

ENERGY, ENVIRONMENT, POWER ELECTRONICS, RENEWABLE ENERGY SYSTEMS, AND SMART GRID

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1.1 INTRODUCTION

This introductory chapter will attempt to set the stage for the remainder of the book by providing an overview of energy, environment, power electronics, renewable energy systems, and the smart grid. The main focus of the chapter is on power electronics for renewable energy systems and smart grid, which is the theme of this book. Many of the challenges for renewable energy systems and smart grid are related to energy and environmental issues. Considering the relevance and their recent importance, these topics have been discussed in some detail. The modern renewable energy system cannot function, and the smart grid cannot be realized, without power electronics. In fact, power electronics is the most important element in these areas. An overview of power electronics [1, 2] is presented that includes power semiconductor devices, converter types, commonly used circuit topologies, converter compositions, and some of the most common power electronics applications, in particular, those related to power grids. Finally, the renewable energy system and smart grid will be considered again with those features that mainly require power electronics. The overview essentially covers the present technology, technology under research and development, as well as future trends.

1.2 ENERGY

Energy is the life-blood of human civilization and the wheel of its progress moves continuously with energy. The present global total energy generation scenario [3–7] is shown in Figure 1.1. About 86% of the total energy is generated by fossil fuels,

Power Electronics in Renewable Energy Systems and Smart Grid: Technology and Applications,
First Edition. Edited by Bimal K. Bose.

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Published 2019 by John Wiley & Sons, Inc.

of which 30% comes from coal, 24% from natural gas, and the remaining 32% comes from oil. About 4% of our total energy is generated in nuclear plants, and the remaining 10% comes from renewable energy sources (RES). The renewable energy segment can be subclassified as: hydroelectric, 20%; solar, 3%; wind, 11%; geothermal, 1%; and biomass (biofuels including biodiesel and ethanol, wood, biomass waste), 65%. The US total energy generation, shown in Figure 1.2, generally follows a similar pattern. It is interesting to note that the recent shale oil and natural gas revolution by hydraulic fracking is altering the energy scenario of the world, particularly that of the USA. The price of these fuels and their share of imports have decreased significantly in the USA, and in fact, shows signs that the USA may become a net energy exporter in the near future. The share of coal is also being replaced by cheaper and cleaner natural gas in energy generation.

The USA has a voracious appetite for energy. Per capita energy consumption there is the highest in the world. With nearly 4.4% of world population (322 million out of 7.4 billion), the USA consumes nearly 23% of world energy, and this reflects a very high living standard (Norway now has the highest living standard, with lower per

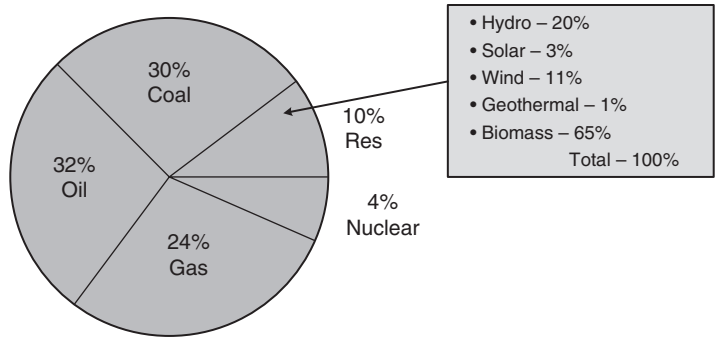


Figure 1.1 Global total energy generation (2014) with the breakdown of renewable energy sources.

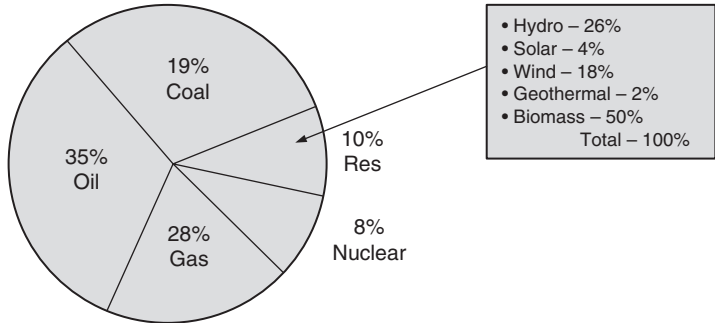


Figure 1.2 US total energy generation (2014) with the breakdown of renewable energy sources.

capita consumption of fossil fuels compared with the USA). In comparison, China (now the world's second largest economy), with nearly 19% of the world population (1.4 billion), consumes a slightly higher total amount of energy than the USA. Of course, this scenario is changing fast due to rapid industrialization of China.

Figure 1.3 shows the projected depletion curves of fossil fuel energy resources [3, 6] considering their present availability and rate of consumption. The curves plot the amount of energy (in 10^9 MBtu) vs. the year, and the area under each curve gives the total available energy. Of the different types of fossil fuels, the world has large reserves of coal. The coal consumption is expected to peak around 2070, and will last around 280 years. As mentioned before, the coal burning rate has decreased recently due to environmental reasons that will be discussed later. The oil and natural gas reserves are small in comparison, but are expected to last around the same period. However, there may be discoveries of new resources in the future. The Arctic Ocean is believed to contain more than 25% of the world's oil and gas, which may be very expensive to explore. With conservation and discovery of new resources, the depletion curves in Figure 1.3 can be extended in time. The nuclear energy availability is small compared with fossil fuel energy and is not included in the figure. Again, Figure 1.3 does not include renewable energy resources, which provide another dimension of infinite and inexhaustible energy sources that are now getting increasing emphasis throughout the world.

Figure 1.4 shows electricity generation by different types of fuel for several selected countries [3]: USA, Japan, China and India. In the USA, around 40% of total energy is consumed in electrical form. Of this, 39% comes from coal, 2% from oil, 27% from gas, 19% from nuclear, and the remaining 13% comes from renewable sources (mainly hydroelectric, as indicated in Figure 1.2). Japan does not have

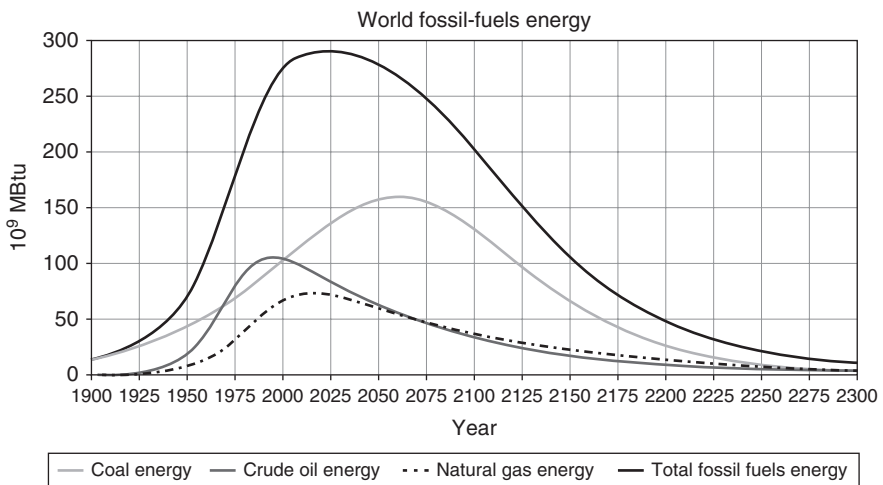


Figure 1.3 Projected global fossil fuel energy depletion curves. (See electronic version for color representation of this figure.)

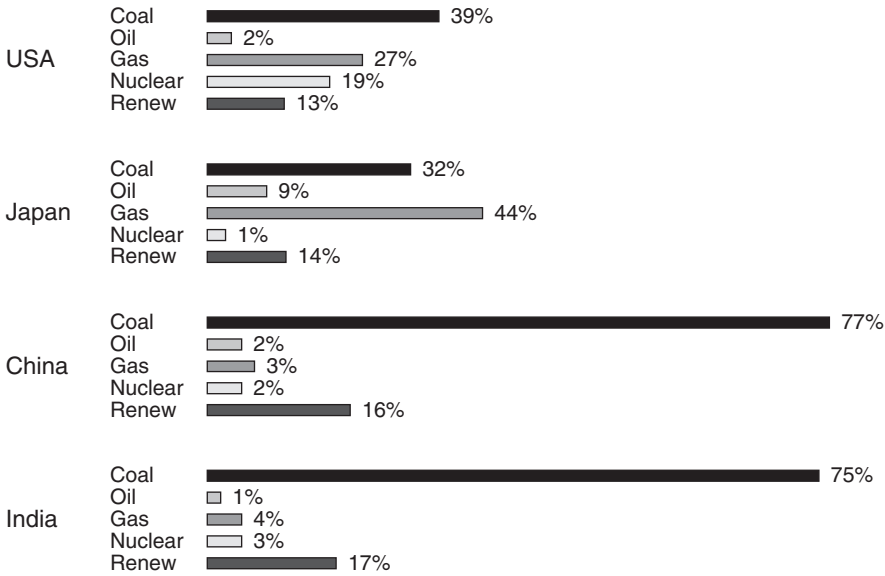


Figure 1.4 Electricity generation for several selected countries (2014).

much indigenous energy resources [8], and mainly depends on imports. The recent nuclear accident in Fukushima has reduced its share from 30% to 1%, which may be revived in spite of public opposition. It is interesting to note that the world’s two fastest developing countries (China and India) mainly depend on coal. Currently the world’s energy generation scenario is changing fast because of the progressively decreasing costs of wind (typically 5 cents/kWh) and photovoltaic (typically 6 cents/kWh) energies in comparison with the cost of coal (typically 5.2 cents/kWh) and gas (typically 10 cents/kWh) [9]. This will be further discussed later.

1.3 ENVIRONMENT

1.3.1 Environmental Pollution by Fossil Fuels

Burning of fossil fuels (coal, oil and natural gas), as mentioned before, produces pollutant gases, such as SO_2 , CO , NO_x , HC , and CO_2 , as shown in Figure 1.5, that cause environmental pollution problems [10–13]. Of these, SO_2 , CO_2 , HC and NO_x gases mix with rainwater and cause acid rain that destroys vegetation. It also acidifies the ocean water, thus affecting marine life. Urban pollution is mainly caused by automobile exhaust gases (CO , NO_x , SO_2 , HC and particulate matter) that are harmful for human breathing. The most dominant effect of fossil fuel burning is the global warming or climate change problems caused by greenhouse gases (GHG) (CO_2 , N_2O , CH_4 (methane), CFCs (chlorofluorocarbons), and others), because they create a “greenhouse effect” by trapping solar heat in the atmosphere. James Hansen, a

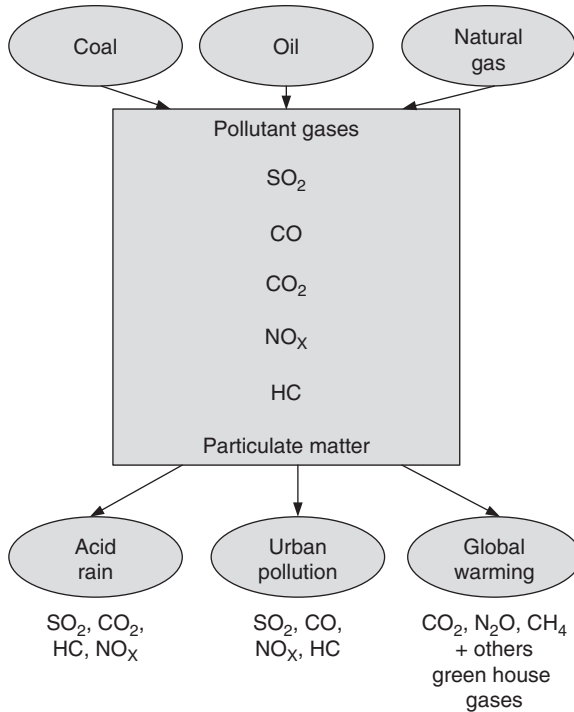


Figure 1.5 Environmental pollution by fossil fuel burning.

NASA scientist (also an activist), first predicted global warming problems in 1988 by this greenhouse effect. The UN-IPCC (Intergovernmental Panel for Climate Change) now predicts with 90% certainty that global warming is caused by burning of fossil fuels. The CO_2 gas generated by burning of fossil fuels is the main cause due to its higher concentration in the atmosphere. Although methane is significantly more harmful than CO_2 , its concentration is low in the atmosphere and it is lighter than air.

Figure 1.6 summarizes the different sources and sinks of GHGs [14]. Note that the Sun is the source of nearly all our energy. Some of this energy is absorbed, and some is reflected to maintain the heat balance and stabilize the Earth's temperature. Besides fossil fuel burning, a considerable amount of GHG is contributed by natural sources, such as volcanic eruptions, land and ocean floor emissions, and so on. Human beings and animals exhale GHGs (human beings exhale CO_2 , but animals exhale CH_4), but trees absorb CO_2 by photosynthesis (called the carbon fertilization effect) and emit oxygen. A considerable amount of GHG is washed away by rain to raise the acidity of ocean water. A secondary cause of global warming is due to the increase in world population and large-scale deforestation that tend to upset the natural ecological balance. In normal conditions, different natural sources and sinks of GHG maintain a stable atmospheric temperature. It is interesting to note,

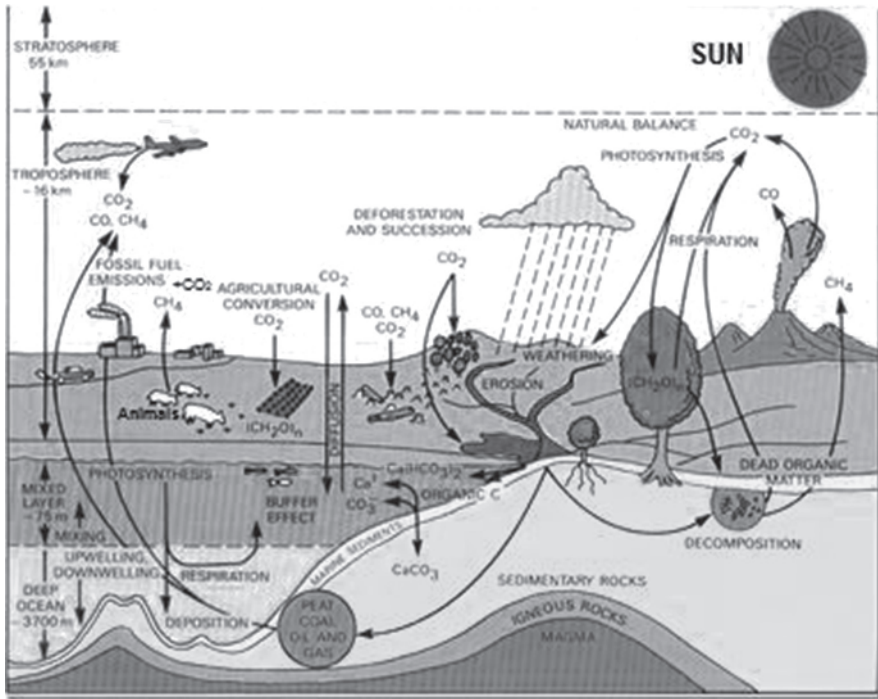


Figure 1.6 Sources and sinks of greenhouse gases. (See electronic version for color representation of this figure.)

however, that a significant amount of greenhouse effect is caused by water vapor in the atmosphere (including the cloud effect), which maintains a bias temperature and helps to sustain plant and animal life on Earth. Global warming processes are extremely complex, and many scientific studies are now being carried out by climate scientists.

Scientists have studied the historical changes in CO_2 concentrations in the atmosphere, going back thousands of years into the past [10] (see Figure 1.7), and have found that the curve is cyclic in nature (called Ice Age Cycles), where the peak is nearly 280 ppmv (parts per million by volume) and the trough is near 180 ppmv. The atmospheric temperature variation (0°C to -10°C) is nearly proportional to this curve, as indicated in the figure. The data for Figure 1.7 were obtained by ice core studies in Antarctica by US National Science Foundation (NSF). In this study, steel tubes were inserted deep in the ice for miles to extract samples of ice that were deposited over thousands of years [14]. Layer by layer, these ice cores are like a fingerprint of atmospheric conditions, such as chemical composition, dust particle composition, air temperature, nuclear radiation, and unusual events like volcanic eruptions. The exact cause for cyclic variation of CO_2 is not known. The one sure thing in Figure 1.7 is that in the past 1000 years (particularly in the post-industrial revolution era), the CO_2 concentration has increased dramatically (see upper curve)

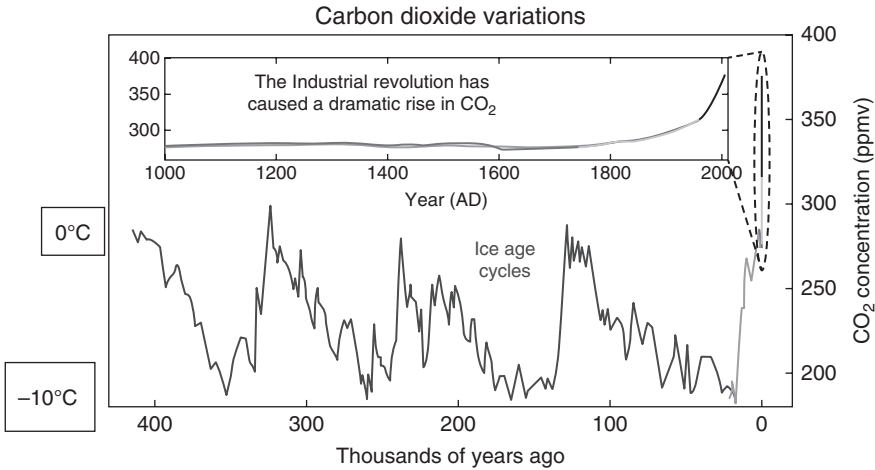


Figure 1.7 CO_2 cycles in the atmosphere over thousands of years, highlighting the rise since the industrial revolution in 1785. (See electronic version for color representation of this figure.)

to near 400 ppmv, which is much higher than the pre-industrial revolution peak values. Scientists now believe that this peak is due to man-made burning of fossil fuels, and may be irreversible. The potential impact of this rise [15], as shown in Figure 1.8, in terms of a consequential rise in global temperature is dangerous.

1.3.2 Climate Change or Global Warming Problems

What are the effects of global warming? Climate scientists around the world are trying to model the climate system (extremely complex) and study it using super-computer simulations [3–14]. Figure 1.9 shows the global warming projections made by different research agencies; they have estimated that the temperature rise will typically be 2–5°C every 100 years. The long-term effects of climate change are very serious, and can be summarized as follows:

- Gradual melting of Arctic and Antarctic ice caps, Greenland and a large number of glaciers around the world will raise the sea-level and cause inundation of low-lying areas. Figure 1.10 shows the melting of the Arctic Ocean and the vanishing habitat of polar bears, and Figure 1.11 shows melting of the Morano glacier in the Andes mountains of South America [16]. The predicted sea-level rise, as studied by the NASA/Poseidon project of NASA/JPL, is typically 1.0 inch every 10 years. The projected sea-level rise over 100 years [3, 17] is shown in Figure 1.12. It has been estimated that, in 2006 alone, half a million square miles of Arctic ice melted, which was three times faster than that predicted by climate model studies. One possible reason for accelerated melting is that 90% of the incident heat is absorbed by water and only 10% by ice.

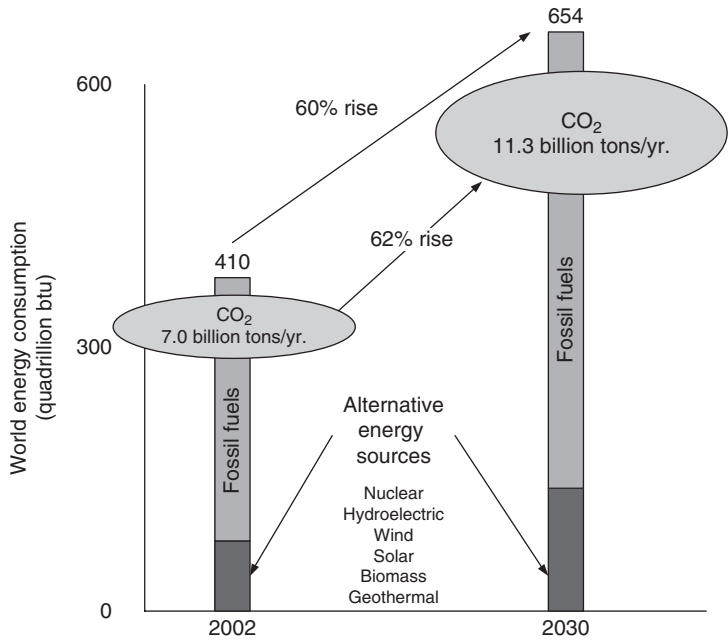


Figure 1.8 Potential rise in emissions of CO₂ during 2002–2030, without control of GHG.

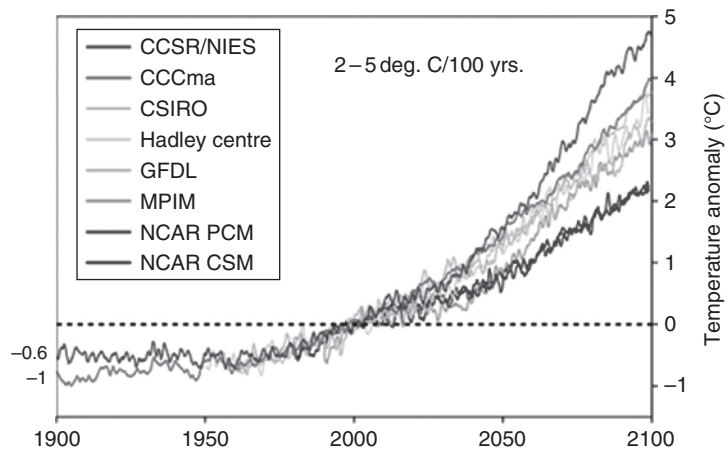


Figure 1.9 Global warming projections by different research agencies around the world, without control of GHG. See electronic version for color representation of this figure.

The Arctic Ocean is predicted to be ice-free by 2050. Sea-level rise has serious consequences because about 100 million people (mostly poor) live within 3 feet of sea-level. With the present rate of global warming, it has been predicted that 50% of Bangladesh (very low-lying ground) (Bose's birth



Figure 1.10 The melting Arctic Ocean and vanishing habitat of polar bears.



Figure 1.11 Melting of the Morano glacier, the Andes mountains, South America.

place) will be under water in 300 years time, displacing about 75 million people. Several island nations in the Pacific Ocean (such as Tuvalu) will be under water within 100 years. It has been estimated that if all the ice in the world melts, sea-level will rise by 210 ft and will completely immerse the island of Manhattan in New York [16, 17].

- Severe droughts in tropical countries such as India and parts of Africa, and particularly near the equator, will damage agriculture and vegetation.

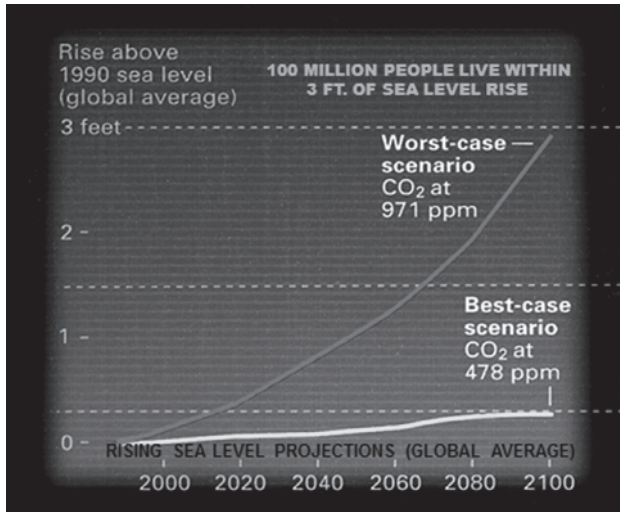


Figure 1.12 Sea-level rise projections over 100 years, without control of GHG.

