind and solar inverter manufacturers are already a significant part of the power device companies' business, with a strong growth rate. According to the Global Wind Energy Council, a cumulated capacity of 487 GW of wind turbines was installed in 2016 [Gwe16]. Taking into account a 50-50% mix of doubly-fed and full-converter wind generators, De Doncker estimated at the IEEE PEDG 2017 meeting that this represents approximately 750 GVA of three-phase power electronic inverters. Furthermore, taking data of PowerWeb [Pow17], which shows that 285 GW of PV systems were installed globally in 2016, he estimates that approximately 315 GVA of grid-connected inverters have been installed (assuming 10% VAR compensation capacity). As a consequence, inverter cost per kVA has dropped significantly over the past decades from 500/kVA down to less than 25/kVA, which is nowadays about the same cost as a 50 Hz standard transformer. [Ded14]. According to Bloomberg, PV module cost in 2016 has dropped to below 0.22 $ per Watt [Blo17], leading to more investments in PV than in wind power. Clearly, with power electronics and PV, both being produced from silicon dioxide (i.e. sand), a sustainable, low-cost energy supply can be built that consumes less copper and steel. Hence, from a technical and economical point of view, all components and sub-systems are now available to allow an electricity supply from 100% renewable resources. Since important renewable sources are fluctuating, storage units and intelligent control are necessary. Power electronic actuators are key elements. They are required to control current flow, to adjust generation, storage and consumption, to deliver and compensate reactive power. A very effective solution for grid stabilization is the implementation of HVDC lines with the Modular Multilevel Converter in full-bridge topology based on high voltage IGBTs [Dor16]. In addition, research is on-going to explore the use of DC distribution systems at medium and at low-voltage to make distribution grids more flexible in routing energy better between decentralized power generators and "prosumers" [Ded14]. Interconnected DC distribution grids have reduced infrastructure and storage costs and operate more efficiently than classical, radial AC grids [Sti16].

Power Device Market Volume Forecast

An analysis of technical trends and forecast for market volume was made in [Mor10], the expected volume is displayed in Fig. 1.8. The study is based on the G8 Summit 2008 results, which aim at a 50% CO_2-reduction until 2050, continuing usage of nuclear energy, introducing carbon capture storage, and targets at only 33% renewable electricity. Meanwhile, the Fukushima disaster occurred. With regard to the upcoming climate disaster, which makes quality of life of future generations questionable, faster and stronger action is required. Therefore, we need to achieve these aims earlier than stipulated. In Fig. 1.8 [Lut17], the volume for solar and wind is doubled and effort for IT is added. The forecast of [Mor10] is given and "2035 this work" from [Lut17] added. Political decisions and framework conditions are of strong influence. However, every forecast for a modern and sustainable society gives a strong increase of the volume of power devices.

While this first chapter discussed power conversion systems from the application view, we will, after discussing in depth the physics and technology of power electronic devices and components, return to the system design at the end of this book from a bottom-up perspective.

One can conclude that with power electronics, vast amounts of energy can be saved (due to efficient control of processes). In addition, power electronics is a key enabling technology to make the electrical energy supply more robust and flexible, so that a more sustainable energy supply can be realized. By definition, at the heart of power electronics are power semiconductor devices that enable this efficient energy conversion. Consequently, a deep understanding of power semiconductors is a must for any electrical engineer who wishes to contribute towards a more sustainable world.

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