The UN has predicted that by 2080 India's agricultural production will decrease by 38% due to drought, but the carbon fertilization effect will offset it by 9%. The African countries have demanded billions of dollars compensation from Western countries, which are blamed for the global warming problems.

- The quality and quantity of fresh water supplies will deteriorate.
- The circulation of air with high moisture content will cause more hurricanes, tornadoes, heavy rains and floods, which are already evident in some parts of the world (including the USA).
- Tropical climates with more moisture will spread diseases.
- Some animal species like polar bears and penguins will become extinct because of their vanishing habitats (see Figure 1.10). Higher acidity of sea-water from dissolved GHGs along with higher temperatures will threaten marine life such as corals (already evident in the Great Barrier Reef of Australia and other parts of the world).

It has been predicted that even if fossil fuel burning is completely stopped today, sea-levels are expected to rise several feet in the next 1000 years. A kind of statistical/ecological balance will tend to occur when natural carbon emissions (volcanoes, ground emission, etc.) and animal exhalation will tend to balance by the sinks due to rainwater and carbon fertilization of trees. There may be other effects of climate change which will be uncovered by further scientific studies.

1.3.3 Several Beneficial Effects of Climate Change

Although climate change problems will have serious harmful effects on our society, there are also a few beneficial effects [3, 17]. As stated before, CO_2 absorption by photosynthesis will tend to help nutrition of plants, but will be offset heavily by droughts. Melting of polar ice caps in the summer is opening shorter transcontinental navigation routes. For example, as shown in Figure 1.13, a new Arctic Ocean route (shown as the Northern Sea route) has opened recently that takes 35 days for a ship to travel between Dalian in China to Rotterdam in the Netherlands during summer (July to November), instead of 48 days by the Suez Canal route that is already open throughout the year [18]. As mentioned before, it is believed that more than 25% of world's oil and natural gas resources lie beneath the Arctic Ocean. However, this exploration is very expensive. Recovery of new land due to melting of ice will enable habitation, agriculture and mining. For example, Greenland will be exposed for Nd mining, which is important for widely used high-energy NdFeB magnets. Although cooling or air-conditioning costs of many countries will

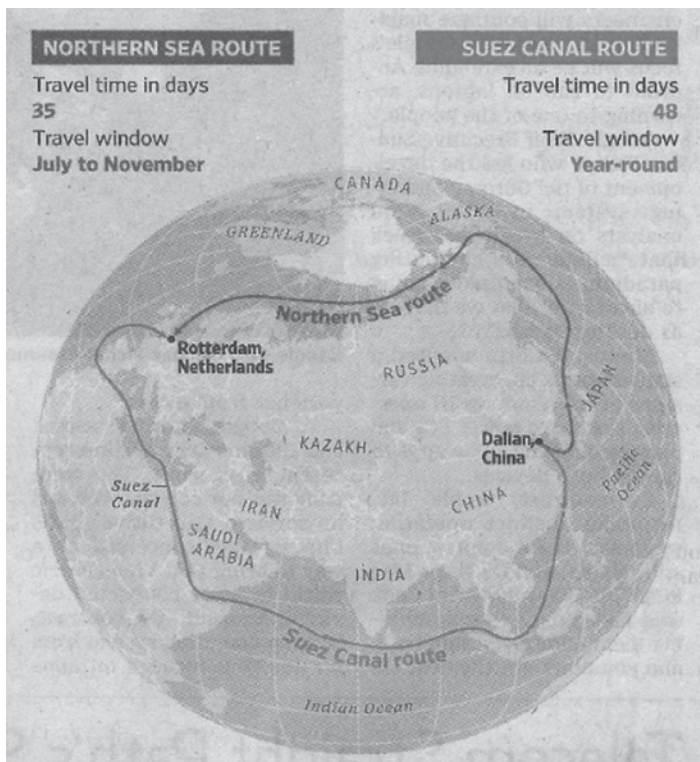


Figure 1.13 The shrinking Arctic Ocean trade route between China and the Netherlands. (See electronic version for color representation of this figure.)

increase, the heating cost of some countries in cold climates will decrease. Melting of polar ice is expected to promote fishing industries.

1.3.4 The Kyoto Protocol and Carbon Emission Control

Considering the serious consequences of climate change, the United Nations (UN) called a series of international meetings over a period of time to discuss the challenges posed by climate change. Finally, as a result, an international agreement called the Kyoto Protocol or Global Climate Treaty emerged in 1997 [14]. Under this treaty, many industrialized nations were assigned quotas for GHG emissions which were essentially based on per-capita emission of CO_2 . The protocol went into effect in 2005, and now has 192 member countries.

However, the USA refused to participate in the Kyoto Treaty for emission control, although its per-capita emissions are the highest in the world, as shown in Figure 1.14 [17]. It is interesting to note that although China's per-capita emissions are much lower than those of the USA, considering its large population and the recent trend of industrialization, the total emissions (given by the area of the rectangle) of China became higher than the USA from 2006. The USA refused to accept the emission control mandate unless China took adequate remedial measures. But China blamed the USA and other industrialized nations for creating this mess and was not willing to sacrifice its growing living standards by reducing its fossil fuel-based energy consumption. With no remedial measures, the projected world CO_2 increase for 2002–2030 is shown in Figure 1.8.

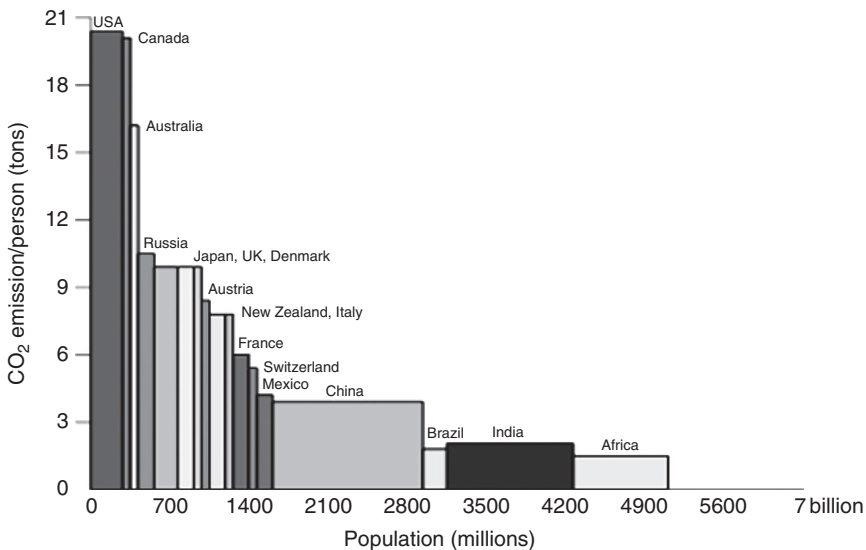


Figure 1.14 Per-capita CO_2 emission vs. population of selected countries in the world (2004) (some Middle-Eastern countries have higher per-capita emissions).

According to the Kyoto Treaty, a country with higher emissions can cap it by advanced technology or by purchasing credits from a country with lower emissions (called cap-and-trade policy). For example, the UK with higher-than-quota emissions can purchase credits from Brazil, which has emissions below its quota. Within a country, a quota can be assigned to an industry or individual person (or family) who can buy or sell credits to satisfy the quota. In 1990, the Clean Air Act (similar to a cap-and-trade policy) was enforced successfully in the USA to control power plant and automobile air pollutions. Alternatively, carbon tax can be imposed on polluters, based on a carbon tax rate (tax on CO_2 emissions per ton per year). Both strategies are difficult to implement. Although many UN conferences have been held since the Kyoto Treaty and policy changes have been made, carbon emission control strategies are not working satisfactorily in the world.

1.3.5 How Can We Solve or Mitigate Climate Change Problems?

The first step we can take is to promote all of our energy consumption to be in electrical form. In a large centralized fossil-fuel based power generating station, it is somewhat convenient to apply advanced emission control standards. Since coal is a dirty fuel for environmental pollution, coal-fired power generation can be cut down and eventually eliminated in the long run. The success of clean coal technology is not promising. CO_2 capture from coal plants and underground sequestration (carbon capture and storage (CCS) strategies) is still expensive. Since trees absorb CO_2 , tropical rainforests (such as the Amazon rainforest) can be preserved and widespread forestation can be promoted to mitigate the global warming problems. Controlling human and other animal populations to reduce GHGs is not easy. A substantial portion of global energy demand can be met by promoting environmentally clean renewable energy sources, and the whole world is now moving in that direction. Fuel cells, although currently expensive, can be promoted if clean energy is used to generate its fuel – the H_2 gas. Internal combustion engine (ICE) vehicles can be replaced by electric vehicles to substantially improve the environment, if the battery-storage electricity is generated by renewable sources. However, if the electricity is generated by fossil fuels, the urban pollution is transferred to generating station pollution. Similarly, other fossil-fuel based transportations (railways, ships, etc.) can be replaced by electric transportation. Promoting mass electric transportation as Japan has done will mitigate the global warming effect. A substantial amount of energy can be saved by improving efficiency in generation, transmission, distribution, and utilization of electrical energy. Finally, wastage of energy can be prevented. Typically, a third of US energy is wasted because it is cheap and people are affluent. Note that power electronics plays a significant role in renewable energy generation, transportation and energy efficiency improvement, as mentioned before, and will be further discussed later.

Unfortunately, as mentioned before, the global climate control strategies are not working satisfactorily. These are progressing more or less on a voluntary basis by piecemeal efforts of different countries. Of course, further R&D is required both

in climate sciences and in methods of mitigation. Many countries in the world are dependent on fossil fuels. The recent glut of oil and gas from shale technology has made these fuels cheaper, promoting their increased consumption. Nuclear energy is pollution free in the traditional sense, but nuclear plants have safety problems. Improvement of safety measures means it has become more expensive in recent years. Besides, nuclear waste remains radioactive for thousands of years and there is no safe method for its disposal. For these reasons, nuclear power generation is gradually decreasing in the USA.

Again, because of long-term effects, environmental problems are not considered seriously. European countries have taken the leadership role in solving the problems, but there is not much enthusiasm in the USA. A segment of the population has tried to propagate the idea that the global warming problem is a hoax. There is also political pressure from coal, oil and gas companies. The US leadership is essential to tackling climate change problems, but recently it has gone in the opposite direction.

1.4 POWER ELECTRONICS

1.4.1 The Role of Power Electronics in Renewable Energy Systems and Grids

From the previous sections, it can be clearly seen that the energy future that will help both the sustainability and environmental issues lies in renewable energy. As will be described in detail in Section 1.5, the most abundant renewable energy sources in the foreseeable future will be wind and solar energy. Modern society runs on electricity or electric energy. For wind and solar energy (or any energy sources for that matter) to be converted to electric energy, conversion equipment is needed. For wind, turbines and generators are used. However, the variable wind turbine and generator speed can lead to variable frequency and variable voltage electricity. In order to meet the grid requirement of fixed frequency of 50 or 60 Hz at certain standard voltage levels, additional electrical conversion equipment, in this case to convert variable frequency, variable voltage to a fixed frequency, fixed voltage, is required.

For solar energy, photovoltaic (PV) cell-based panels are the most popular technology to convert solar energy to electrical energy. However, PV panels produce DC power at unregulated low voltage (e.g., PV panels typically rated around 60 V). In order to meet the grid requirement for frequency and voltage, a DC-to-AC converter that converts DC source at various voltage levels to a fixed-frequency, fixed-voltage AC supply is required.

In fact, all energy sources require conversion equipment to convert them into electrical energy sources at fixed frequency and voltage. For traditional electrical energy sources, thermal power (including nuclear power) is converted to electricity through steam or gas turbines and fixed speed or frequency synchronous

generators; and hydro-power is converted to electricity through hydro turbines and fixed speed or frequency synchronous generators. Unlike wind and solar power conversion, no frequency conversion equipment is generally required for thermal and hydro-power.

After its generation, electric energy generally must be transferred or delivered before consumption, since the energy sources, such as thermal power plants, hydroelectric dams, and wind farms, are often some distance away from loads. The energy/power delivery is realized through the electrical power system, or *grid*. In addition, electrical energy needs to be controlled as well, since the energy delivery and use often require electricity in a form different from the original form generated at the source. Examples are the voltage magnitude and frequency. For long-distance transmission, the voltage needs to be stepped up at the sending end to reduce the energy loss along the lines, and then stepped down at the receiving end for users. For many modern consumer devices, DC voltage is needed and obtained through transforming the 50 or 60 Hz utility power to DC power. Note that electric energy delivery and control is often used interchangeably with the electric power delivery and control. This is because in the modern electric power system or grid, there is still very limited energy storage and the energy generated must be consumed at the same time.

Since the beginning of the electricity era, electric energy delivery and control technologies have been an essential part of electrical power systems. Many types of equipment were developed and applied for these purposes. The commonly used equipment includes transmission and distribution lines, generators (which are both for mechanical to electrical energy conversion and for control), transformers, switchgears, inductors or reactors, and capacitor banks. The traditional equipment is electromechanical or electromagnetic in nature, and all has limited control capability. Many cannot be controlled at all or can only be controlled to connect or disconnect with mechanical switches; others have a limited control range, such as transformers with tap-changers. Even with fully controllable equipment such as generators, the control dynamics is relatively slow due to the electromechanical or magnetic nature of the controller. Almost no traditional control and delivery equipment has frequency conversion capability (a rotating transformer is an exception), as needed by some loads, similar to the cases of wind and PV energy sources. To achieve frequency conversion, power electronics-based conversion equipment can provide convenient solutions. In addition, power electronics converters can have many other advantages over traditional electromechanical or electromagnetic equipment.

Power electronics are based on semiconductor devices. These devices are derived from transistors and diodes used in microelectronic circuits, with additional large power-handling capability. Due to their electronic nature, power electronic devices are much more flexible and faster than their electromechanical or electromagnetic counterparts for electrical energy conversion, delivery, and control. Since the advent of power electronics in the late 1950s, they have steadily gained ground in electrical grid applications. Today, power electronics converters and

controllers are an important part of equipment for electrical energy generation, delivery, and control, and their role is growing rapidly with the continuous improvement of power electronics technologies, as well as with emerging needs like renewable energy systems, smart grid, and electronic loads. The examples of electronic loads include motor drives, electric vehicle (EV) charging stations, data centers, LED and compact florescent lighting, and other digital systems.

1.4.2 Fundamentals of Power Electronics

Power Semiconductor Devices

At the heart of the power electronics conversion equipment or converters are power semiconductor devices. Different from semiconductor devices in microelectronics, the power electronic semiconductor devices only act as switches for desired control functions, such that they incur minimum losses when they are either on (closed) or off (open). As a result, the power electronics converters are basically switching circuits. The power semiconductor devices or switches are therefore the most important elements of the power electronics converters. Since the 1950s, many different types of power semiconductor devices have been invented and developed, and can be selected based upon the applications.

The performance of a power semiconductor device is mainly characterized by the voltage and current ratings, conduction or on-state loss, as well as the switching speed (or switching frequency capability) and associated switching loss. The most popular and practical types of power semiconductor devices are listed with their symbols and the state-of-art ratings and frequency range in Table 1.1.

- Power diode – a two-terminal device with similar characteristics to diodes used in microelectronics but with higher voltage and power ratings.
- Thyristor – also called a SCR (silicon controlled rectifier). Unlike a diode, a thyristor is a three-terminal device with an additional gate terminal. It can be

TABLE 1.1 Commonly used Si-based power semiconductor devices and their maximum ratings.

Types	Symbol	Voltage	Current	Switching frequency
Power diode		Max 80kV, typical <10kV	10kA	Various
Thyristor		Max 8 kV	4.5 kA	AC line frequency
GTO		Max 10 kV	6.5 kA	<500Hz
Power MOSFET		Max 4.5kV, typical <600V	1.6 kA	Tens of kHz to MHz
IGBT		Max 6.5kV, typical >600V	2.4 kA	1 kHz to tens of kHz
IGCT		Max 10kV, typical >4.5kV	6.5 kA	<2kHz

turned on by a current pulse through the gate but can only be turned off when the main current goes to zero by external means. A thyristor has low conduction losses but slow switching speeds compared with other devices.

- GTO – stands for gate-turn-off thyristor. A GTO can be turned on similarly to a regular thyristor and can also be turned off with a large negative gate current pulse. GTOs have been largely replaced by IGBTs and IGCTs due to their complex gate driving needs and slow switching speed.
- Power bipolar junction transistor (BJT) – similar to a bipolar transistor for microelectronics and requires a sustained gate current to turn on and off. It has been replaced by IGBTs and power MOSFETs (metal-oxide semiconductor field effect transistors) with simpler gate signals and faster switching speeds.
- Power MOSFET – similar to a metal-oxide semiconductor field effect transistor for microelectronics, and can be turned on and off with a gate voltage signal. It is the fastest device available but has a relatively high conduction loss and relatively low voltage/power ratings.
- IGBT – stands for insulated-gate bipolar transistor. Unlike a regular BJT, it can be turned on and off with a gate voltage like a MOSFET. It has a relatively low conduction loss and fast switching speed. The IGBT is becoming the workhorse of power electronics for medium to high power applications.
- IGCT – stands for integrated-gate-commutated thyristor. It is basically a GTO with an integrated gate drive circuit allowing a hard driven turnoff. It therefore has faster switching speeds than a regular GTO but is slower than an IGBT.

Except for diodes, all other devices above can be turned on and/or off through a gate signal, so they are active switches, while diodes are called passive switch. A thyristor is sometimes called a semi-active switch, due to its lack of controlled turn-off capability.

Note that devices in Table 1.1 are all based on Si. Since the invention of Si thyristors in the 1950s, Si power semiconductor devices have gone through many generations of development in the last 60 years and are approaching material theoretical limitations in terms of blocking voltage, operation temperature, and conduction and switching characteristics. In recent years, semiconductor devices based on wide bandgap (WBG) (energy bandgap significantly higher than 1 eV) materials have progressed rapidly and promise to revolutionize next-generation power electronics converters. Compared with the Si (energy bandgap around 1 eV) devices, WBG devices feature high breakdown electric field, low specific on-resistance, fast switching speed and high junction temperature capability. These characteristics are beneficial for efficiency, high power and voltage capability, size, and cost of power electronics converters, which are all important for the needs of renewable energy systems and smart grid applications.

The WBG devices under rapid development and commercialization include silicon carbide (SiC) and gallium nitride (GaN) devices, with SiC mainly targeting

high-voltage, high-power (600V, kilowatts or above) applications, and GaN for low-voltage, low-power (600V, kilowatts or below) applications [19, 20].

Figure 1.15 summarizes the status of SiC-based power devices, including Schottky diodes, PIN diodes, MOSFETs, junction gate field effect transistors (JFETs), IGBTs, BJTs, and thyristors with the voltage range from 400V to 22.6kV. It is observed that low-voltage (from 400V to 1700V) SiC devices are becoming commercially available. Among them, the current rating per die approaches up to 100A, and with multiple dies in parallel, state-of-the-art SiC power modules on the market can deliver hundreds of amperes of current. On the other hand, the high-voltage SiC (referred to here as 3.3 kV and above) are generally in the development stage with limited commercial availability and a small current rating per die [22].

Currently, SiC MOSFETs are the most developed active switches, with some JFETs, IGBTs, BJTs, and thyristors also available. SiC MOSFETs have been used commercially in electric vehicles (EVs) and PV applications. More SiC applications are expected, including for renewable energy systems and power grids.

GaN theoretically offers even better high-frequency and high-voltage performance compared with SiC, due to its higher breakdown electric field and electron velocity. However, GaN wafer fabrication technology is still a major challenge for vertical devices. Currently, lateral devices called heterojunction field-effect transistors (HFETs), also known as high electron mobility transistors (HEMTs), offer an effective alternative that takes advantage of the high-mobility layer formed at the heterojunction between GaN and AlGaN. HFETs have been fabricated on substrates of Si, SiC, and sapphire. Si is considerably cheaper than

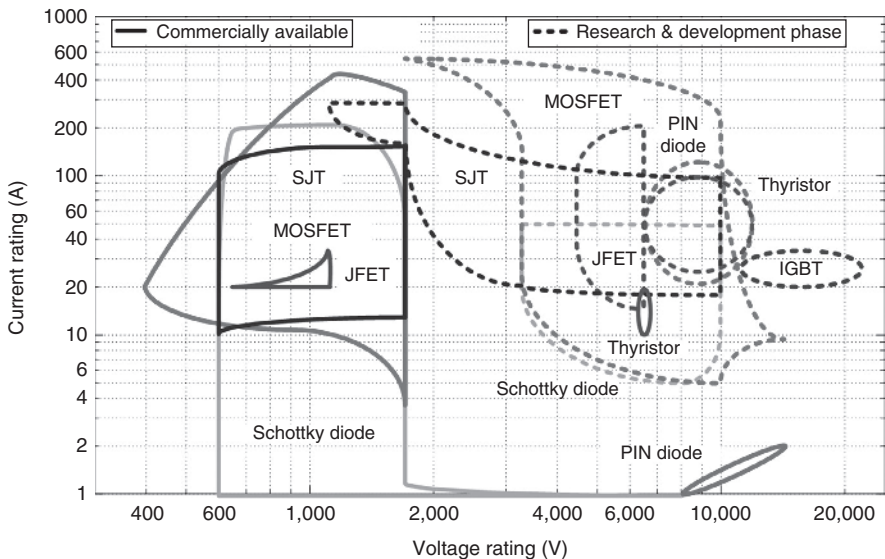


Figure 1.15 Summary of status of SiC power devices (updated January 2017) [21].
(See electronic version for color representation of this figure.)

other alternatives, and as a result, commercially available GaN power transistors on today's market use Si as a substrate (GaN-on-Si). Due to the lateral structure, their voltage rating is limited to below 650 V, with up to about 100 A current rating. Several manufacturers and researchers are exploring other GaN devices, such as vertical GaN-on-GaN JFETs and new HFET gate structures to increase the breakdown voltage. But these are all in the research and development phase, and no GaN devices have been released commercially above 650 V at this time. Consequently, GaN device applications related to renewable energy systems and grid are still very limited, even in exploratory research. They are suitable for small PV inverters like micro-inverters and single-phase inverters for rooftop PV.

Power Electronics Converter Types and Basic Topologies

Discussions above explained that a power electronics converter functions as electric energy to electric energy conversion equipment. The energy is preserved while the voltage and/or frequency will be converted. Power electronics converters are based on power electronics circuits containing power semiconductor switches. With different types of power semiconductor switches, many power electronics circuits have been developed. Based on their conversion functions, they can be classified as four basic types:

- Rectifier – rectifiers convert AC to DC. Depending on AC sources, rectifiers can be three-phase or single-phase; depending on device types, they can be passive (diode-based), phase-controlled (thyristor-controlled), or active (active switch-based).
- Inverter – inverters convert DC to AC. They again can be three-phase or single-phase. Inverters generally require active switching devices.
- DC–DC converter – also called choppers, DC–DC converters convert one DC voltage level to another. Sometimes they include a magnetic isolation. A DC–DC converter generally requires active switching devices.
- AC–AC converter – directly converts one AC to another, either only the voltage magnitude or both magnitude and frequency. The former can also be called an AC switch and the latter can be called a frequency changer. Active devices are needed for these types of converters.

Furthermore, each of the converter types can be further clarified. For example, a converter can have unidirectional power flow or bidirectional power flow. In addition to DC–DC converters, other types can have isolation as well, though this is less popular in application.

There are a variety of converter topologies for each type of converter listed above. The most commonly used basic topologies for power system or grid applications are shown in Figure 1.16. These basic topologies can be expanded through using devices and/or converters in series or parallel to achieve higher current and voltage ratings.

For high-power applications like renewable energy systems and utility grid, the basic state-of-the-art topology is the VSC shown in Figure 1.16b, and its

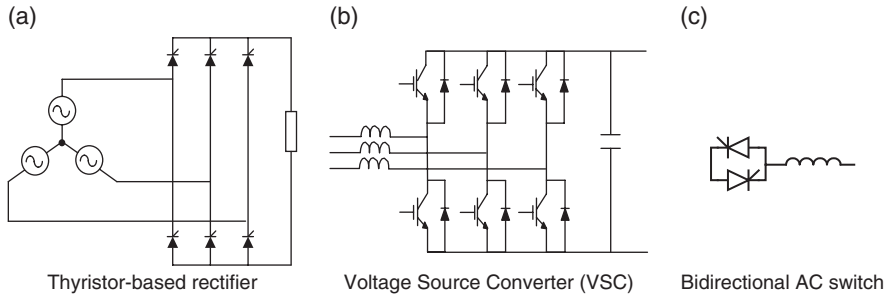


Figure 1.16 Commonly-used basic power electronics converter topologies (only one phase shown for the AC switch).

variations. The VSC based on Si IGBT becomes the topology of choice in three-phase AC–DC or DC–AC applications due to its circuit and control simplicity, and overall good performance and reliability. In some cases, the thyristor-based line or load commutated converters in Figure 1.16a, or the bidirectional AC switch in Figure 1.16c still dominate, such as in classic high-voltage direct current (HVDC) and flexible alternating current transmission systems (FACTS), which will be presented in more detail in Section 1.6, due to their simplicity and low losses. Thyristor-based topologies are older technologies with drawbacks in performance (e.g., high harmonics and low power factor), and therefore require bulky and heavy filters and compensators.

In order to increase power rating, improve efficiency, power density, and reliability, many advanced topologies beyond basic VSCs have been proposed, and some of them have already been employed in applications including renewable energy systems and grid.

Multilevel Converters Multilevel converters refer to a family of converters that synthesize AC voltages using more than two DC voltage levels, as in the case of the basic VSC in Figure 1.16b. The benefits of the multilevel converters include lower AC ripple, lower voltage stress on semiconductor devices and loads (e.g., motors), and higher equivalent switching frequency. Many types of multilevel converters have been proposed. The commercially adopted converters include the neutral-point clamped (NPC) multilevel converter, the flying capacitor multilevel converter, the cascaded multilevel converters, modular multilevel (MMC) converters, and Vienna-type multilevel converters. These topologies are shown in Figure 1.17 and compared in Table 1.2. The three-level NPC is a suitable topology for medium voltage (several to tens of kilovolts) when using Si IGBT or IGCT, considering the power and voltage levels of these converters (MWs and kVs) and availability of medium voltage IGBT and IGCT (kVs and kAs). The NPC converter has the advantage of high power density due to its low requirements on passive components. Therefore, NPC and its variants (including ANPC and Vienna-type) are often preferred for applications where high power density is important, such as

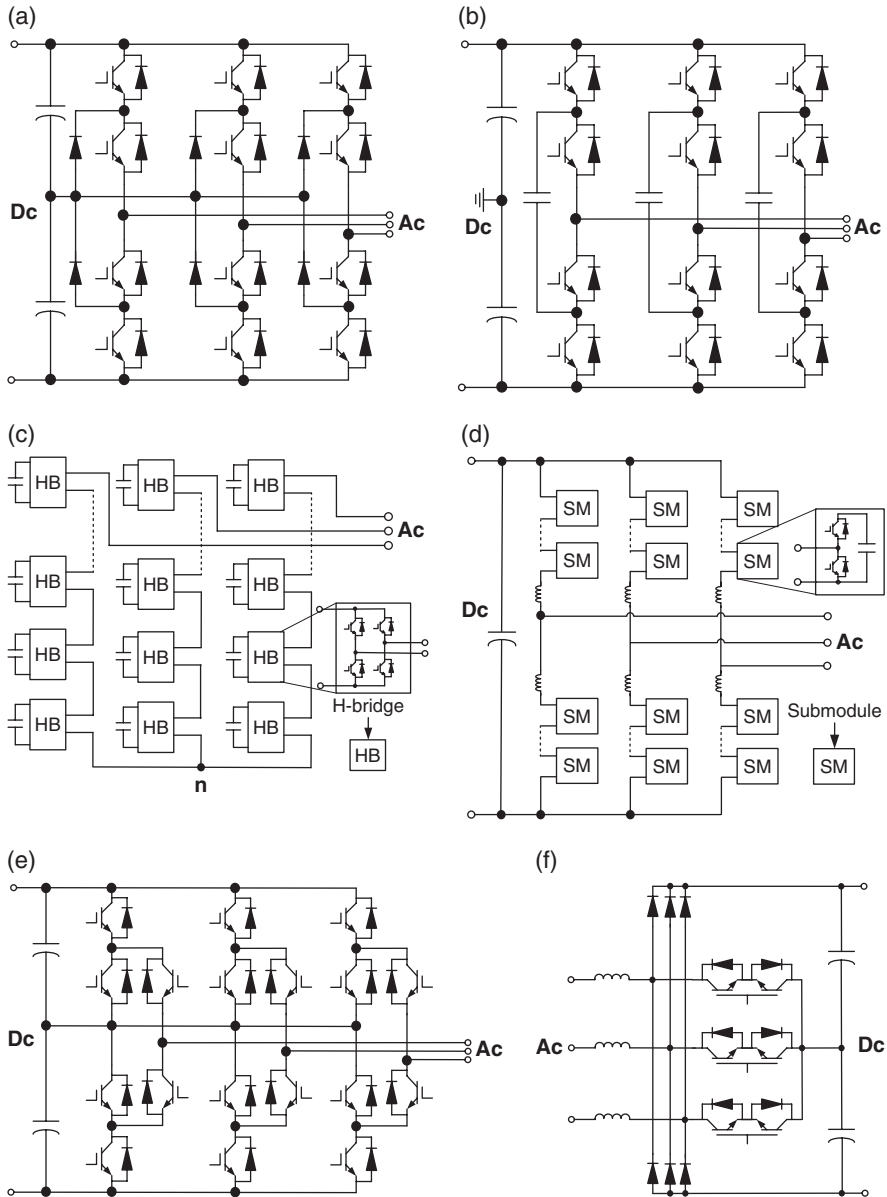


Figure 1.17 Multilevel converters: (a) three-level NPC; (b) three-level flying capacitor (FC) converter; (c) cascaded H-bridge (CHB) converter; (d) MMC; (e) three-level active NPC (ANPC); and (f) a Vienna-type rectifier.

TABLE 1.2 Multilevel converter comparison summary.

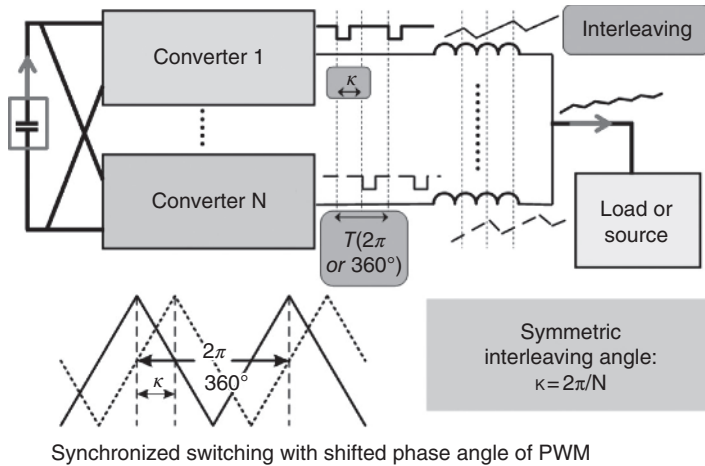
	NPC	FC	CHB	MMC	Vienna-type	ANPC
Device utilization*	1.25	1	1	1 to 2	1	1.5
Modularity	No	No	Yes	Yes	No	No
Capacitors	Low	Medium	High	High	Low	Low
Inductors	Low	Low	Low	High	Low	Low
Transformers	Low	Low	High	Low	Low	Low

*Assume two-level voltage source converter is 1.

shipboard or aircraft power systems. Cascaded converters and MMC are modular, fault-tolerant, can switch slow, use low-voltage devices, and have high efficiency and good harmonic characteristics. On the other hand, they require high numbers of capacitors and have inferior power density. In Table 1.2, note that the device utilization is calculated based on the total kVA ratings, using the peak voltages and currents that the switches and diodes will experience. In real converters, the device ratings, especially current ratings, will be determined based on thermal design.

Interleaved Converters Multilevel converters fundamentally employ the series converter strategies, with each converter switching phase-shifted with respect to others to achieve better ripple reduction while attaining higher voltage capability, or switch slower to achieve higher equivalent switching frequency. Interleaving refers to the strategy of paralleling identical converters, with each converter switching phase-shifted to achieve better ripple reduction while attaining higher current capability. Figure 1.18 illustrates the principle of interleaving. Similar to multilevel converters, interleaved converters have lower AC ripple, lower current stress on semiconductor devices, and higher equivalent switching frequency. Note that interleaving can cause circulating current problems for paralleled converters. The circulating current can be both common mode (zero-sequence) and differential mode. As a result, interphase inductors may be necessary for interleaved converters, which will increase design and control complexity, and add more components. For motor drives, the interphase inductor function could be integrated as part of the motor windings.

Multiphase Converters Most converters in high-power applications such as renewable energy systems and smart grid have three-phase AC input and/or output. For loads such as motors, multiphase motors with a phase number greater than three may be beneficial to cost, performance, power density and/or fault-tolerance. Correspondingly, the converters can also be more than three-phase, which can be realized with multiple three-phase converters or dedicated multiphase converters. In addition to modularity and redundancy, the multiphase converters may generate lower common mode voltages, which will be beneficial to motors and lead to lower filter requirements.



Synchronized switching with shifted phase angle of PWM

Figure 1.18 Two two-level voltage source inverters on interleaving. Interleaving and multilevel technologies can be combined for further performance and power density gains.

Soft-switched Converters DC–DC converters often employ resonant topologies to realize zero-voltage switching (ZVS) or zero-current switching (ZCS), to reduce switching loss and enable high-frequency switching. Many soft-switching topologies have been proposed for three-phase AC converters by adding auxiliary circuits to the original hard-switched topologies, including two-level VSCs, three-level NPC and ANPC converters [23]. Among these techniques, the zero-current-transition (ZCT) technique appears to be suitable for high power converters. The basic idea of this technique is as follows: during the switching commutation, the current flowing through the operating device is forced to zero prior to turning off the device with the assistance of an auxiliary circuit. Thus, the ZCT techniques can almost eliminate turn-off losses and overvoltage spikes during the turn-off transient, and greatly reduce turn-on losses and alleviate reverse-recovery issues during turn-on. In addition, the low power rating auxiliary switches have no switching losses [23–25]. However, the soft-switched converters have not been much adopted in practical applications due to the added complexity and cost, and limited benefits to motor drive type applications, where extra high-switching frequencies and fast dynamics are not required.

Composition of Power Electronics Converters

In addition to power semiconductor switches, it should be noted that passive components, such as inductors and capacitors, are essential parts of power electronics converters, as can be seen in Figure 1.17 with all kinds of VSC examples. In fact, power electronics converters convert or control the electrical energy by storing it temporarily in inductors or capacitors while reformatting the original voltage or current waveforms through switching actions. The other key function of the passive components is filtering the harmonics or noise caused by switching.

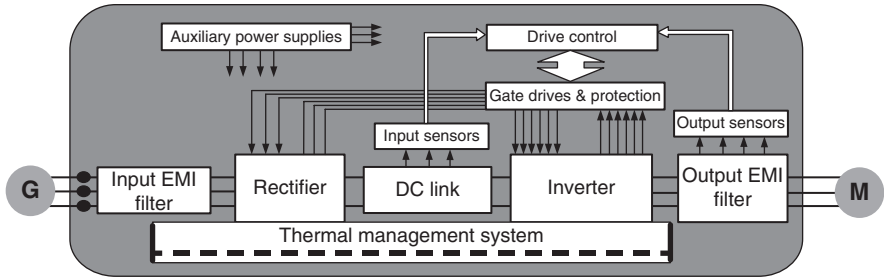


Figure 1.19 Functional block of a typical motor drive.

Figure 1.19 shows the functional block for one of the most popular types of power electronics converters, a motor drive, which is an AC–AC converter used to drive and control an electric motor. It converts the electric energy from the grid at a fixed voltage and frequency to electric energy at a variable voltage and variable frequency, which is required to adjust the motor speed and torque per the motor load need. Clearly, in this case, the AC to AC conversion is realized through a three-phase AC to DC rectifier and then a DC to three-phase AC inverter.

As can be seen in Figure 1.19, in addition to the rectifier and inverter circuits, a power electronics converter also includes: (1) passive energy storage components, for example, DC link capacitors and AC line inductors; (2) a thermal management system; (3) filters, e.g. electromagnetic interference (EMI) filters; and (4) control and auxiliary components, including gate drive, protection, controller, sensors, and auxiliary power supply. Since these subsystems and components are essential parts of the converter, and will impact on the overall converter performance, efficiency, size, cost, and reliability, the technologies related to these subsystems and components are reviewed here.

Passives Passive components, including inductors, capacitors, and transformers, are essential part of power electronics converters for energy storage and filtering. They often make up significant portion of volumes and weight of the converters and can also incur loss.

Magnetics: Magnetics include inductors and transformers. Inductors are used for filtering and energy storage, while transformers are used for isolation and voltage step-up/step-down operations. Both inductors and transformers are made by winding wires around cores made of a magnetic material. The material properties, core geometry, and number of winding turns determine the characteristics of the inductor or transformer. Inductors and transformers can be made with tape wound or cut cores, power cores, or ferrite cores. Tape wound and cut cores are made from soft magnetic alloys, which are summarized in Table 1.3 with selected materials and their notable properties. Note that the first four materials are based on silicon steel or nickel–iron alloys suitable for low-frequency (e.g., AC grid and harmonic frequencies) applications, with each made for high flux density or permeability.

TABLE 1.3 Fundamental characteristics of materials used in tape wound and cut cores.

Core material	Saturation flux density* (T)	Electrical resistivity ($\mu\Omega\text{-cm}$)	Upper frequency limit** (kHz)	Material density (g/cm^3)	Loss density*** (kW/m^3)
Silicon steel	1.8	47	0.1–2	7.67	5800–8400
Supermendur	2.1	26	0.75–1.5	8.15	
Orthonol	1.5	45	1.5–8	8.25	
Permalloy	0.65–0.75	55–60	4–40	8.72–8.77	1200–3400
Alloy 2605	1.5	130	20–500	7.19	2200
Nanocrystalline	1.0	120	500	7.3	300

*Maximum achievable after processing.

**Dependent on tape thickness; based on operation near the saturation flux density.

***At 100 kHz, 0.2 T flux density, and 25 °C temperature.

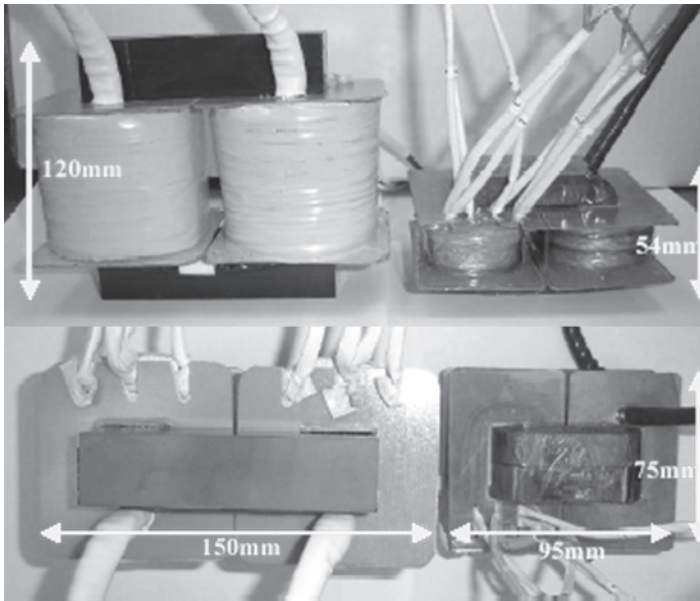


Figure 1.20 Transformers based on nanocrystalline (smaller) and ferrite (larger) cores.

Alloy 2605 is a metal–glass amorphous alloy that is good for medium frequency (100s of Hz to 10s of kHz) applications.

Nanocrystalline magnetic materials have been developed more recently. They are based on ultra-fine grains of Fe, Si and other elements with a typical grain size of 10–15 nm, and exhibit excellent soft magnetic properties. They have much lower loss density than Fe-based amorphous and much higher flux density than ferrite. Figure 1.20 shows a comparison of two high-frequency transformer prototypes built for the same 200 kHz, 30 kW DC/DC converter

application [26]. The size of the transformer using the nanocrystalline material is approximately a fifth of that based on ferrite.

Powder cores are cores with distributed air gaps. They are made from a magnetic alloy that has been ground to a fine powder, and then mixed with an insulating material to increase resistivity and create distributed air gaps. The powder cores are used mostly in high-frequency applications. Common core materials include iron powder, molypermalloy powder (MPP, low loss), nickel–iron powder (high flux cores), and Kool-M μ (an iron–silicon–aluminum alloy with moderate cost and lower losses and better thermal properties than iron powder).

Ferrite cores are made of oxides of metals such as iron, zinc, and manganese. Because of the inherent insulating property of these oxides, ferrite cores have high resistivity, which leads to low losses. As such, ferrite cores can be used up to extremely high frequencies. The oxide is fired, ground, pressed into shape, and re-fired to create a core. This process allows the construction of many core shapes, including standard E, I, U, and so on, as well as toroids and pot cores. Additionally, any custom shape may be machined to meet user-specified requirements. Ferrite cores are good choices for high-frequency applications, including EMI filters [27, 28]. Saturation flux densities for ferrite cores are low, on the order of 0.4–0.5 T.

Nanocomposites, a new class of nanocrystalline materials, are being developed with better performance. They are composed of ferromagnetic nanocrystals embedded in an amorphous matrix, where nanocrystals contribute to desired magnetic properties and the amorphous phase enables small grain size and large resistivity. The nanocomposites offer several better properties compared with typical commercially available nanocrystalline materials, including high operating temperature ($\geq 770^\circ\text{C}$) and high saturation flux density (1.5–2.1 T). Low hysteresis and eddy current losses, compact size and light weight, improved mechanical properties, and enhanced corrosion resistance can also be achieved by nanocomposite materials [29].

Capacitors: A high power converter in grid applications, such as a three-phase AC–DC converter, is likely to utilize almost every type of capacitor. Applications range from lower power control circuitry, gate drive circuitry, and high-frequency EMI filter, to high-power AC and DC filters and energy storage. Commercially available capacitor technologies fall into four broad categories [30]: ceramic, film, electrolytic, and electrochemical. Each category may be further classified. Film capacitors can be of natural (paper or mica) or synthetic (e.g., polystyrene or polypropylene) type. Electrolytic capacitors can be distinguished by the anode materials (e.g., aluminum, tantalum) or electrolyte (e.g., liquid or solid) [30, 31]. Electrochemical capacitors are also called “super capacitors” or “ultra-capacitors” for their very high capacitance values. Table 1.4 and Table 1.5 summarize commonly used capacitor technologies. The selection of a particular type of capacitor depends on a number of considerations, including applications, voltage and ripple current ratings, capacitance values, power loss, reliability (mainly failure modes and lifetime), temperature capability, density, and cost. The application considerations include: AC vs. DC, low frequency vs. high frequency, and filter vs. energy storage. Different capacitor technologies may be better in

TABLE 1.4 Summary of commonly used capacitor technologies.

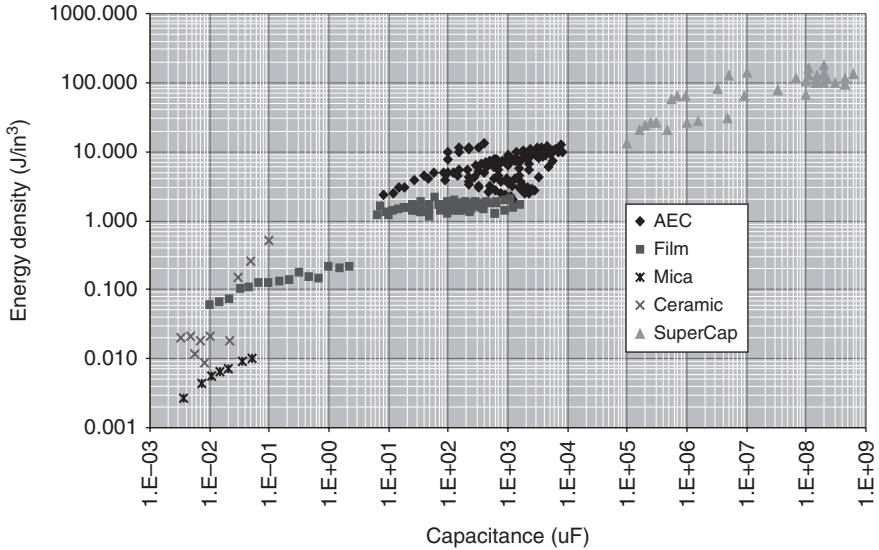
Technology	Advantages	Disadvantages	Failure modes	Applications
Ceramic (general purpose)	High capacitance-to-volume ratio; low cost	Poor temperature stability; susceptible to shock and vibrations; poor reliability	Mechanical cracking; surge currents; dielectric breakdown	High-frequency blocking, bypassing, filtering, and coupling
Ceramic (temperature compensating)	Temperature and time stable	Low capacitance values only; susceptible to shock and vibration; low capacitance-to-volume ratio	Mechanical cracking; surge currents; dielectric breakdown	Compensation for variation in temperature
Paper	Reliable; average stability; low cost	Average capacitance-to-volume ratio; high resistance	Dielectric breakdown	Low-frequency filtering and coupling; power-factor correction; contact protection; motor start and run
Mica	Low dielectric losses; good temperature, frequency, and aging characteristics; low AC losses; reliable; low cost	Low capacitance-to-volume ratio	Dielectric breakdown	High-frequency blocking, bypassing, filtering, and coupling; resonant circuits; high voltage
Poly-film	Wide range of capacitance and voltage ratings; low dissipation factor; stable; high-temperature stability	Relatively high cost	Dielectric breakdown; open circuit	Mid-frequency blocking, bypassing, filtering, and coupling; timing
Aluminum electrolytic (AEC)	Highest electrolytic capacitance-to-volume ratio; highest electrolytic voltage rating; high ripple capacity	High leakage current; requires reforming after long storage periods; high cost for high reliability; susceptible to dynamic environments; damaged by chlorinated hydrocarbons	Dielectric breakdown; open circuit	Low-frequency blocking, bypassing, filtering, and coupling
Chemical double layer (super cap)	Highest capacitance; highest energy density	Low operating temperature; low frequency capability; relatively high cost	Similar to AEC	Energy storage

TABLE 1.5 Electrical characteristics of commonly used capacitors.

Technology	Typical dielectric constant (air = 1.0)	Capacitance range	DC voltage range	Volume efficiency ($\mu\text{FV}/\text{in}^3$)	Dissipation factor (25 °C)	Capacitance change from -55 to 125 °C (% ΔC from nominal)
Ceramic	12-400,000	0.1 pF-12 μF	25V-30kV	273-55,000	0.006-2.5 (1 kHz) 0.006-7 (1 MHz) 0.2-0.5 (120 Hz) 0.2-1 (1 kHz)	0 (temp. comp.) -10 to +2 -10 to +8
Paper	4.0	100pF-200 μF	50V-200kV	130-300	0.04-0.06 (120 Hz) 0.05-0.5 (1 kHz) 0.05-0.9 (1 MHz)	-2 to +1
Mica	7.5	1 pF-10 μF	50V-100kV	11-600	0.007-0.9 (1 kHz) 0.02-0.45 (1 MHz) 3-80 (120 Hz)	+1 to -1 (polystyrene) -30 to +25
Poly-film	3.0	20pF-400 μF	30V-10kV	34-5,000	1-6 (120 Hz)	-8 to +10
Aluminum electrolytic	10	0.5 μF -2 F	3-700 V	16,000-82,000		
Tantalum electrolytic (solid)	26	0.1 μF -8 mF	3-125 V	5,800-87,500		

certain aspects but not others. Note that density for a capacitor can mean power or energy density. Some capacitors have high power densities but low energy densities, while others are just the opposite. Figure 1.21 shows energy and power densities for different types of capacitors vs. their typical capacitance range.

(a)



(b)

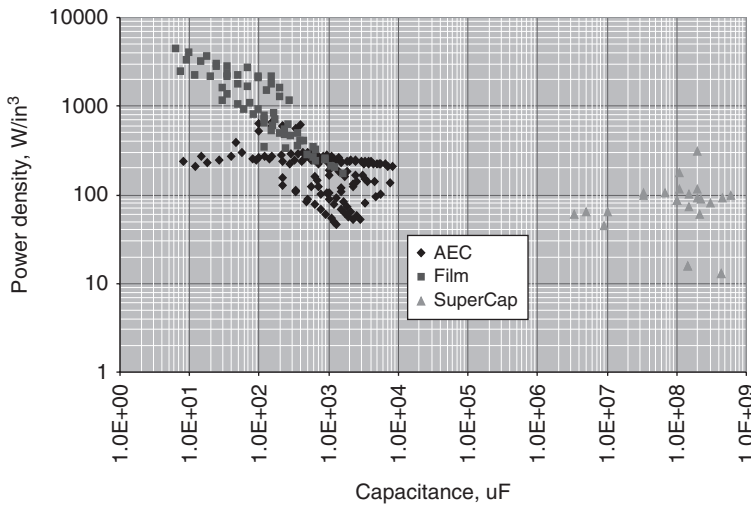


Figure 1.21 Capacitor technologies: (a) energy density vs. capacitance; and (b) power density vs. capacitance. (See electronic version for color representation of this figure.)

Most commercial capacitors have temperature ratings below 85 °C, with some rated at 105 °C. With WBG devices, high-temperature capacitors (e.g. 200 °C rating) become necessary and are receiving considerable attention in research and development. Several novel dielectric materials are under development for improved temperature capability and overall performance. For example, high-temperature polyetherimide (PEI) film with a high dielectric constant is being investigated to achieve less use of films and more than 25% volume reduction. High dielectric strength through nanocoating of PEI films also enables high breakdown voltage [32]. Additionally, it is reported that ultrathin (5–100 μm) glass sheet, as an inorganic material with significantly high thermal stability (>500 °C), enables high capacitance and energy density [33].

Thermal Management System Thermal management is essential to power electronics converters. Appropriate cooling is necessary in order for power semiconductor devices and other components to maintain a safe operating temperature. Additionally, the thermal management system takes up a large percentage of the total converter size, weight, and cost. A sample design shows that for a GaN FET-based rooftop PV inverter, its heat sink is the highest cost item, even more than the GaN devices used in the design. It is important to identify and choose efficient and effective thermal management strategies.

Cooling methods: The most common thermal management strategy for high power converters is forced convection cooling, with either air or liquid. They are adequate for today's power electronics devices, which have thermal densities of the order of 100 W/cm². For high-density converter designs with WBG devices and more integration, the thermal density can reach as high as 1 kW/cm² [34], beyond the thermal handling capability of traditional forced convection cooling methods.

To overcome the barrier of conventional cooling methods, advanced technologies, such as phase-change and direct liquid cooling techniques developed in microelectronics, have begun to be applied to power electronics. Phase-change techniques involve boiling the liquid coolant, or changing its phase to gas, as it extracts heat from the components. The coolant used in phase-change methods must have a boiling point significantly below (e.g., 10–40 °C) the device operating temperature [35]. Because of the high energy required to boil a liquid, phase-change is a very effective cooling technique. In direct liquid cooling, the component is either directly submerged in the coolant, or the coolant is forced onto or across the surface of the device. Direct liquid cooling can also be combined with phase-change; in this case, the coolant directly touches the device, and boils as a result of the heat absorption. The direct cooling methods include liquid immersion, jet impingement, and spray cooling. All these can be combined with phase change. For example, pool boiling is the phase-change liquid immersion technique. Methods such as jet impingement and spray cooling are designed to meet the cooling needs of 1 kW/cm² thermal density.

Most of the advanced phase-change and direct cooling methods for power electronics are still in their development stage. One exception is heat-pipes, which have been used successfully in high power density converters. Heat-pipes are a form of phase-change cooling with the coolant enclosed in a pipe that is either embedded in the device or a cold plate. The entire pipe is a closed system; as such, the coolant is not pumped through the pipes. Instead, the coolant boils near the heat source, and travels towards the condenser end of the heat-pipe, where the liquid condenses. Since these systems cannot always rely on being oriented such that gravity pulls the coolant back down to the heat source, they often incorporate a wicking material enclosed in the pipe. This wick draws the condensed coolant back towards the heat source.

Heat sinks: For a given cooling method, heat sinks to large extent determine the cooling performance. Both configurations and materials of heat sinks are important for their performance. For air-cooling heat sinks, metal structures with fins are typical configurations for increased heat transfer. In recent years, pin fin heat sinks start to be used more, due to their better performance than traditional flat fins in certain applications, although the true heat sink performance must be determined considering air flow. For liquid cooling, metal cold plates with embedded cooling loops are generally used. The geometry of the liquid loops can be simple circles or squares, but can also be designed to be more sophisticated for improved heat transfer. For example, fin structures, which can help to create turbulent flow for more efficient heat transfer, have been used in the liquid cooling loops for some electric vehicle inverters. Microchannel cooling, using channels around $10\mu\text{m}$ in diameter, pumps liquid coolant directly onto the device, or through a heatsink attached to the device. There is also mini-channel cooling, where the channel diameter is of the order of 1 mm. Microchannel can be combined with phase-change, where the liquid coolant is boiled inside the channel, close to the heat source. One potential issue with micro- or mini-channel cooling is its requirement for purity of the coolant to avoid clogging.

Thermal materials: Materials with good thermal properties are desired throughout the construction of a power converter, from the substrate of the power semiconductor device module, to heat spreaders, thermal interfaces, and heat sinks. For the effective removal of heat, it is desirable to use materials with high thermal conductivities. An equally critical consideration is matching of the coefficient of thermal expansion (CTE) at material interfaces. Poorly matched CTEs result in excess mechanical stresses due to thermal cycling, leading to premature failure.

In general, thermal materials may be classified as first-, second-, or third-generation materials [36]. First-generation materials consist mainly of the traditionally used aluminum, copper, and their alloys. While copper offers high thermal conductivity, it is also heavy. The rather high CTE of copper is another drawback. Aluminum is 30% lighter than copper, but also has lower thermal conductivity and even greater CTE. Still, aluminum heat sinks have been a popular low-cost choice

for lightweight applications. To further reduce the size and weight of thermal management solutions, however, advanced materials with higher conductivity and lower mass density are required.

The bulk of second- and third-generation materials are composites, in which a matrix material is used for rigidity and the reinforcement material is used to manipulate the thermal properties. One thermal material that has received considerable attention is graphite. Many of these advanced materials, including graphite, do not have the same thermal conductivity in all directions, unlike copper and aluminum. Instead, the thermal conductivity may be very high in the directions in-plane through the material, but considerably lower in the direction normal to that plane. At first, this may seem to be a very undesirable characteristic, but it can actually be quite useful. The orientation of the material can be chosen when fabricating the heat spreader or heat sink, such that the thermal conductivity is extremely high in two dimensions, and low in the other. This can be useful in evenly spreading the heat from multiple sources, or even directing the heat flow to a cooler area. One issue with graphite is its negative CTE, which may be compensated for with metal meshed with graphite. Other promising thermal materials include carbon nanotubes.

Filters Power electronics converters rely on switching devices and will inevitably generate noise, ripples and harmonics. The switching transients can also lead to voltage and current spikes. As a result, filters are needed for protection, electromagnetic compatibility (EMC), and power quality. The fast-switching WBG devices may result in more demanding requirements for filters. Since the filters are mostly realized with passive components, they can be important contributors to converter size and weight, and therefore cost. The main filter types include: harmonic filters to meet power quality requirements, EMI filters for EMC, and dv/dt filters to relieve stress on loads, especially motor loads which have limited insulation capability. In the topology and passive sections above, some of the filter reduction topologies and components have been introduced. Additional technologies that can benefit power converter filter design and reduction include active harmonic and EMI filters, integrated filters, and switching control schemes such as random or variable frequency pulse width modulation (PWM).

An active EMI filter, composed of noise sensing circuits, operational amplifiers and noise injection elements (capacitors for current and transformers for voltage), is able to cancel the propagating noise. As a result, the required passive components can be significantly reduced for improved power density. For example, Figure 1.22 illustrates a noise spectrum comparison between a 4 mH common mode inductor and a hybrid active filter plus a 300 μ H common mode inductor. In the lower frequency range (10–200 kHz), the hybrid filter is at least as effective as the passive filter, while reducing the inductance by a factor of 10 [37, 38].

Integrated filtering is another promising technique. For example, based on transmission-line theory, the converter busbar structure can also be designed to function as a transmission-line filter. This type of filter structure fully utilizes the converter busbar as the filter winding, thus eliminating the extra winding weight

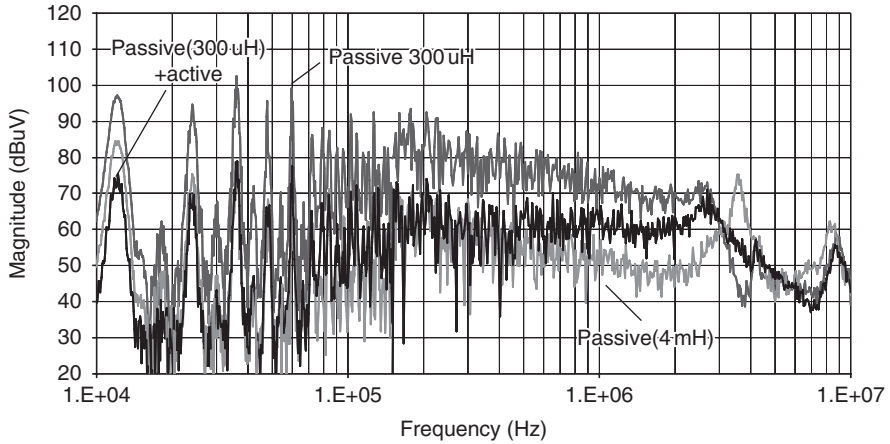


Figure 1.22 Comparison of hybrid and passive common mode filters. (See *electronic version for color representation of this figure.*)

[39–41]. To increase its effectiveness, a multilayer structure can be used for the busbar; together with some external magnetic cores, the required equivalent inductance can be achieved. The capacitance can also be realized within the busbar with high permittivity insulation layers.

The PWM switching scheme impacts ripple and EMI noise spectrum. The random PWM and variable-switching frequency PWM can effectively spread the noise spectrum and shrink the EMI filter without compromising loss or affecting performance [42, 43].

Control and Auxiliary Components Compared with traditional power conversion equipment, power electronics converters are more intelligent due to their controllability. Control is an essential part of the power electronics converters. A suitable power electronics converter control architecture for high-power applications is the layered hierarchical control shown in Figure 1.23, and as recommended in [44]. There are several levels of controls necessary for converters in renewable energy systems and grid applications. The basic functions of these control layers are briefly summarized below.

1. System control layer: All functions involved in the determination of the system mission and thus the duties of the power electronics system or their mode of operation. For a motor drive, this will correspond to the operation mode control of the drive.
2. Application control layer: Dictates the operation of the power electronic system in order to meet the mission determined by the system control. For a motor drive, the speed, torque and even flux control will belong to this layer.
3. Converter control layer: Enables the application control layer to perform its mission by implementing many of the functions common to all converters

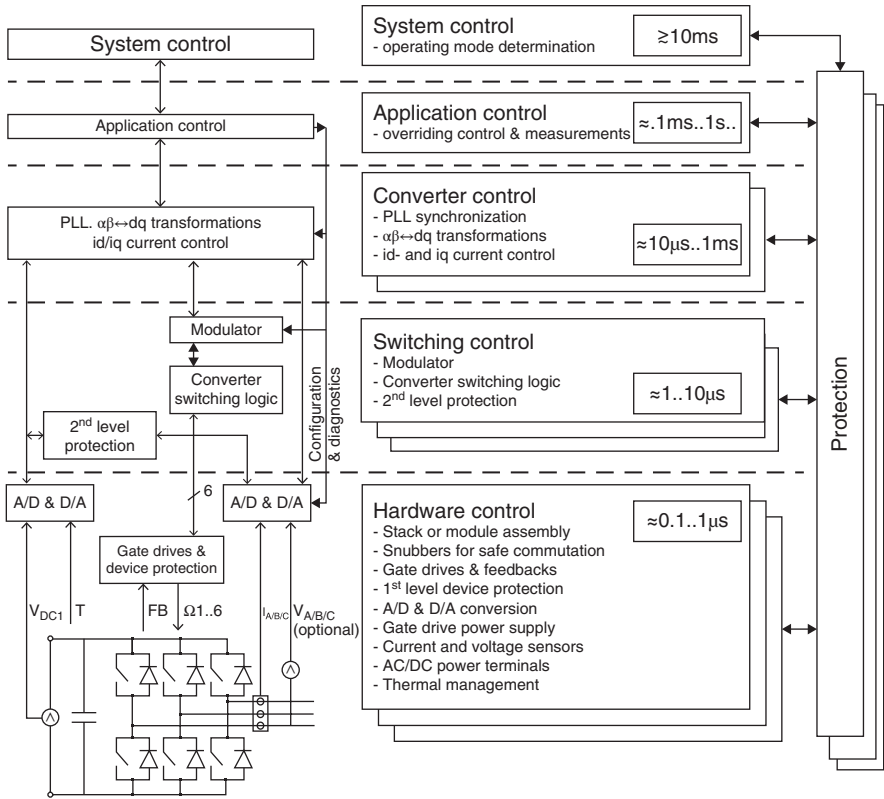


Figure 1.23 Recommended control architecture for power electronics applications [44].

such as synchronous timing (phase-locked-loop), current and voltage filtering, measurements, and feedback control calculations. This layer will include the current control loop, which is independent of the application.

4. **Switching control layer:** Enables the power electronics to behave as a switch-mode controlled source and includes modulation control and pulse generation.
5. **Hardware control layer:** Manages everything specific to the power devices, such as gate drives and protection circuits. Gate drive is particularly important as it is responsible for controlling the switching action of power semiconductor switches.

The above control functions are realized with control hardware and software. The system, application and converter control layers are usually implemented with software in digital controllers such as digital signal processors (DSP); the switching

control is often implemented with digital hardware circuit, such as a field-programmable gate array (FPGA); and the hardware control is usually implemented through an analog circuit.

To realize the control functions, several important auxiliary components are needed, including sensors and auxiliary power supplies. Sensors are needed to provide converter operation information (e.g., voltages, currents, temperature, etc.) to the controllers. Auxiliary power supplies, which are usually AC–DC or DC–DC converters themselves, are needed to provide power needed for controller hardware and circuit boards. Note that sensors and power supplies, together with the hardware control layer circuit (e.g. gate drive), need to interface both with the power electronics converter main circuit, which is often at a high voltage level, and with the digital control circuit, which is at signal voltage level. Therefore, isolation is important. The isolation between the switching control layer and hardware control layer is often achieved by optical means: opto-coupler in lower voltage, lower power (<1 kV, hundreds of kW) cases, or optical fiber in higher voltage, higher power cases. The isolation for the gate drive power supply is often achieved through magnetic transformer. With higher voltage grid application and faster WBG devices, isolation in power electronics converters becomes an increasingly challenging issue.

Note also that the hierarchical layered control architecture has been developed mostly based on Si power electronics converter technology. With WBG device technology, the partitions between layers are becoming less clear due to the faster switching and interactions between subsystems. Better control architecture may be needed in the future.

1.4.3 Power Electronics Applications

The role of power electronics is for electrical energy and power conversion. There are many applications that can and have used power electronics converters. It is not an overstatement that almost all things electrical today contain some sort of power electronics converters. From tiny mobile and medical devices, small home appliances and tools, bikes and cars, to large industrial, commercial and medical equipment, data centers, transportation infrastructure, and gigantic power grids, all of them use one or more types of power converters described earlier in this section. Since the theme of the book is grid power electronics, the application discussion here will focus on those related to the grid.

From the grid standpoint, the applications can be classified into three broad categories: source related, load related, and delivery (transmission and distribution) related. The source-related applications are mainly regarding the generation source, which will be discussed in the renewable energy systems section (Section 1.5), and the delivery-related applications are mainly regarding the energy transmission and distribution, which will be discussed in the smart grid section (Section 1.6). This subsection will focus on the load-related applications, with focus on the major loads.

According to the US Energy Information Administration (EIA) report, the total electricity consumption in the United States was about 3.82 trillion kilowatt hours (kWh) in 2017. The sales of electricity to major consuming sectors and percentage shares of total electricity sales in 2017 were:

- Residential: 1.38 trillion kWh (37.4%)
- Commercial: 1.35 trillion kWh (36.6%)
- Industrial: 0.95 trillion kWh (25.7%)
- Transportation: 0.01 trillion kWh (0.2%, mostly to public transit systems)

Two main types of loads within the first three sectors are motors and lighting. As a result, the application discussion will focus on them, together with fast-growing transportation and data centers.

Motor Drives

Motor loads account for a large percentage of total electricity use. In 2017, the US industrial sector spent 48.2% of total electricity consumption on machine drives, not even considering the motors used in facility heating, ventilation, air conditioning, and cooling, which accounted for 9.5% of electricity usage, nor motors in process cooling and refrigeration, which was another 7.3% of electricity usage. The residential and commercial sectors also use motors extensively, through ventilation, cooling and refrigeration. For the residential sector in the US, these load types accounted for 36.3% of total electricity usage in 2017, while for the commercial sector, they accounted for 35.8% of total electricity usage during the same time period. Needless to say, motor loads are the most important type of loads for the power grid, in terms of energy consumption.

More and more motors are driven by power electronics converter-based motor drives, to meet the variable speed and torque requirements. Compared with fixed speed motors or other types of speed control (e.g., gearbox), power electronics-based motor drives have higher efficiency, higher reliability, and better performance.

There are many different types of motor drives. Two broad categories are DC drives for DC motors and AC drives for AC motors. In the early days, DC drives dominated due to easy speed control of DC motors, even though DC motors themselves are generally less desirable than AC motors in terms of performance, reliability, and cost. In the last 30 years or so, AC drives have advanced significantly and become dominant on the market due to the digital control and power electronics technology.

AC drives basically generate variable frequencies and voltages to control AC motor speed. There are many ways to further classify AC drives. Some of them are listed below [45]:

- Based on input power sources, a drive can be either DC or AC fed.
- Based on motor types, an AC drive can be induction motor drive, or synchronous motor (including a permanent magnet or PM motor) drive. Note that a DC brushless motor is one type of DC-fed PM drive and motor.

- Based on voltage ratings, a drive is low voltage if the AC line rms voltage is lower than 1000 V, or a medium voltage drive otherwise.
- Based on converter topologies, AC drives on the market include cycloconverters, load-commutated inverters, PWM current source inverters (CSI), and PWM voltage source inverters (VSI). The former two are older, thyristor-based, and mostly used in special high-power applications. CSI requires reverse blocking devices and large DC link inductors, and therefore are only used in limited applications. PWM-VSI based on IGBT is dominating the market. Different voltage source converter topologies listed in Section 1.4.2 are employed in motor drives depending on power, voltage, and other requirements.
- Based on power device technologies, a drive can be a GTO, IGCT, IGBT, MOSFET or silicon controlled rectifier (SCR) drive. As mentioned earlier, Si IGBT is the device of choice currently. With the emerging SiC and GaN devices, the landscape is changing in some applications. For example, the faster-switching WBG devices will be more suitable for high-speed motors, like motors for compressors or for EV and airplanes.
- Based on cooling technology, a drive can be naturally cooled, forced air-cooled, or liquid-cooled.
- Based on control technologies, a drive can be analog or digital, open-loop controlled, or closed-loop regulated, scalar-controlled or vector-controlled, with (speed) sensors or sensorless. Modern AC drives are mostly vector-controlled using digital controllers.
- Based on energy flow capability, a drive can be regenerative with bi-directional energy flow, or nonregenerative. Note that for nonregenerative drives, a dynamic brake is often provided to allow limited reverse energy flow for motor stopping functions, and so on.
- Based on applications, a drive can be stand-alone, or a system drive where multiple drives are used in a coordinated system, such as paper machines or rolling mill stands. System drives usually require high precision control. There are many specific drive applications [45], including those used in transportation and electric power utility. The motor drives in utility include turbine starters, boiler and cooling tower fans and pumps. Converters connected with wind turbine generators and microturbine generators are essentially motor drives, except they work in regenerative modes.

Motor control is a key technology for motor drives. Figure 1.24 shows a typical drive control scheme with two control loops. The outer loop is the speed control loop with a speed regulator, and the inner loop is the torque loop with the torque regulator. Since the torque is determined by motor flux and current, the torque regulation is generally realized through flux and current regulation. For an AC motor, the flux and current are both vectors, and the angles between them are variable. In order to control the torque precisely, both the magnitudes and angles of the flux and

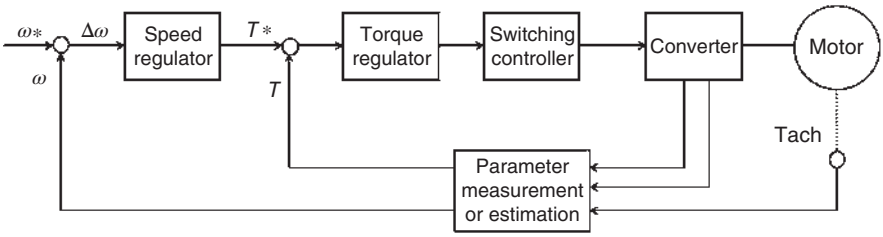


Figure 1.24 Typical drive control scheme (ω , angular speed, ω^* , speed reference, T , torque, T^* , torque reference).

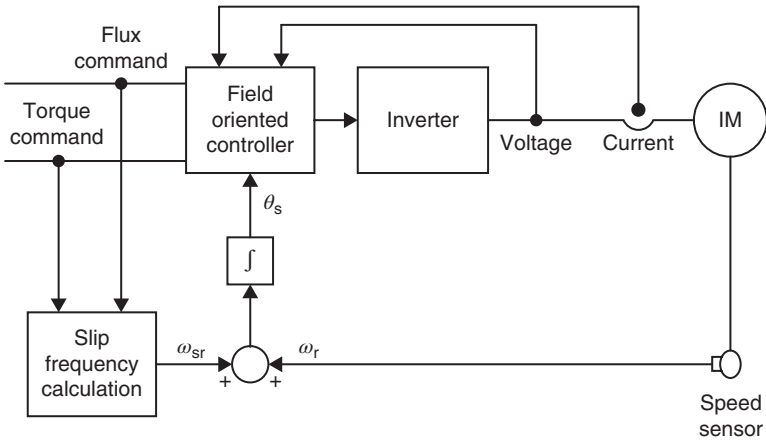


Figure 1.25 Indirect field-oriented control scheme for induction motor (θ_s , rotor flux angle, ω_r , rotor angular speed, ω_{sr} , slip frequency).

current must be controlled. Hence, the corresponding control is called vector control, or field-oriented control, as the magnetic field is vector-controlled.

Figure 1.25 shows the popular indirect field-oriented control scheme for an inductor motor drive. It first determines the slip based on the motor model parameters, magnetizing current I_y and torque producing current I_x , and then adds to the rotor speed to determine rotor flux position. By orienting I_y to the rotor flux and I_x to its quadrature, the two currents are decoupled and the torque can be precisely controlled dynamically.

Lighting

Lighting also consumes a large percentage of electricity in the grid. In 2017, the lighting loads in the US accounted for 9.4%, 10.6%, and 6.5% of the total electricity consumption respectively for the residential, commercial and industrial sectors.

Traditional lighting dominated by incandescent lights is now obsolete. The more efficient forms of lighting all use power electronics controllers. The compact florescent lamps (CFLs), high-intensity discharge (HID) lamps, and other similar

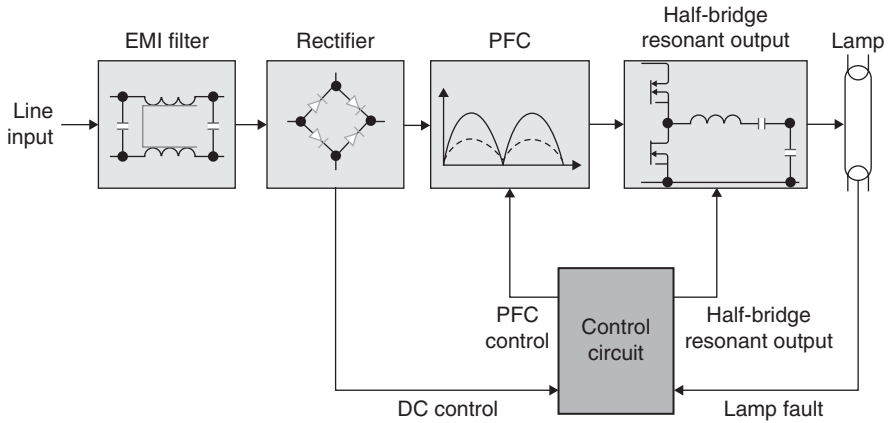


Figure 1.26 Conceptual electronic ballast.

lighting technologies based upon discharge, use electronic ballast, while LED lamps are driven by AC–DC converters.

A ballast is placed in line with the lamp to limit the current. A conceptual electronic ballast is shown in Figure 1.26. The ballast first rectifies the input line frequency AC power to DC, and then inverts the DC to high-frequency AC of 20 kHz or higher. The high frequency substantially reduces the flicker, a result of the line frequency interacting with fluorescent lighting. Advanced electronic ballasts may allow dimming via pulse-width modulation or via changing the frequency to a higher value, depending on the inverter circuit topology.

LED lamps have revolutionized lighting with their superior efficacy and characteristics. LED lamps are driven by DC, and therefore a rectifier is needed for the LED driver. In addition, the lumen of the LED is determined by current. As a result, often a current-controlled DC/DC converter is used. Figure 1.27 shows a LED driver circuit with isolated flyback and buck-boost circuits respectively. The current control reference is the dimming control signal.

Transportation

Although the use of electricity by transportation accounted for a mere 0.2% of electricity use in the US in 2017, the worldwide usage was about 2%, reflecting more reliance on public transportation by the rest of the world. The usage is expected to grow significantly in future due to the electrification of transportation, including electric vehicles and electrified railroads. The outlook for the worldwide electricity usage by transportation will more than double by 2040, and will grow to account for about 5% of the total consumption.

Electric Vehicles Electric vehicles (EVs), including plug-in electric hybrids and all-electric vehicles, offer a pathway to reduce our dependency on oil and reduce greenhouse gas emissions. The efficiency of an electric traction drive motor

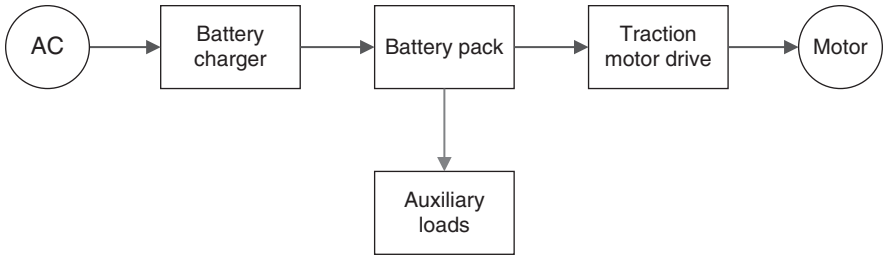


Figure 1.28 EV power flow diagram.

circuit topologies, and system controls, have been playing a key role to achieve the goal of high efficiency, high power density, and low costs.

A typical EV power flow diagram is shown in Figure 1.28. The EV battery charger is primarily responsible for transferring power from the utility grid to the EV battery storage system. For a plugged-in electric vehicle (PEV), the battery is the only energy storage, so the driving range depends mainly on the energy capacity of the battery pack. For an extended range electric vehicle (EREV) [47, 48] or fuel cell vehicle (FCEV) [49, 50], the battery can be charged by engine or fuel cell when the battery requires energy. In EVs, the electric motor is powered from the battery pack through the boost converter and traction inverter. The auxiliary loads in EVs receive power from the buck type DC–DC converter.

The power flow architecture for a PEV is shown in Figure 1.29. For PEV, the high voltage battery stores all the energy at voltage levels ranging from 200–400 V. The DC–DC boost converter is used to boost up the voltage to 650 V for the HV DC bus. The inverter then converts the HV DC to AC, which drives the electric machine. Based on the set point or reference set by the EV operator, the inverter controls the EV traction motor speed and torque. The EV may also have low voltage bus through a buck converter for the low power loads. A lower capacity LV battery can also ensure a continuous power flow to the loads. Low power loads includes user interface electronics and outlet ports. There are also high power loads like a compressor motor, water pump, and air-conditioning unit. Those loads are also powered by a separate lower power inverter.

One of the important power electronics applications related to EVs is the charging station. In Figure 1.28, the battery charger can refer to an onboard or off-board charger. In either case, an equivalent AC/DC power conversion is needed. The battery DC voltage normally ranges in the 100s of volts. The input AC voltage can be single-phase or two-phase residential voltage, or three-phase voltage at low voltage (<1 kV) or medium voltage (>1 kV) used in commercial fast chargers. Based on the voltage and power level, and for performance and economics reasons, multistage conversions are often used. For example, for the low power level 1 (3 kW with 120 V single-phase AC) and level 2 (6 kW with 240 V single- or two-phase input AC voltage) onboard chargers, a single-phase power factor correction (PFC) plus a DC/DC converter is often used; for medium power level 3 (60 kW with often

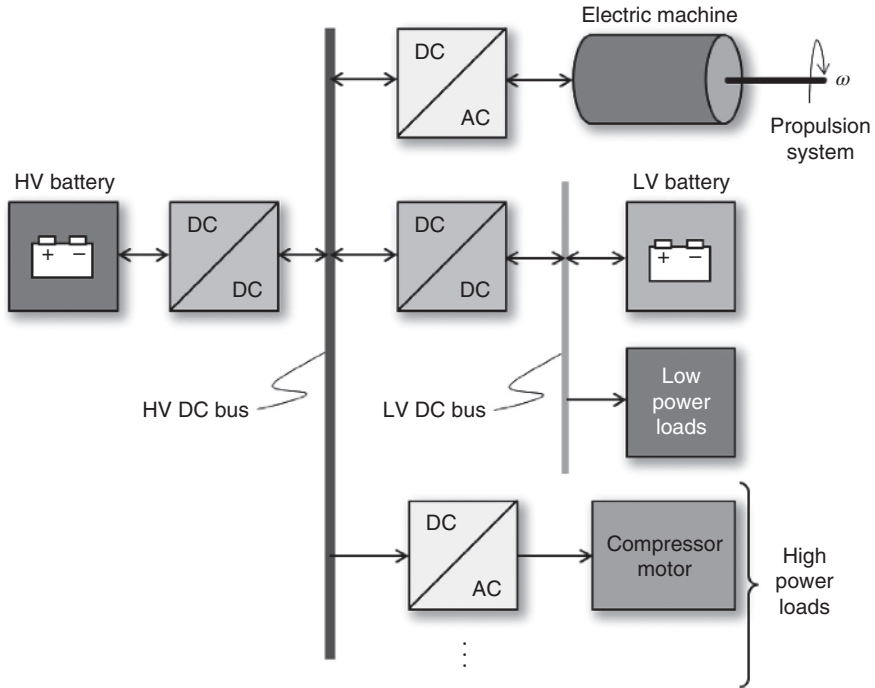


Figure 1.29 EV powertrain power system architecture [51].

with three-phase input AC voltage) or higher power off-board fast charger, a three-phase PFC plus a DC/DC converter is often used. Very often, an isolation transformer is required, which can be realized with isolated DC/DC in onboard chargers, or low-frequency transformer or isolated DC/DC in off-board chargers. With SiC devices, medium voltage can be directly converted to DC without bulky low-frequency transformers, and the isolation can be realized with medium voltage high-frequency transformers embedded in the DC/DC converter. One promising architecture for the future of EV charging stations will be individual DC/DC off-board fast chargers forming a DC grid, supplied by a common medium voltage AC/DC rectifier connected to the AC distribution grid.

Electrified Railways The conventional configuration of a railway traction system is shown in Table 1.6 and Figure 1.30. In this configuration, the single-phase AC catenary is connected to the primary winding of the low-frequency transformer (LFT) and grounded through the rail. The secondary winding of the LFT is connected to an AC–DC rectifier to provide the DC voltage for the variable speed drive system, which comprises a three-phase inverter and a motor. Note that the nominal voltage for this conventional configuration is 15 kV or 25 kV.

TABLE 1.6 Summary of existing configurations of locomotives.

	Front-end		Inverter
	Transformer	Topology	Topology
Configuration I	Line frequency	3 L-NPC	3 L-NPC
Configuration II	Line frequency	2 L	2 L

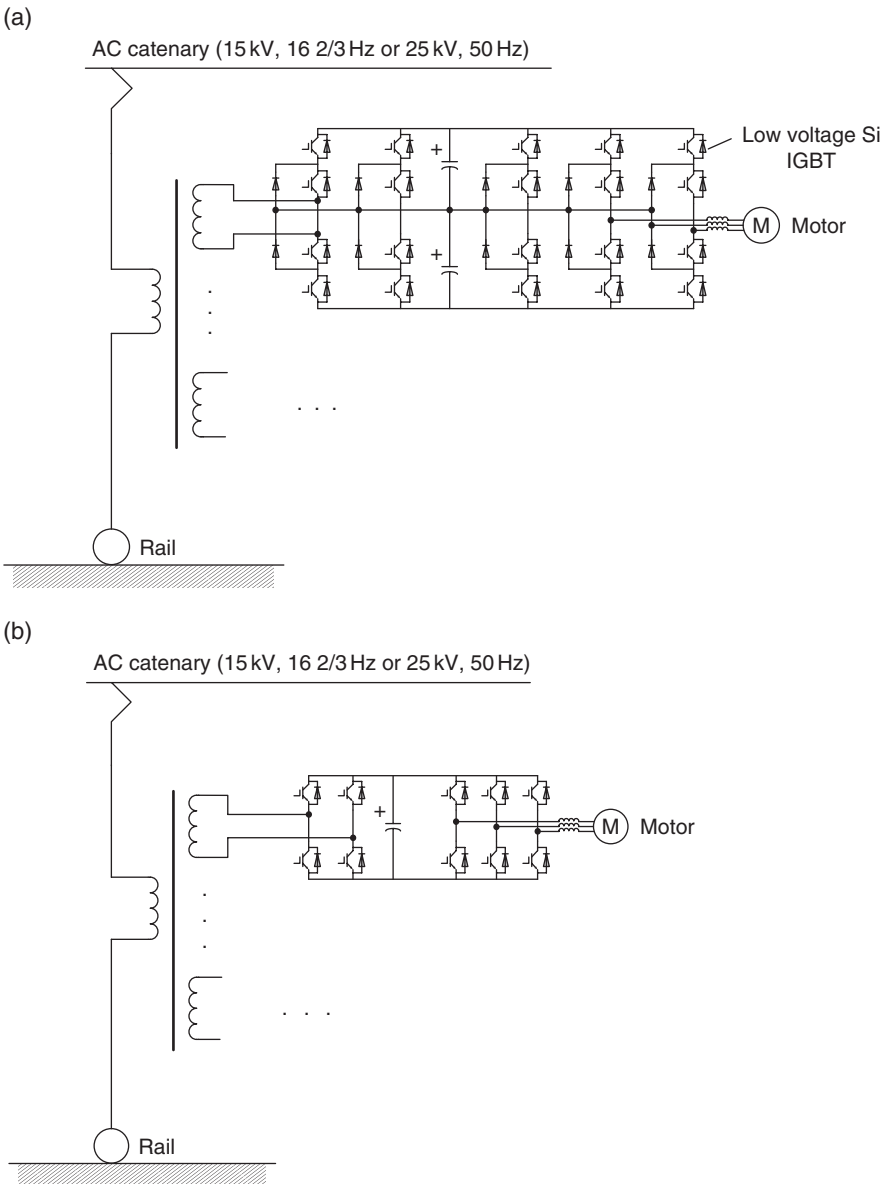


Figure 1.30 Configurations of the conventional medium-voltage rail traction system. (a) Three-level (3L)-NPC configuration; (b) two-level (2L) configuration.

The LFT in the traction system is usually optimized to minimize the weight and volume, and are heavily loaded. Hence, the efficiency is poor, even in the range of 90–92%. Meanwhile, since oil is commonly used for cooling and insulation, potential environmental problems should be taken into account in case of leakage [52, 53].

Instead of LFT-based isolated configuration, power electronics based medium-frequency (defined in this chapter as hundreds to thousands of Hz) transformers (MFTs) or HFT (high frequency defined as above 10 kHz in this chapter) transformers can be employed. MFT and HFT are so-called solid-state transformers (SSTs). Due to space limitation in locomotives, it is necessary to reduce the volume and weight. With MFT or HFT, the system power density can be greatly improved. The MFT- or HFT-based products are not as mature as the LFT-based products. The configuration of an ABB-developed MFT-based converter for locomotive application is shown in Figure 1.31 [54]. The low-voltage Si-IGBT-based cascaded topology is used in the AC side. In particular, seven cells are connected in series, with an additional cell used for redundancy.

A Si-IGBT based MFT energy conversion system can be further improved by using SiC devices, especially high voltage (e.g., 10 kV) devices. The cascaded MFT based on Si devices can be replaced by the HFT with only one cell of HV SiC devices. Since MV SiC devices have sufficient voltage rating for the AC catenary, no cascaded topology is needed. Hence, the system can be simplified. With the nominal DC output voltage at around 1–2 kV in HFT (e.g., in ABB's MFT the DC voltage is 1.5 kV), two-level converters can be used as the inverter stage. Higher voltage inverters and motors can be used for further power density and efficiency gains. The ABB MFT has a frequency of 1.5 kHz. With high voltage SiC, the frequency can be an order of magnitude higher, leading to higher power density.

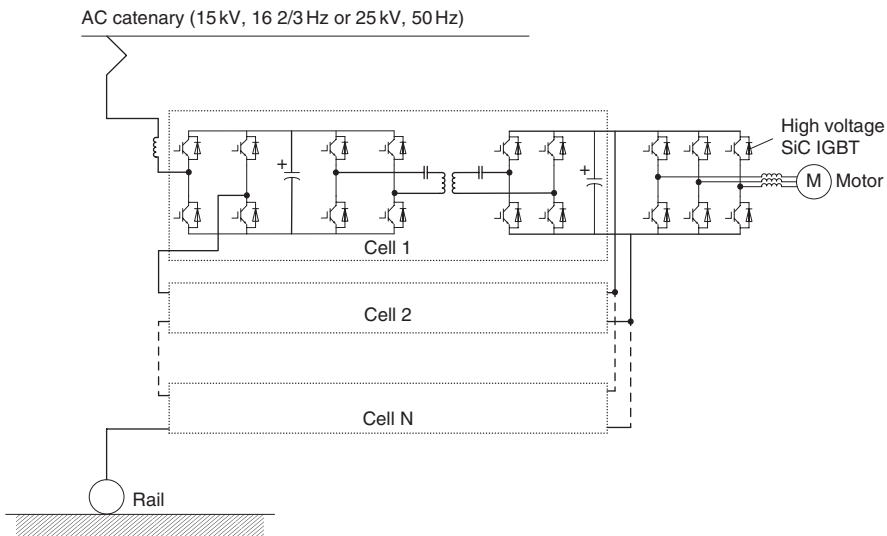


Figure 1.31 Configuration of a traction system based on medium-voltage SiC devices.

GE's prototype HFT developed under the DARPA-ONR High Power Electronics Program (HPE) used 20 and 40 kHz switching frequency, though it was developed for shipboard applications.

All-electric Ships and More-electric Aircraft Ships and planes are not connected to the grid, therefore less relevant to the theme of the book. They are included here for completeness. Power electronics converters are a key enabler for modern all-electric ships. Figure 1.32 shows an example state-of-the-art shipboard electric power system based on zonal distribution with podded propulsors [55]. The configuration is also said to be of an integrated power system (IPS) architecture due

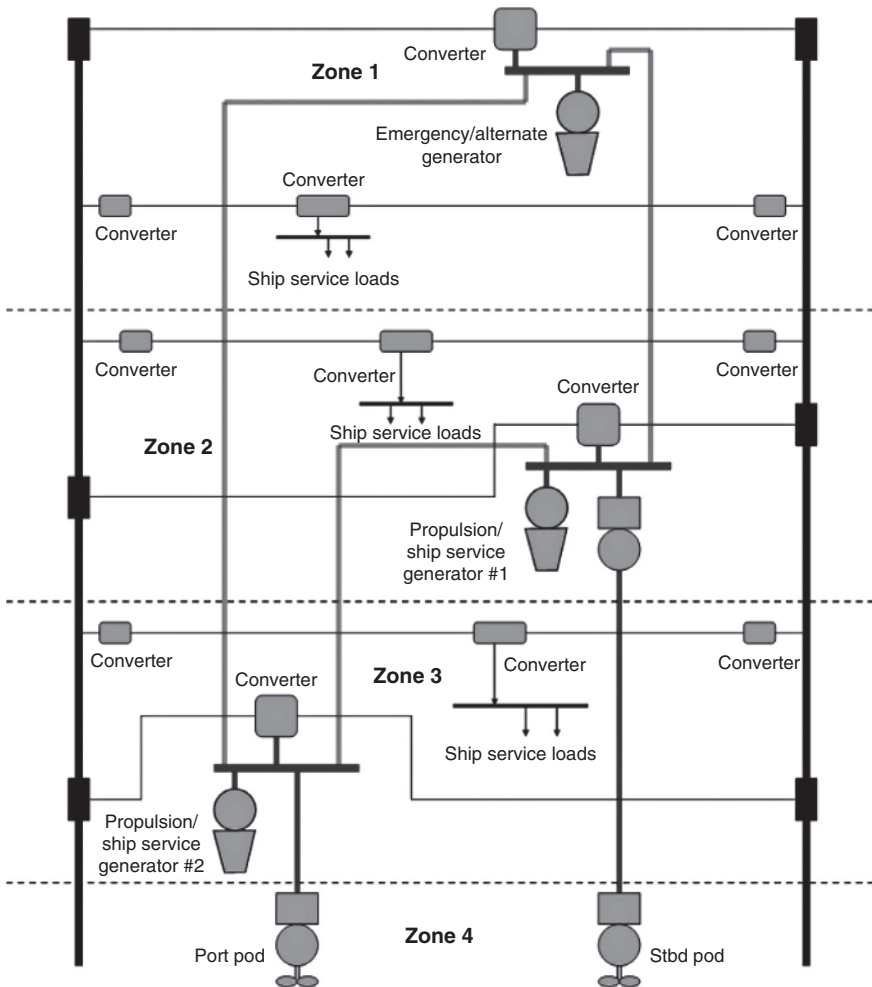


Figure 1.32 Shipboard electric power system example: zonal distribution with podded propulsors [55].

to the integrated nature of its propulsion and service power systems. Clearly, power converters are an essential part of the system, converting the AC power produced by generators at fixed voltage and frequency (e.g., 13.8 kV and 60 Hz) to AC powers at various voltage levels and frequencies, and DC powers at various voltage levels, needed for supplying and controlling propulsion motors, ship service loads, mission loads, and distribution buses. Size, weight, and efficiency are critical to shipboard power converters. As such, WBG devices are expected to significantly advance the power electronics for ships. Another interesting development is that the shipboard power distribution system is going towards medium voltage DC, due to the perceived advantage of such a system.

More-electric aircraft (MEA) power almost all loads with electric power, except the propulsion. Figure 1.33 shows the architecture of a conceptual commercial MEA electrical system, which covers the environmental management system (EMS), entertainment system, actuation, and so on. Power conversion equipment includes high-power AC/DC from 115 or 230 V variable frequency AC bus to 270 or 540 V DC bus, which is often realized using an auto-transformer rectifier unit (ATRU); AC/DC from AC bus to 28 V DC application, which is often realized using a transformer rectifier unit (TRU); and DC/AC from DC bus to AC 400 Hz bus. Note that a DC bus can also directly drive motor controllers (inverters), battery chargers, and load DC/DC converters. Even more than ships and EVs, airplane power converters must be light, compact, and efficient. WBG device technology should have a promising future in aircraft applications.

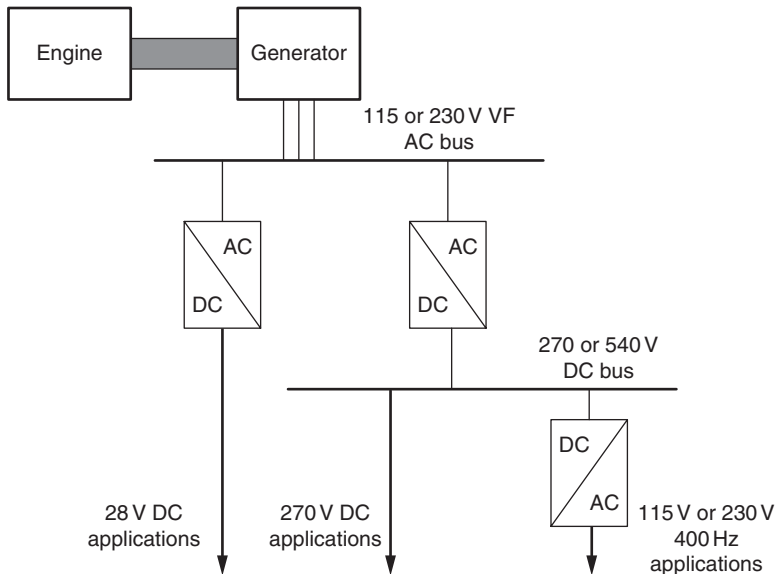


Figure 1.33 A conceptual MEA electrical system.

There is strong interest in using electric propulsion for future aircraft. They are expected to be more efficient and environmentally friendly. The technical challenges include battery technology.

Data Center

The economy and our daily life are increasingly going digital and data-driven. Data centers are becoming an important type of load. It is projected that the energy consumption of data centers in US will reach 139 billion kWh by 2020, about 3.6% of the 2017 total electricity consumption.

Figure 1.34a shows an AC power architecture that is widely used in data centers. The power supply train of this architecture contains several parts, such as the UPS (uninterruptible power supply), PDU (power distribution unit), PSU (power supply unit), and VR (voltage regulator). It can be seen clearly that there are many power electronics converters: three-phase 480 V AC to DC, DC to single-phase 120 V AC, single-phase AC to 400 V DC, 400 V to 12 V DC, and 12 V to 1 V VR. One issue with this architecture is its low energy efficiency. Although the efficiency of each stage is quite high, the multiple conversions result in an overall low efficiency. As reported in [56], for this architecture with 120 V AC intermediate distribution, the efficiency can only reach 67%. Considering additional losses in distribution and cooling, less than half of the input power is delivered to the computing and data processing load. Note there are some AC architecture variations to the one in Figure 1.34a, such as a 48 V DC intermediate bus with improved overall efficiency.

More recently, a new kind of power architecture for data centers was proposed, called 400 V (or 380 V) DC power architecture [57, 58], as shown in Figure 1.34b. The efficiency can be improved to 73% compared with 67% in Figure 1.34a with the same power conversion technology. In this power architecture,

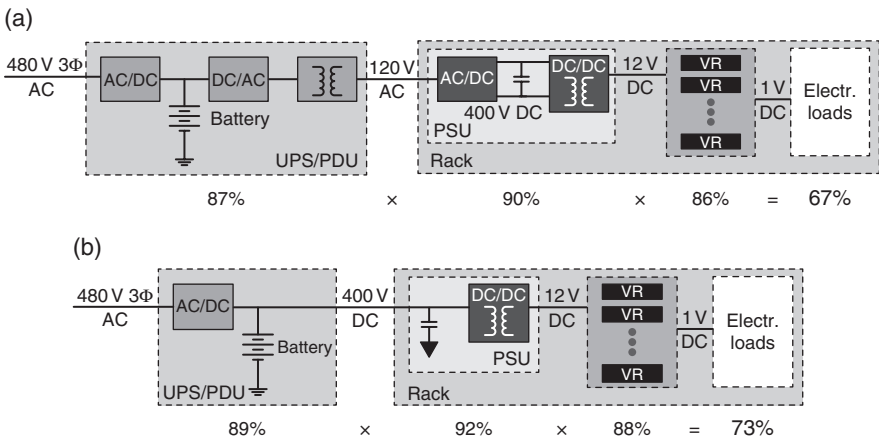


Figure 1.34 Power distribution architecture of data center power supply. (a) 120 V AC power architecture; (b) 400 V DC power architecture.

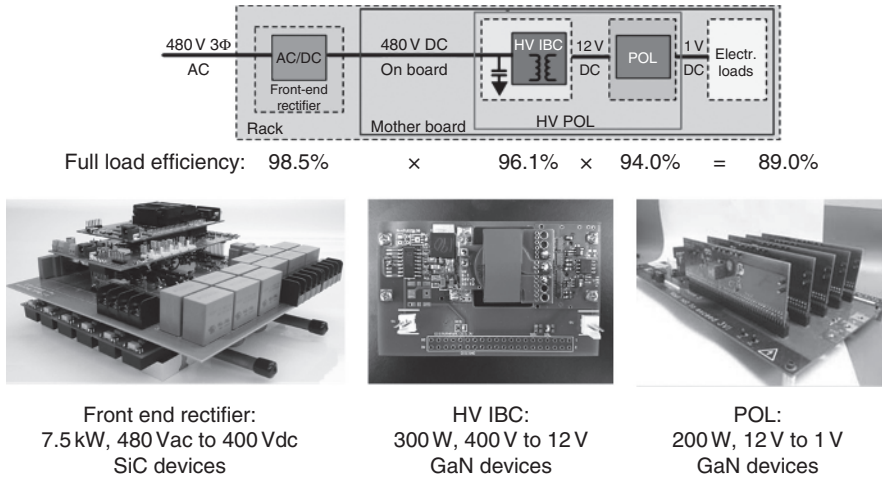


Figure 1.35 Prototype data center power supplies using WBG devices.

the DC/AC converter in the UPS and AC/DC converter in the PSU are removed, and the DC link voltage is 400V. The benefits are not only efficiency improvement, but also space saving, reliability improvement, and simplified wiring. This DC power architecture is the trend for future data centers.

If WBG devices are used to replace the Si devices, power conversion efficiency for data centers can be significantly improved. Figure 1.35 shows the architecture and efficiency of a UTK/Auburn-built data center converter system. It is a rack level three-phase 480VAC and blade level 400VDC power distribution architecture. The topologies for the AC/DC stage, high-voltage intermediate bus converter (HV IBC) stage and point-of-load (POL) stage are, respectively, three-phase current source rectifier, LLC resonant converter, and multiphase buck converter. Using SiC for the rectifier, and GaN for the HV IBC and POL, the three-stage efficiency reaches 89%. The corresponding best available Si solution using the same architecture would have an efficiency of 83%.

1.5 RENEWABLE ENERGY SYSTEMS

A renewable energy source, unlike fossil fuel and nuclear sources, does not get depleted with usage. The principal types of renewables [59–67] are hydroelectric, wind, solar, biofuels, geothermal, wave, and tidal, which are environmentally clean and abundant in nature. Biofuels are environmentally neutral because plants absorb CO_2 while growing, but emit CO_2 while burning. For these reasons, the whole world is now putting tremendous emphasis on exploring renewable energy sources. *Scientific American* has published an article [68] indicating that all of our energy needs can be met by renewables with adequate storage and transmission capabilities. The UN-IPCC estimates that 50% of total energy can be met

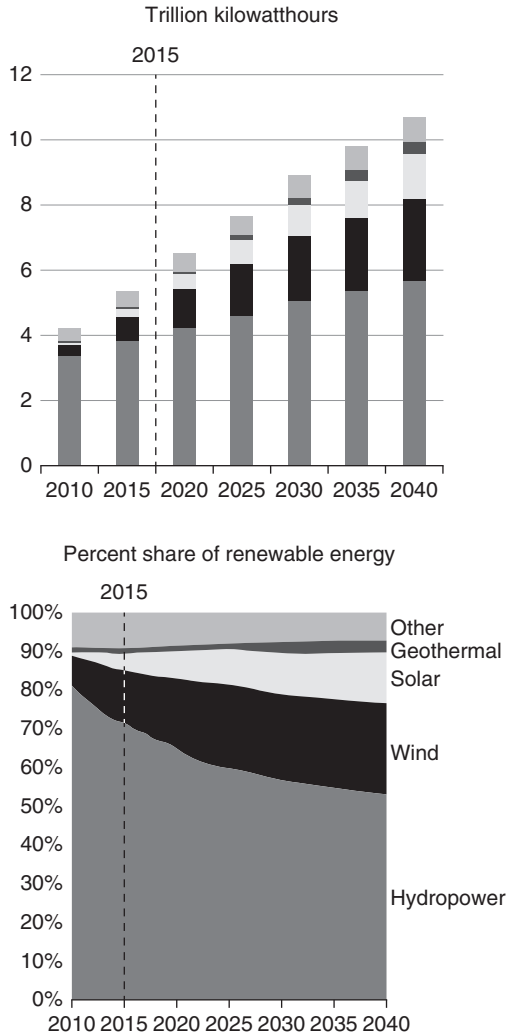


Figure 1.36 World net electricity generation from renewable energy sources.
(See electronic version for color representation of this figure.)

from renewables by 2050. Among all the renewables, wind and photovoltaic (PV) are particularly important and dependent on power electronics, and therefore will be discussed further.

Solar and wind also dominate the renewable generation increase forecast, as shown in Figure 1.36 [69]. For solar, installed capacity globally has seen immense growth, reaching approximately 227 GW by the end of 2015, equivalent to producing 1% of the electricity used globally. At the same time, PV module prices have declined 80% from about \$4/W in 2007 to \$1.8/W in 2015. Global wind power

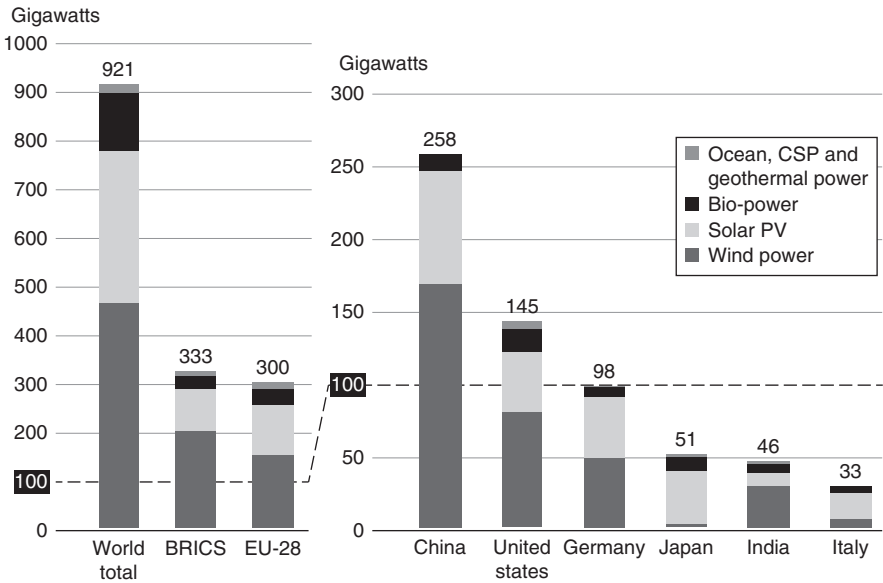


Figure 1.37 Renewable power capacities in the world, BRICS, EU-28 and top six countries. (See electronic version for color representation of this figure.)

generation capacity increased by 16.4% in 2014, 17.2% in 2015, and at 435 GW, represented around 7% of total global power generation capacity. Specifically, wind power contributed 42% and 13% of the electric generation in Denmark and Germany, respectively [70, 71].

Renewable power generating capacity saw its largest annual increase ever in 2016, with an estimated 161 GW of capacity added, as shown in Figure 1.37. The ongoing growth and geographical expansion of renewable energy was driven by the continued decline in prices for renewable energy technologies (in particular, for solar PV and wind power), by rising power demand in some countries, and by targeted renewable energy support mechanisms. Solar PV and onshore wind power are now competitive with new fossil fuel generation in an increasing number of locations, due in part to declines in system component prices and to improvements in generation efficiency. More than 170 countries have renewable energy targets, and an estimated 150 countries have policies that support renewable energy.

1.5.1 Wind Energy Systems

In a typical wind generation system [2], as shown in Figure 1.38, a variable speed wind turbine (normally horizontal axis) couples to the shaft of an AC machine (induction or synchronous) through a speed-up gear. The variable voltage, variable frequency power is then converted to constant voltage and constant frequency helped by a two-sided PWM converter system. The converter can be full-power rating connected to a machine stator, in the case of a PM synchronous generator

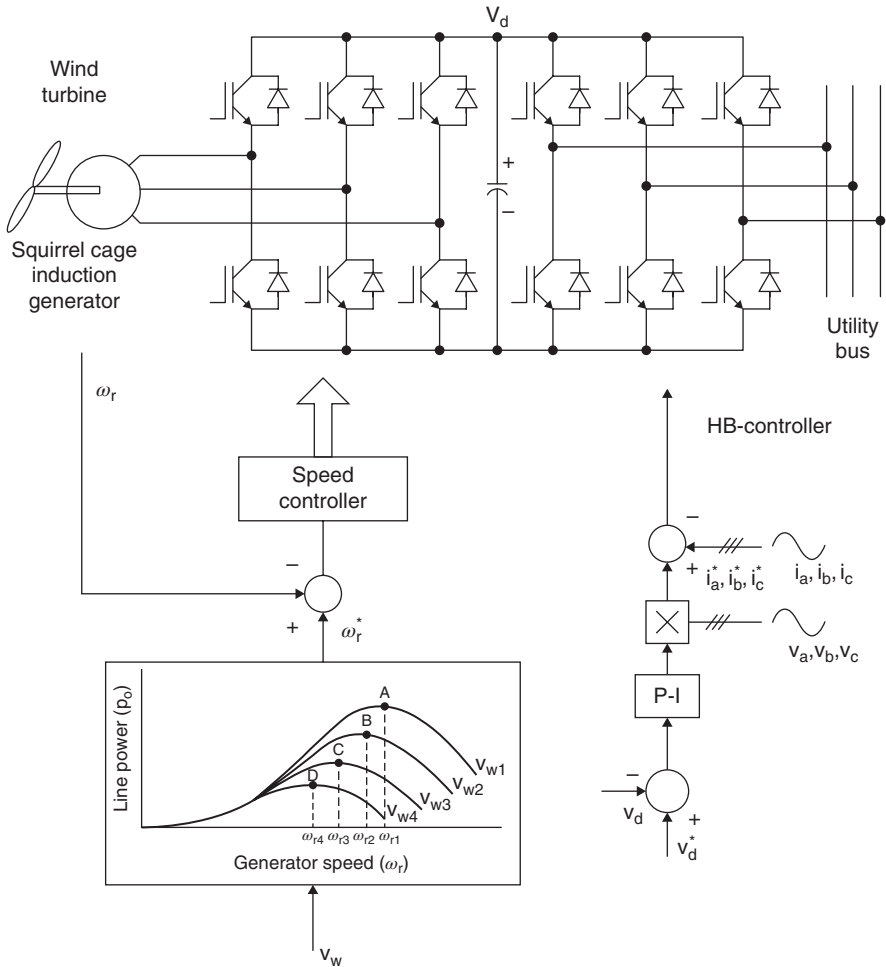


Figure 1.38 Wind energy system with an induction generator.

(Type IV wind), or can be partial power rating, connected to a machine rotor, in the case of a doubly-fed induction generator (Type III wind). The “grid codes” require wind energy system support for various grids needs, such as low voltage ride-through (LVRT) or VAR support. The DC link of the converter system can be used for energy storage. The control system, as shown, measures or estimates the wind velocity and controls the generator speed to optimize the power generation (improving the aerodynamic efficiency of the turbine) by MPPT (maximum power point tracking) control. The line-side converter controls the DC link voltage. It is possible to control both active (P) and reactive power (Q) by the line-side converter. Currently, wind energy cost per unit is nearly equal to that of fossil fuels. One disadvantage of a wind generation system is that the availability of power is sporadic and depends on the wind velocity. Therefore, back-up power or bulk energy storage

is needed. The configuration in Figure 1.38 is also used in four-quadrant motor drive systems, except in the case of a drive, energy mainly goes from the grid to the machine, opposite to the wind energy system.

The future trends for power converters in wind generation systems include: medium-voltage converters for multi-MW wind turbines, for better efficiency and reliability; transformerless topologies for high power-density, especially for off-shore wind; and topologies with fault-tolerant capabilities. At the system level, wind energy systems and converters are increasingly asked to provide grid support functions, including frequency and voltage support. Different operating modes other than MPPT are being implemented, including voltage mode, virtual synchronous generator mode, and inertia emulation. Of course, WBG devices can help at both the converter and system levels.

1.5.2 PV Systems

Solar electrical energy is generally classified into solar thermo-electric and PV systems [72]. In the former case, solar energy is concentrated by mirrors to heat water and produce steam. This steam then operates a turbo-generator system to convert to electricity. In a PV system, PV devices (crystalline or amorphous Si, CdTe, and copper indium gallium selenide) convert sunlight directly into electricity. The generated DC is then converted to AC and fed into a grid, or used for autonomous load. Figure 1.39 shows a typical PV system configuration, where a PV array (series-parallel connection of cells) is connected to a DC/DC converter to boost the DC voltage and then converted to AC by a PWM inverter. Multiple units are coupled by transformers and then feed to the AC grid. The DC/DC converter controls the maximum power output of the array by a MPPT (maximum power point tracking) algorithm, as indicated. For high power, multilevel converters can be

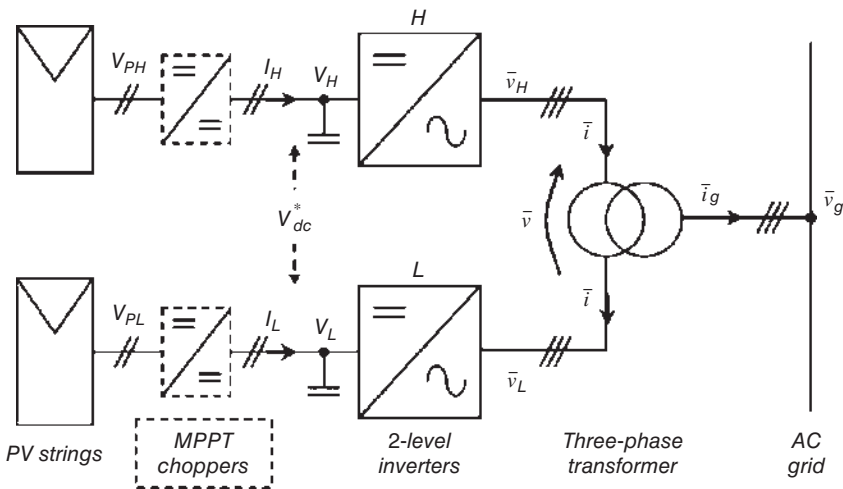


Figure 1.39 A photovoltaic power conversion system.

used. The inverters can control both active and reactive powers, as desired. The advantages of PV systems are that they are static, safe, highly reliable, and require little repair and maintenance. However, energy availability is sporadic depending on the availability of sunlight and requires energy storage or back-up power like wind energy systems. Although PV systems are generally more expensive than wind systems, the price of PV cells is falling sharply with the present trend of research, and as a result, its applications are growing very rapidly in roof-top installations, autonomous and grid-connected systems. The US PV energy market is now around 0.5% and has a goal of 20% by 2030. Europe has ambitious plans for exploring PV energy from African deserts and connecting to its grid system through HVDC transmission. With the expected growth rates, the IEEE predicts that, by 2050, PV will supply 20% of global energy.

Similar to the wind power converters, PV converters are being advanced at both the converter and system levels. The converter-level development trends include: single-stage replacing multistage (e.g., Quasi-Z-Source inverter); low-frequency transformer replaced by high-frequency transformer or transformerless with leakage current minimization (e.g., HERIC inverter); multilevel converter topologies enabling medium-voltage grid connection (e.g., 3L-NPC, cascaded H-bridge, MMC); hybrid system topology with PV and BESS; and topologies on modular integrated DC–DC converters. WBG devices are enabling switching frequencies of hundreds of kHz for reduced passives and better efficiency. Grid support functions are also being developed and implemented for PV inverters.

1.5.3 Grid Energy Storage

As mentioned before, the renewable energy systems, such as wind and PV, require bulk energy storage to store the surplus energy and then replenish it when the available energy falls short. The various methods [73, 74] of grid energy storage can be summarized as: pumped storage in hydroelectric plants, battery storage, flywheel storage, superconducting magnet energy storage (SMES), ultracapacitor (UC) storage, vehicle-to-grid (V2G) or grid-to-vehicle (G2V) storage, H_2 gas storage, and compressed air energy storage (CAES). In pumped storage systems, the hydrogenerator works as a pump, to pump water from “tail” to “head” of a water reservoir using off-peak grid energy. During peak demand, the head water runs the generator to supply power. It is possibly the cheapest storage method at a favorable site, and has been widely used in hydroelectric plants. In general, battery storage is mostly favored, although it is still expensive. In this case, the surplus grid energy is converted to DC that charges a battery. In peak times, the battery energy is converted to AC and supplies to the grid. Although lead-acid batteries have been extensively used in the past, recent batteries used for storage are NiCd, NaS, Li-ion and vanadium redox flow batteries. It appears that flow and Li-based batteries are more favorable for grid storage. H_2 storage is very interesting because it can use cheap and abundant renewable energy to generate H_2 gas by electrolysis of water, which is convenient for easy storage and pipeline transmission. It can be used in fuel cells or burnt as a gas in an IC engine. The concept of a future hydrogen economy is based on a clean H_2 gas source.

1.6 SMART GRID

Smart grids generally refer to grids equipped with smart sensors/meters (e.g., phase-measurement unit), real-time data collection and processing, fast communications (e.g., fiber-optics), visualization and situational awareness tools, and intelligent controllers (e.g., intelligent switchgear and power electronics controllers). Smart grid technologies will lead to better economics, reliability, power quality, and eventually better energy efficiency and environmental performance. This section will focus on controller and controllable grid architecture associated with smart grids using power electronics.

Smart grids should be controllable grids for electric energy transmission and distribution. The traditional equipment in power grids today, including electrical transmission and distribution lines, generators, transformers, switchgears, inductors or reactors, and capacitor banks, has limited control capability. Many cannot be controlled at all or can only be connected or disconnected with mechanical switches; others have limited range, such as transformers with tap-changers. Even with fully controllable equipment such as generators, the control dynamics is relatively slow due to the electromechanical or electromagnetic nature of the equipment [75].

Due to their electronic nature, power electronics-based equipment is much more flexible and faster than their electromechanical or electromagnetic counterparts for electrical power transfer and control. Since the advent of power semiconductor devices in the 1950s, power electronics have steadily gained ground in power grid applications. Today, power electronics controllers are an important, albeit small, part of equipment for power transfer and control in power grids. Their role is growing rapidly with the continuous improvement of the power electronics technologies, and with the need for better control performance as smart grids grow.

This section focuses on power electronics-based technologies for controlling electrical power for transmission and distribution. For transmission, these technologies generally belong to two basic categories: flexible alternating current transmission systems (FACTS), and high-voltage direct current (HVDC) transmission systems. In recent years, some new concepts have been developed, including distributed FACTS, partial FACTS, hybrid AC/DC, variable or low-frequency high-voltage AC (HVAC), and supergrid. For distribution, custom power has been developed as a counterpart to FACTS. In recent years, due to RES and DER (distributed energy resources) growth, other distribution level technologies have been developed, including microgrids.

1.6.1 FACTS Technologies

A modern electrical power transmission system is a complex interconnected grid, which provides reliability and economic benefits compared with point-to-point or standalone transmission systems. On the other hand, interconnected grids are more challenging to control. For example, the power flows within the grid are determined by the bus voltages and line impedances, which have either very

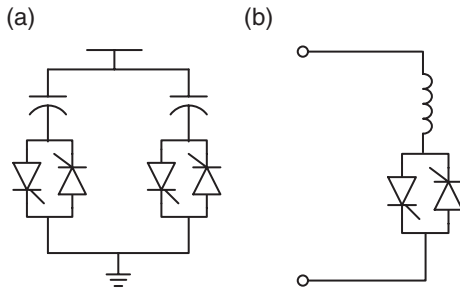


Figure 1.40 Schematic diagram of (a) TSC, and (b) TSR.

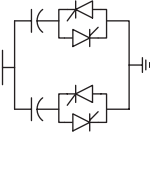
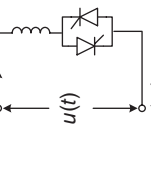
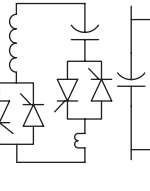
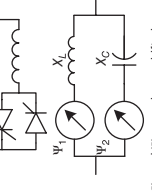
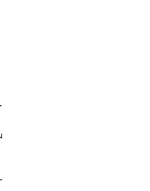
limited control ranges (in the case of bus voltage) or are fixed (in the case of line impedance). In order to improve the controllability of a power grid, various series or shunt-connected devices have been developed. For the AC grid, well-known devices include the shunt-connected switched capacitor banks and series capacitor compensation, with the former mainly for reactive power or VAR and voltage support, and the latter for power flow control. These technologies are simple and of low cost, but they do not provide continuous control and may cause instability; their reliance on mechanical switches can also result in high maintenance costs [76]. To improve controllability and avoid instability, power electronics were introduced into the conventional switched compensators. Figure 1.40 shows a capacitor and reactor respectively in series with a bi-directional switch, made up of two anti-parallel thyristors, to allow bi-directional current flow. By controlling the conduction time of the thyristors over one AC cycle, also called phase-angle, the equivalent capacitance or reactance can be continuously adjusted, resulting in thyristor-switched capacitors (TSCs) and thyristor-switched reactors (TSRs). Paralleling TSR with capacitor banks will form the well-known static VAR compensator (SVC), allowing continuous generation or absorption of reactive power [77].

To better characterize the family of the power electronics-based devices for AC transmission system control, the term *flexible alternating current transmission systems* or FACTS was proposed in the 1980s, and defined as “alternating current transmission systems incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer capability” by the IEEE Power Engineering Society in 1997 [78]. Although a number of FACTS devices existed before the term (e.g., SVC), many new devices have been developed since then. The more popular ones with practical installations are listed in Table 1.7 with their circuit configurations, main system functions, control principles and basic power electronics functions.

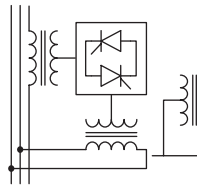
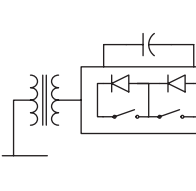
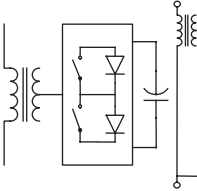
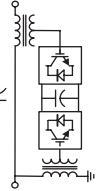
Classification of FACTS Devices

FACTS devices can be categorized in several ways. The most straightforward way is by their connections in a system [79]:

TABLE 1.7 Summary of relatively common FACTS devices.

Controller	One-line configuration	System functions	Control principle	Basic power electronics function
TSC – thyristor-switched capacitor		• Stability enhancement • VAR compensation	VAR control through varying C in shunt connection	Controlled bi-directional AC switch
TSR – thyristor-switched reactor		• Stability enhancement • Voltage regulation	VAR control through varying L in shunt connection	Controlled bi-directional AC switch
SVC – static VAR compensator		• Stability enhancement • Voltage regulation and VAR compensation	VAR control through varying L & C in shunt connection	Controlled bi-directional AC switch
TCSC – thyristor-controlled series capacitor		• Power flow control • Stability enhancement • Fault current limiting	Power and VAR control through varying C & L in series connection	Controlled bi-directional AC switch
IPC – interphase power controller		• Power flow control • Stability enhancement • Fault current limiting	Power control through phase angle control in series connection	Controlled bi-directional AC switch

ψ_1 and ψ_2 are phase-shift elements

TCPST – thyristor-controlled phase-shifting transformer		• Power flow control • Stability enhancement • Fault current limiting	Power control through phase angle control in both shunt and series connection	Controlled bi-directional AC switch
STATCOM – static synchronous compensator		• Stability enhancement • Voltage regulation and VAR compensation	VAR control through current control in shunt connection	Bi-directional AC/DC voltage source converter
SSSC – static synchronous series compensator		• Power flow control • Stability enhancement • Fault current limiting	VAR control through voltage control in series connection	Bi-directional AC/DC voltage source converter
UPFC – unified power flow controller		• Power flow control • Stability enhancement • Fault current limiting	Power and VAR control through back-to-back converters in both series and shunt connections	Bi-directional AC/DC voltage source converter

1. Shunt-connected FACTS devices include thyristor-switched capacitors (TSCs), thyristor-switched reactors (TSRs), static VAR compensators (SVCs), and static synchronous compensators (STATCOMs).
2. Series-connected FACTS devices include thyristor-controlled series capacitors (TCSCs), static synchronous series compensators (SSSCs), and interphase power controllers (IPCs).
3. Hybrid-connected FACTS devices have both shunt and series connections, including unified power flow controllers (UPFCs), which can be regarded as a combination of STATCOM and SSSC, and thyristor-controlled phase-shifting transformers (TCPSTs).

FACTS devices can also be categorized by the semiconductor technologies they use. The earlier devices were mostly based on thyristors, which have large power handling capability and low losses, but are only semi-controllable, since thyristors can only be turned on but cannot be turned off through gate control signals. The newer FACTS devices are based on full switching devices, such as insulated-gate bipolar transistors (IGBTs) and integrated-gate-commutated thyristors (IGCTs).

FACTS devices can also be classified into impedance control, injected current control, and inserted voltage control through their functions or operating principles [80]. The thyristor-controlled FACTS devices are generally for impedance control, while the injected current control is generally achieved via switching device-based shunt-connected FACTS devices, and inserted voltage control achieved via switching device-based series-connected FACTS devices.

Recent Developments in FACTS Technologies

Power electronics-based FACTS devices can greatly improve power system controllability. However, the applications of such devices in power grids today are very limited due to their relatively high cost and complexity. The complexity also leads to high maintenance requirements and perceived low reliability. Continued improvement in power electronics technologies should help improve the FACTS technologies. In addition, new concepts have been developed to address the shortcomings of the conventional FACTS technologies. Two notable concepts are distributed FACTS and partial FACTS.

Distributed FACTS devices consist of many modular power electronics-based converters installed along a transmission line in a distributed fashion. Each converter functions as a small FACTS device; together, they perform the equivalent control function as a centrally located large FACTS device. Since each converter is small in a distributed FACTS scheme, low-cost power electronics semiconductor devices with low voltage and low current ratings can be employed. The modular distributed configuration can easily enable redundancy implementation for improved reliability. Ref. [81] describes a distributed series reactor realized through low-voltage, low-current windings powered by a low power converter, and clamped onto the high-voltage, high-current transmission line. Since the converter is floating on the transmission line, no costly high-voltage insulation is

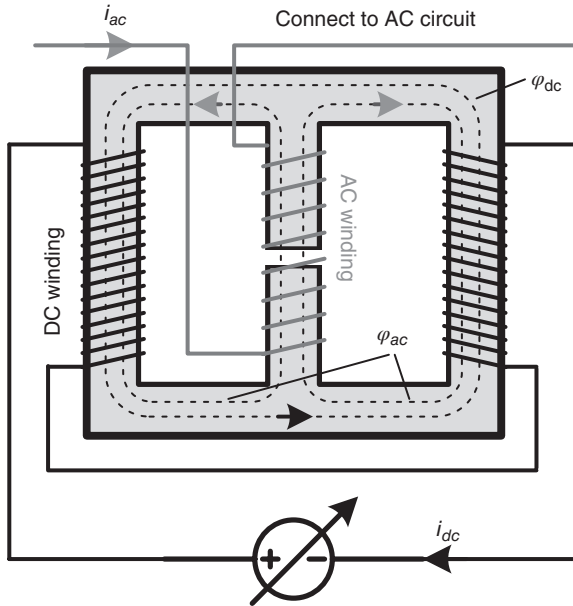


Figure 1.41 Schematic diagram of a CVSR. (See electronic version for color representation of this figure.)

needed. One complexity of the distributed FACTS device is its control. Many of the required control functions can be locally realized at each converter level; however, in order to achieve the system-level coordinated control, the control signals must be communicated to each converter, which can be achieved through wireless technology.

Partial FACTS devices utilize power electronics to improve the controllability of the conventional electromagnetic or electromechanical devices. One example is a transformer with power electronics tap changer. The traditional tap changer is mechanically based and can only control the transformer voltage in a very limited range with slow dynamics. The power electronics tap changer can extend the control range and improve dynamics. Another example of a partial FACTS device is the continuously variable series reactor (CVSR) shown in Figure 1.41. The AC winding is the controlled element that can be connected into an AC line, while the DC current regulator is the controlling element for CVSR through DC winding, which can vary the DC bias flux as well as the magnetization level of the saturable-core. As a result, the AC reactance reaches the maximum value when the bias DC flux equals zero, and the minimum value when the core is fully saturated. The DC current controller is realized through a power electronics converter with a rating of only a small fraction of the AC winding.

1.6.2 HVDC Technologies

HVDC Background

Modern transmission grids are predominantly based on high-voltage alternating current (HVAC) schemes due to the superior performance and low cost of AC generators and transformers. However, HVDC transmission schemes also have some distinct advantages [82], including:

- lower costs for long-distance bulk power transmission;
- lower costs for cable transmission (subsea, offshore);
- ability to exchange power between two asynchronous power systems, even two systems with different frequencies;
- AC system support capabilities, including power flow control, frequency and voltage support, oscillation damping, and fault current limiting;
- better use of right-of-way;
- environmental benefits, such as less corona and audible noise.

On the other hand, HVDC lines are embedded in HVAC grids and require power electronics converters and other associated station equipment, including filters, communications and special transformers. The high cost of converter stations makes the HVDC a niche, albeit important technology in today's transmission grid. With new advances in power electronics, the growth of renewable energy resources in remote and offshore locations, and concerns about environmental impacts, HVDC is getting more attention and is expected to play a more significant role in future power grids.

At the heart of the HVDC technology is the AC/DC power converters. There are two basic types of HVDC converters: the current source converters (CSCs) and the voltage source converters (VSCs). The CSCs are based on older thyristor technology developed in the 1970s. The most common CSC converter is the line-commutated converter (LCC) based on a phase-controlled thyristor rectifier bridge as illustrated in Figure 1.42a. The LCC HVDC controls the

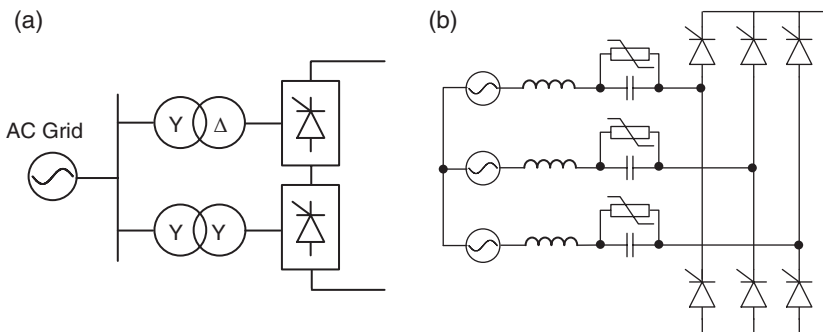


Figure 1.42 Schematic diagram of (a) LCC, (b) CCC.

power flow through the DC voltage difference between the two terminals of the HVDC line. The line commutation requires the AC grids on both sides of the HVDC line to be strong; specifically, the short-circuit ratio (SCR) should be greater than 2. Since the current of the bridge (Figure 1.42) is unidirectional, in order to reverse the power flow of a LCC HVDC line, the DC voltage polarity must be reversed, making it difficult to build a DC grid or multiterminal HVDC line with this technology. Another drawback with LCC HVDC is its low power factor and high harmonics, requiring large filters on both AC and DC sides, VAR compensators, and therefore a large station footprint. On the other hand, the LCC scheme is relatively simple, low-cost, and with low losses due to the excellent conduction characteristics of the thyristors. As a result, the LCC HVDC is still the scheme of choice for point-to-point bulk power HVDC transmissions.

An alternative CSC HVDC converter is the capacitor-commutated converter (CCC), which adds series capacitors to the AC side of the thyristor bridge, as shown in Figure 1.42b [83]. The series capacitors can affect the thyristor valve voltages and supply reactive power, enabling both leading and lagging power factor operation. With proper design, the CCC can operate successfully in weaker AC systems with a short-circuit ratio around 1, and need much smaller AC filters than the LCC. However, the extra commutating capacitors will add cost, and may also cause operational issues during transients and unbalanced conditions. As a result, the CCC HVDC is not widely used.

Both the LCC and CCC are mature technologies. Recognizing the drawbacks of these technologies as the result of their reliance on the phase-controlled and line-commutated thyristors, the VSC HVDC was developed when high voltage and high current IGBT and IGCT became commercially available in the 1990s. Similar to the LCC HVDC, the power flow of the VSC HVDC is also controlled through the voltage difference between the two terminals of the HVDC line. Unlike LCC HVDC, the VSC can have bi-directional current flow. Therefore, the power reversal can be easily achieved through the DC current polarity reversal, making the VSC a convenient topology for multiterminal HVDC or DC grid.

Other advantages of VSC HVDC include: (1) low harmonics due to the fast switching of IGBT and IGCT; (2) black start capability, as VSC can operate with low or even zero AC voltages; (3) independent active and reactive power control. As a result, the VSC HVDC does not require large filters, VAR compensators, or special transformers, resulting in a compact converter station footprint. It also possesses improved AC fault ride-through capability. On the other hand, the VSC HVDC is generally more expensive than its LCC counterpart. The relatively high conduction loss characteristics of IGBT, and high switching losses due to high switching frequencies, also make VSC HVDC less efficient. The power capability of the VSC HVDC is also lower, mainly due to the HVDC cable technology limitations, as most VSC HVDC projects today have been commissioned for cable transmissions such as subsea applications.

Two-level and Three-level Converters

The VSC HVDC is still an evolving technology. Driven by cost and efficiency improvements, the topology of VSCs has continually evolved for the past two decades. The main topologies used commercially include two-level and three-level converters, and modular multilevel converters.

Before 2010, the commercial VSC HVDC converters were all based on either two- or three-level converters [84]. Their basic circuit schematics are given in Figure 1.43.

With two-level VSCs, the AC terminal voltage will be either equal to the positive DC voltage or negative DC voltage in each switching instant. Through proper switching actions, for example using pulse width modulation (PWM) switching strategy, a desired fundamental frequency AC voltage can be realized after filtering the switching frequency harmonics. With the three-level VSCs, at a given switching instant, the AC terminal voltage can also be equal to the DC side middle-point voltage, in addition to the positive and negative DC voltages. Compared with the two-level VSC, the three-level VSC has lower harmonics with the same switching frequency, or can operate with lower switching frequency to

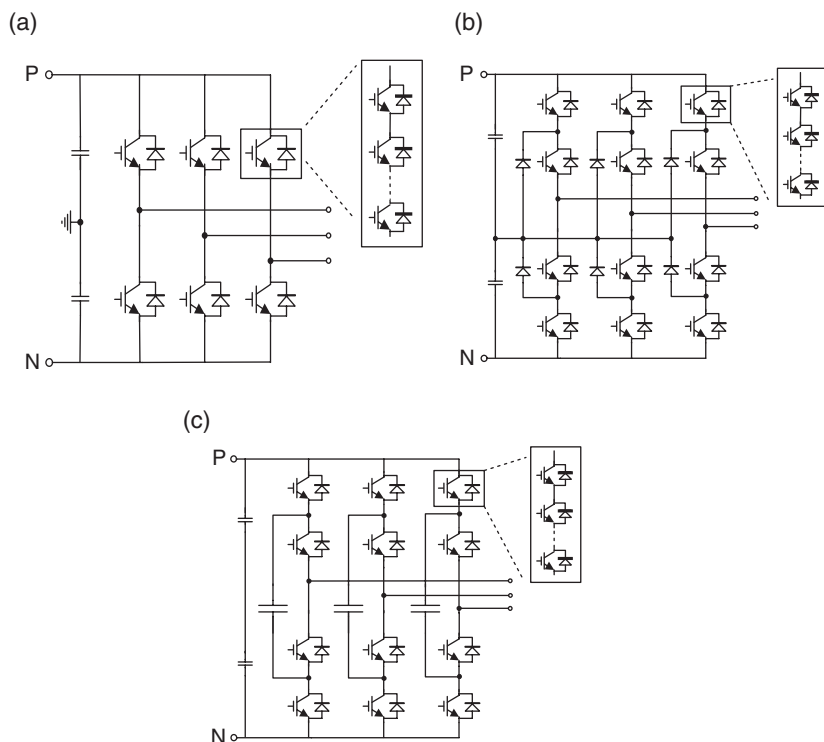


Figure 1.43 Configurations of (a) two-level VSC, (b) neutral-point clamped (NPC) three-level VSC, and (c) flying capacitor (FC) three-level VSC.

achieve the same harmonics. On the other hand, the three-level VSC will require more semiconductor devices (diodes as in the NPC case) or more passive components (capacitors as in the FC case), and its control is also more complex.

Although the two-level and three-level VSCs were used in the earlier VSC HVDC projects, they pose design, operation and performance issues [85]. One issue is the difficulty in balancing the voltages of power devices, as individual IGBT or IGCT devices have limited voltage capabilities (below several kV) and many of them need to be connected in series to withstand the HVDC voltages (normally tens or hundreds of kV). In addition to voltage balancing during on and off periods, devices also need to be turned on and off simultaneously to prevent breakdown, which is challenging to achieve. Another issue is the lower efficiency, as compared with the LCC HVDC. The switching frequency of two-level and three-level converters normally ranges between 1 to 2 kHz, significantly higher than LCC, which operates at line frequency and also turns off naturally with zero turnoff loss. High switching frequency reduces harmonics but increases switching loss. Typically, the losses of two-level and three-level VSC HVDC are around 3% and 2.2%, respectively. Utilizing the optimized PWM scheme, the losses of two-level converters can be reduced to 1.7%, while the LCC HVDC has a much lower loss of 0.8% [86].

Modular Multilevel Converters (MMCs)

The newest VSC for HVDC is based on a modular multilevel converter (MMC), which eliminates the need for series connection of devices [87]. The configuration of a MMC is shown in Figure 1.44a. Each phase leg of the MMC consists of one upper and one lower arm connected in series between the DC terminals. Many series-connected submodules (SMs) and one arm inductor L_{arm} form an arm. Each SM can be realized by half-bridge, full-bridge or clamped-double circuits, as illustrated in Figure 1.44b–d. The number of SMs in each arm depends on the HVDC voltage level and individual IGBT device voltage capability. Given that the IGBT ratings are in kV and HVDC ratings in hundreds of kV, often several hundreds of SMs are used for one MMC. In addition to simplified series connections, MMCs also feature [88]:

1. Higher quality AC voltage. With high numbers of SMs in each arm, the AC voltage of the MMC is synthesized by DC voltages of selectively inserted SMs and therefore becomes more sinusoidal, which leads to smaller AC filters.
2. Lower switching frequency and loss. High numbers of SMs per arm enables each individual device to switch very slowly and still achieve a high equivalent switching frequency. In commercial applications, the device average switching frequency is generally below 200 Hz. Consequently, the state-of-the-art of MMC HVDC has a loss level about 1%, close to that of a LCC.
3. Modular design and inherent redundancy.

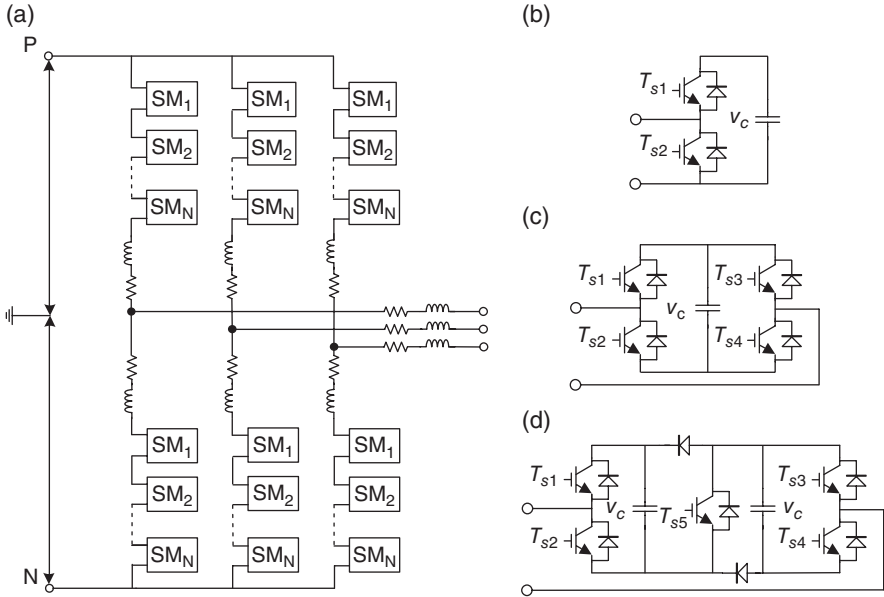


Figure 1.44 (a) Circuit configurations of a MMC with (b) half-bridge submodule, (c) full-bridge submodule and (d) clamped-double submodule.

The potential disadvantages of MMCs include the high number of capacitors required of SMs, design and control complexity due to the abundant SMs, and additional arm inductors needed, as shown in Figure 1.44, to limit the circulating current. Because of the circulating current, the total IGBT device ratings for a MMC will also be slightly higher than for the two-level VSC.

Most VSCs, including two- and three-level VSCs, and MMCs with half-bridge SMs, suffer high fault currents in DC side pole-to-pole short-circuit faults. This is because when DC voltage is low, as in the case of a short-circuit fault, the VSC will lose its controllability. Even if all IGBTs are turned off, fault current can still be sustained from the AC side through diodes in parallel with IGBTs. This fault current can only be broken off with AC or DC side breakers. Since the mechanical breakers are slow, the fault current must be limited with AC or DC inductors, adding to cost and design complexity. This is a drawback for VSC; in comparison, LCC, as a CSC, can control the fault current better during the DC side short-circuit fault.

To overcome the high short-circuit fault current issue, MMCs with full-bridge or clamped-double SMs have been developed, as shown in Figure 1.44c and d. For the full-bridge MMC, turning off all IGBTs during a fault will insert the capacitor voltage into the fault current loop to limit the fault current rise rate and current level; for the clamped-double MMC, there is a fault current interrupting the IGBT module in each SM, whose opening during a short-circuit will also insert the capacitor voltage into the fault current loop. During normal operation, this IGBT stays on such that the SM behaves like two half-bridge SMs in series. The MMC with

full-bridge SMs can generate both positive and negative voltages, which enables flexible, reactive power control even during zero DC voltage.

The MMCs with full-bridge or clamped-double SMs require more switching devices, which also incur more losses due to the series-connected devices in the current path within a SM. As a result, almost all commercial MMC HVDC projects today use half-bridge SMs [89]. In order to reduce the cost and maintain the fault current limiting capability, some hybrid topologies have been proposed to use full-bridge SMs partially in a MMC or to have hybrid MMC and two-level VSC [90].

Recent Developments in HVDC and Related Technologies

VSC technology, especially the MMC with various SMs, continues to improve, driven by performance, efficiency and cost needs as mentioned above. Components technologies are also making progress. SiC-based switching devices with high voltage ratings ($>10\text{ kV}$) can potentially replace Si devices in future HVDC converters, with their superior losses and switching characteristics. Cables with higher voltage ratings than today's 525 kV are being developed to improve the voltage and power capability of VSCs.

Another important technology associated with HVDC is the DC breaker. The traditional AC circuit breakers will not work for DC due to the lack of zero current crossing. A paralleled resonant circuit can be added to create zero current, or purely using a solid-state semiconductor switch. However, the mechanical switch is too slow and the semiconductor switch has unacceptably high losses. The recently developed hybrid DC circuit breaker, as shown conceptually in Figure 1.45, can achieve both low losses and fast breaking time, which is the trend for future DC breaker development [91].

Despite many advantages, HVDC lines make up only a small portion of the transmission grid, mainly due to the high converter cost. Some alternative schemes have been proposed, including hybrid AC/DC and low-frequency AC schemes.

1. **Hybrid AC/DC.** One of the main advantages of the HVDC scheme is its superior power transmission capability over the HVAC scheme. To increase its transmission capability, an existing AC line can be converted to a DC line by fully or partially rebuilding the line and adding HVDC converter stations at both terminals. An alternative is to convert the AC line into a hybrid AC and DC line with both AC and DC currents flowing in the same line. Figure 1.46 shows a basic hybrid AC/DC scheme based on a double-circuit, where the DC

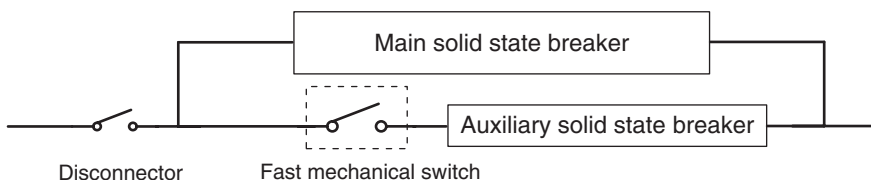


Figure 1.45 Configuration of hybrid DC breaker.

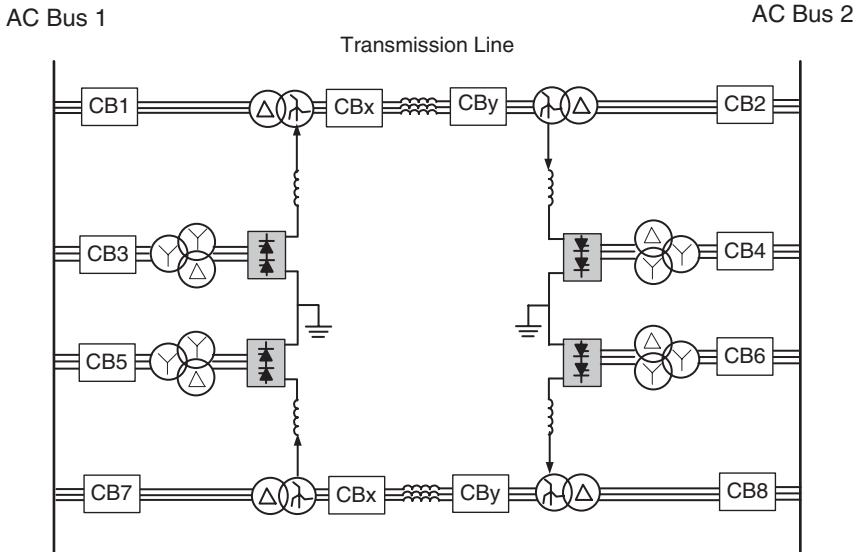


Figure 1.46 Basic scheme of hybrid AC/DC transmission (CB: circuit breaker).

current can be injected into the AC lines through the neutral point of a three-phase transformer. With hybrid AC/DC, the total transmission power capability can be significantly increased compared with the original AC-only transmission [92]. A special zigzag transformer is needed for DC current injection in order to avoid saturation. A small line conditioner may also be required to deal with line imbalance issues [93]. Even with the additional components required, the hybrid AC/DC scheme can still be more cost-effective than the full HVDC conversion.

2. *Low-frequency AC transmission.* One significant issue with HVDC transmission is the lack of cost-effective DC breakers during a DC line short-circuit fault. Given that the power transmission capability for a long AC line is inversely proportional to the line impedance, reducing the line frequency can increase the power transfer capability, while preserving the short-circuit current control with AC breakers. In this case, relatively low-cost, thyristor-based cycloconverters can be used to convert the 50/60 Hz to below a third of the nominal frequency.

1.6.3 DC Grid and Supergrid

Multiterminal HVDC Grid

As mentioned previously, today's power grids are predominantly based on interconnected HVAC lines, with limited point-to-point or two-terminal HVDC lines embedded to serve certain special needs. With the development of HVDC

technologies, especially the VSC HVDC, interest in multiterminal HVDC (MTDC) or DC grids are growing. Increased penetration of renewable energy resources has also driven the research and development of MTDC technologies. For example, with a MTDC system or a DC grid, wind energy from several distributed offshore wind farms can be transferred to multiple onshore AC grids, offering better transmission flexibility. In comparison, if relying on only point-to-point HVDC, each wind farm will need to have a separate HVDC link connected to an onshore AC grid. Compared with the point-to-point HVDC links, the MTDC offers the following merits [94]:

- Lower costs: When more than two adjacent AC systems need to be connected, MTDC provides a more economical solution than employing several point-to-point HVDC links.
- Improved reliability: The faults on a point-to-point HVDC link can lead to significant power transfer interruption and the whole system may need to be shut down. For a MTDC network, the faulted link can be isolated by DC breakers and continuous power transfer is possible through power flow rearrangement.
- Reduced curtailment from renewable energy sources: If a renewable energy source, such as an offshore wind farm is connected to an AC grid through a point-to-point HVDC link, energy curtailment may be necessary to follow the load profile of the corresponding AC system. With MTDC, the surplus renewable energy can be better exchanged among different AC area systems.
- Low spinning reserve requirement: Connected with multiple renewable energy sources and AC grids through MTDC, the spinning reserve requirement for AC systems can be reduced.
- High power exchange and trading flexibility: Energy exchange and trading can be realized among multiple renewable energy sources and the AC grids they are connected to, which will help to reduce the electricity price.

A MTDC system has more than two converter stations, which can be connected either in series or in parallel [95]. As shown in Figure 1.47a, in the series structure of a MTDC network (assuming four terminals), the converters are connected to form a voltage loop, and identical DC current will flow through each converter. The system is grounded at only one point, and the insulation levels for different converter stations are distinct, making insulation coordination complicated and challenging. Moreover, it is very difficult to expand an existing series-connected MTDC system because of the varied insulation levels. Furthermore, the entire MTDC needs to be shut down when a DC fault occurs.

In contrast, the converters in a parallel MTDC system have identical voltage ratings, while their current ratings can be different based on the power needs. The parallel structure can have either radial or meshed connection, as illustrated in Figure 1.47b and c, respectively. In a radial system, disconnection of one line or converter will interrupt power flow to at least part of the grid. This type of segment

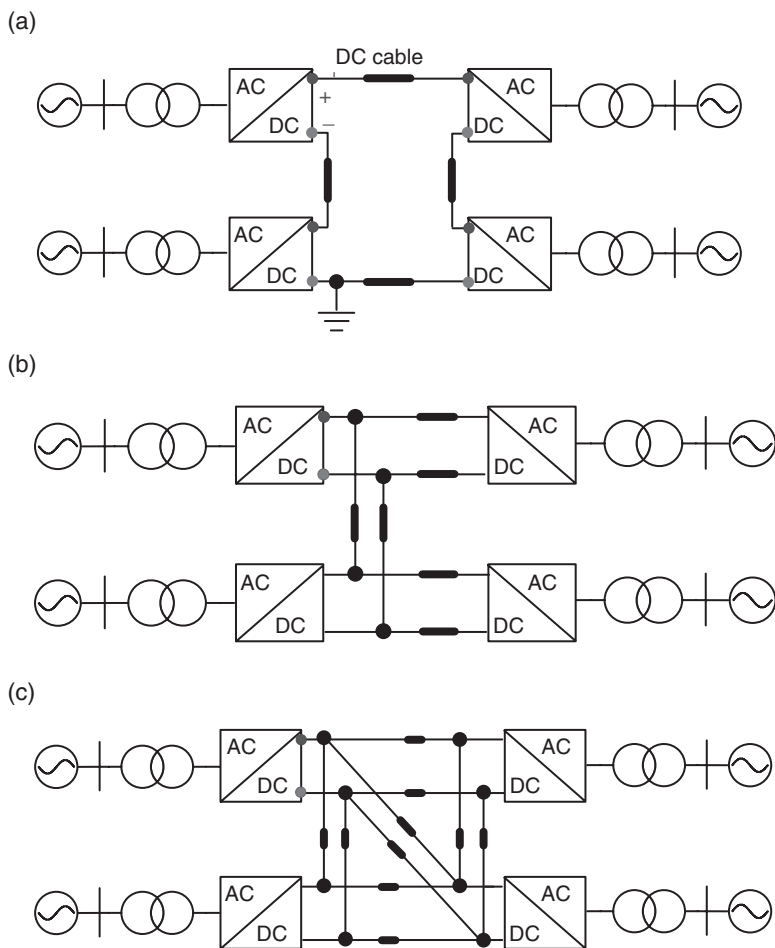


Figure 1.47 A MTDC network with (a) series connection, (b) radial connection, and (c) meshed connection.

removal, however, will not cause power transfer disruption in a meshed MTDC grid, if lines, cables and converters have enough capacity. Consequently, meshed MTDC provides higher reliability and control flexibility. Compared with the series structures, the parallel structure also enables reduced control complexity and easier expansion.

Hybrid connection structures have also been proposed, where several HVDC converters with relatively lower voltage ratings are first connected in series to form a string, and then the whole string can be connected to the full voltage MTDC grid with multiple paralleled strings. The scheme may be advantageous in applications like wind farms, similar to string inverters in photovoltaic cases.

For series connections, the CSC topology is easier to implement. The DC currents in all converters will be the same and the power control can be realized through individual converter DC voltage controls. The power reversal can be realized through voltage polarity reversal. For parallel connections, the VSC topology is much easier to implement. The DC voltages for all converters will be at the same level, with differences only accounting for the small voltage drops due to line resistances. The power control can be realized through individual converter current control and the power reversal can be conveniently achieved through current polarity reversal.

The advantages of a MTDC grid cannot be fully realized without DC breakers or equivalent DC fault current prevention/protection equipment. At present, cost-effective and fast HVDC breakers are not yet available. Consequently, there have been very limited commercial MTDC projects. Table 1.8 lists all existing MTDC projects in the world [96]. The first two started from point-to-point links and then extended to multiterminal schemes using LCC. The second pair were built more recently as pilot projects, and adopted half-bridge MMC as their converters. All four projects employed parallel connection. China is also planning to build the first meshed MTDC project, called the Zhangbei Project, in northern China.

Supergrid

The concept of the “supergrid” was first proposed in Europe as a continent-wide solution to transfer renewable energy from remote resource locations to load centers. Some of the more abundant renewable energy resources in Europe include offshore wind in the North Sea and the Baltic Sea, solar energy around the Mediterranean Sea, and hydropower in Scandinavia and the Alps [97]. Since the existing HVAC transmission grids were not designed for high power transfer from remote regions, new transmission capabilities are needed. As these transmissions will involve long distances and offshore locations, HVDC can provide a more economical solution. In particular, MTDC grids should be employed to deal with the distributed resources and multiple connection points to existing AC grids. Another motivation for supergrid is the wide-area energy balance to counter the intermittency of the wind and solar energy [98].

A precise definition of “supergrid” does not yet exist. It is generally understood as an “overlay” or assimilation of HVDC and HVAC networks. Tying with the existing grids, the supergrid connects and serves entire regions and markets, with the objective of integrating large-scale renewable energy sources into the grid [99]. The supergrid can hence be characterized by:

- high flexibility in power balancing of the whole system;
- bulk power transfer capacity;
- geographically long distances between energy sources and load centers.

Employing HVAC, HVDC and FACTS, the supergrid can increase transmission capacity. The overall system reliability, efficiency and economics can be improved

TABLE 1.8 Global MTDC projects.

Project	Commissioning year	Location	Terminal no.	Power transmitted	DC voltage (kV)	Topology
Italy–Corsica–Sardinia (SACOI)	Phase I: 1967	Phase I: Sardinia, Italy	3	Dalmazio: 300MW	200kV	LCC
	Phase II: 1988	Phase II: Corsica		Codranganos: 300MW		
Hydro-Quebec-New England	Phase I: 1986	Canada, USA	5	Lucciana: 50 MW	450kV	LCC
	Phase II: 1992			Radisson: 2250MW Nicolet: 2138MW Des Cantons: 690MW Comerford: 690MW Sandy pond: 1800MW		
Nan'ao	2013	China	3	JN: 100MW QA: 50 MW SC: 200MW	±160 kV	Half-bridge MMC
Zhoushan	2014	China	5	ZhouShan: 400MW Daishan: 300MW Qushan: 100MW Yangshan: 100MW Sijiao: 100 MW	±200 kV	Half-bridge MMC



Figure 1.48 A conceptual plan of a European supergrid [100]. (See electronic version for color representation of this figure.)

by pooling the resources of all participating parties (countries, utilities, etc.). The potential issues caused by large-scale renewable energy fluctuation can be greatly reduced or even eliminated with wide-area coordination.

Figure 1.48 represents the conceptual supergrid in Europe [100]. This huge supergrid will link large-scale offshore wind farms from the Baltic Sea to the Mediterranean, via the North Sea and the Atlantic. Energy from wind turbines will be transferred and distributed among countries, driving a single energy market in Europe. Some initial planning has already been developed for this European supergrid, in parallel with an ambitious plan to entirely phase out coal-based and nuclear power, and replace them with renewable energy by 2050 [101]. The Phase I plan requires that, by 2020, the remote bulk offshore wind plants be developed and linked together to form a meshed DC grid for high reliability and control flexibility. Meanwhile, coal and nuclear power plants can be phased out. Power flow control will be implemented over the whole of Europe to balance power generation and demands from the large populated load centers. Phase II will be from 2020 to 2050, when a Europe-wide overlay grid can be achieved through system integration. Based on DC transmission, this supergrid will link large-scale wind farms as well as pumped hydro-storage in the north, and bulk solar power plants in the south, then together supplying power for the European load centers. A transcontinental power

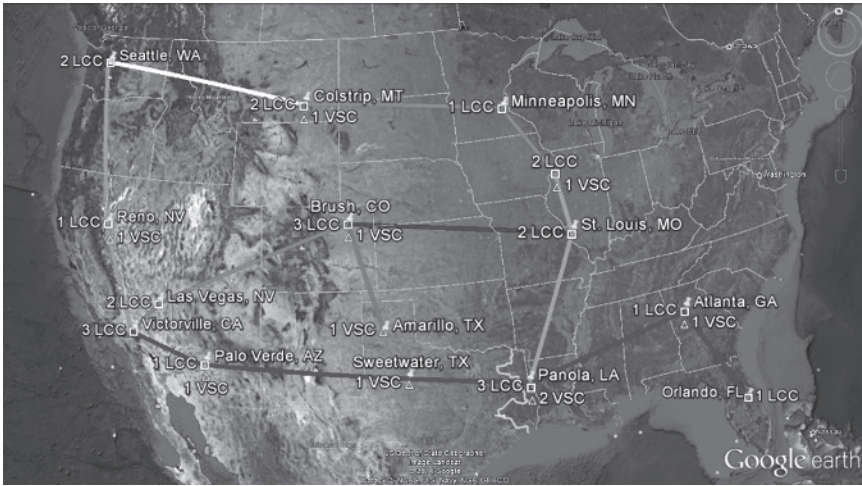


Figure 1.49 A conceptual US HVDC supergrid by MISO [106]. (See electronic version for color representation of this figure.)

transmission system is also under consideration, which can use power from solar power plants in the deserts of northern Africa.

Since the supergrid concept was proposed, several European countries have already met their 2020 renewable energy penetration targets. Overall, the share of renewables in gross final energy consumption in Europe in 2013 reached 15%, and the target set for 2020 is 20%, which is very much achievable [102]. On the other hand, the offshore wind farms grew slower than planned, due to higher costs than expected.

Similar supergrid concepts have also been proposed for Asia-Pacific and the Americas. One scheme envisions a pan-Asia-Pacific supergrid based on ultra-high-voltage (± 800 kV or higher) DC transmission grids, connecting wind farms in Siberia, Mongolia, and offshore Australia, and solar power in China and Australian deserts [103, 104]. The total power could supply the electricity needs of the whole region. In the United States, the continent-wide DC overlay has been preliminarily investigated, with one example shown in Figure 1.49, which connects all three North American Interconnections with HVDC lines.

The implementation of the supergrid, however, will face numerous challenges [105]. Technically, since it relies on DC grids, it has to overcome the same barriers that the MTDC grid faces, such as the lack of cost-effective and fast DC circuit breakers. In addition, coordinated wide-area control involving several system operators will require new methods, rules, and standards to ensure system reliability. Also, the societal acceptance of large grid infrastructures will be low, and the economic and environmental benefits of such an overlay grid must be clearly established to gain public support. Furthermore, a supergrid may suffer quite difficult decision-making processes in order to satisfy all parties involved.

1.6.4 Power Electronics for Distribution Grids

Due to the rapid growth of DERs, power electronics loads, and microgrids, distribution grids are the new frontier for power electronics applications for grids. This subsection will highlight some of the power electronics technologies for distribution grids.

Custom Power

Parallel to FACTS technology for transmission grids, Custom Power has been proposed and developed for the distribution grid. Custom Power can be classified into three broad categories:

1. Power flow control and interruption includes solid-state transfer switch (SSTS), solid-state circuit breaker (SSCB), and solid-state fault current limiter (SSFCL).
2. Power system conditioning and compensation includes distribution static synchronous compensator (DSTATCOM), static VAR compensator (SVC), dynamic voltage restorer (DVR), thyristor-controlled voltage regulator (TCVR).
3. Power quality enhancement equipment includes shunt active power filter (APF), and unified power quality controller (UPQC).

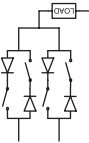
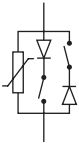
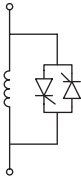
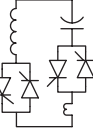
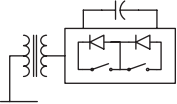
Table 1.9 shows the corresponding circuit configurations for the above-listed controllers, with their main functions, control principles and basic power electronics functions. Note the similarities between some of the Custom Power devices and the FACTS devices.

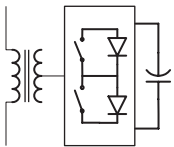
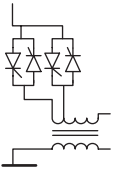
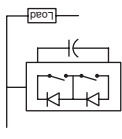
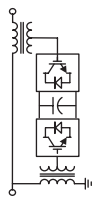
Microgrids

The US Department of Energy (DOE) describes a microgrid as “... a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.” Microgrids (MGs) are expected to enable grid modernization; enhance integration of distributed energy resource (DER); provide efficient, low-cost, clean power; reduce peak loads; promote customer participation; and significantly improve reliability and resiliency of the power grid, especially during major outages [107].

Figure 1.50 illustrates a conceptual diagram of the microgrid design being developed at University of Tennessee, Knoxville. It shows the microgrid connecting to the grid through multiple points of common coupling (PCC) – one feeder serving as a primary PCC and two backups. The diagram also illustrates the concept of a central microgrid controller interfacing directly with the utility distribution management system and, through local controllers, the distributed generation and loads at the site. During an outage, the microgrid will first choose a healthy feeder to connect to, if any. With the microgrid, it is expected that the outage time of

TABLE 1.9 Common Custom Power equipment.

Controller	One-line configuration	System functions	Control principle	Basic power electronics function
SSTS – solid-state transfer switch		• Power supply transfer for reliability and power quality • Power flow control	On–off control of thyristors	Controlled bi-directional AC switch
SSCB – solid-state circuit breaker		• Protection • Power flow control	On–off control of thyristors	Controlled bi-directional AC switch
SSFCL – solid-state fault current limiter		• Protection • Stability enhancement	Phase angle control of thyristors	Controlled bi-directional AC switch
SVC – static VAR compensator		• Voltage regulation and VAR compensation	VAR control through varying L & C in shunt connection	Controlled bi-directional AC switch
DSTATCOM – Distribution static synchronous compensator		• Power enhancement • Voltage regulation and VAR compensation	VAR control through current control in shunt connection	Bi-directional AC/DC voltage source converter

DVR – dynamic voltage restorer		• Power quality and stability enhancement • Power flow control • Fault current limiting	VAR control through voltage control in series connection	Bi-directional AC/DC voltage source converter
TCVR – thyristor controlled voltage regulator		• Voltage control • Motor starter	Voltage control through on–off thyristor control, like electronic tap changer for transformer	Controlled bi-directional AC switch
Shunt AF – shunt connected active filter		• Harmonic current filtering	Harmonic current injection through harmonic voltage control	Bi-directional AC/DC voltage source converter
UPQC – unified power quality controller		• Power flow control • Power quality enhancement • Fault current limiting	Power and VAR control through back-to-back converters in both series and shunt connections	Bi-directional AC/DC voltage source converter

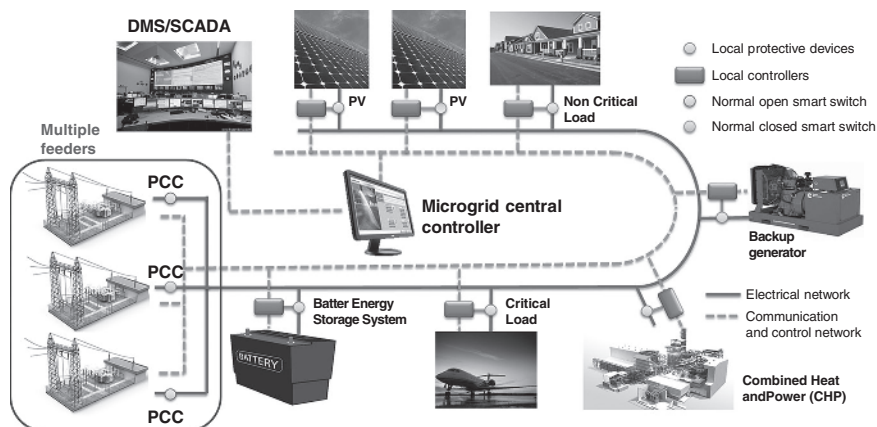


Figure 1.50 A conceptual microgrid and its controller. (See electronic version for color representation of this figure.)

critical loads will be reduced by >98% at a cost comparable to non-integrated baseline solutions (uninterruptible power supply plus backup generator); emissions will be reduced by >20%; and the energy use efficiencies will be improved by >20%. It can clearly be seen that power electronics interface converters are present for PV and battery energy storage systems. These power converters need to operate with different grid support modes during the grid-connected and islanded modes.

More Recent Developments

There are many newly emerging power electronics controllers under development to solve various issues with distribution grids. SST, mentioned earlier, is a well-known equipment that can help with distribution grid power flow and voltage regulation. There are also a number of so-called grid-edge solutions using power electronics to deal with voltage and other issues associated with roof-top PV and other DERs.

1.7 SUMMARY AND FUTURE TRENDS

The chapter discusses briefly and comprehensively the basics of energy, environment, power electronics, renewable energy systems, and smart grids. The important points are summarized here:

1. The energy and environmental issues are extremely important today. The rising global population with an appetite for higher living standards is causing increasing energy consumption. Most of our energy comes from burning fossil fuels, which causes environmental pollution, and correspondingly climate change problems. These will cause serious unrest in our society. With

determination and the united efforts of humanity, we can solve these problems. Energy and environmental issues are the main motivating factors for modern R&D on smart grid and renewable energy systems, where power electronics plays a very important role.

2. Power semiconductors have been the main driving force for power electronics technologies. So far, Si has dominated power electronics converters, with devices like thyristors and IGBT. WBG SiC- and GaN-based devices are the future, with their superior characteristics with lower losses, higher voltage, higher switching speed and capability, and higher temperature capability. Other attributes of the power electronics converters like passives, thermal management systems, control, and filters are also important to the overall performance and cost of the converter.
3. Grid-related power electronics can be classified as related to source, loads, and transmission and distribution. The grid becomes increasingly power electronics-based due to the rapid growth of power electronics-interfaced sources and loads. The key power electronics loads in today's and future grids include: motor drives, lighting (fluorescent, HID, and LED lamps), EV charging stations, and data centers.
4. Renewable energy systems, mainly wind and PV solar systems, require power electronics interfaces. The most promising energy storage systems, battery energy storage systems, also require power electronics interfaces to deal with the variability of the renewable energy sources. The key development needs for these power converters are grid-support functions traditionally performed by rotating generators. They also need to tolerate grid conditions such as fault, imbalance, and transient overvoltages.
5. Smart grids require more controllability and better power quality, two areas with which power electronics can help. Power electronics-based grid controllers include more conventional FACTS and HVDC for transmission, and Custom Power for distribution. Most of these technologies are thyristor-based. Newer IGBT-based and future WBG device-based converters will enable new technologies such as SST and DC grid.

Power electronics have progressed steadily since the invention of thyristors in the 1950s. The progress is in all aspects: semiconductor devices, passives, circuits, control, and system integration, leading to converter systems with better performance, higher efficiency, higher power density, greater reliability, and lower cost. Because of these developments, the power electronics applications in power systems have become more and more widespread. However, in general, power electronics controllers are still not sufficiently cost-effective, reliable, or efficient. Many improvements are needed and expected, especially in the following areas:

- *Semiconductor devices.* Devices used today are almost exclusively based on silicon. The emerging devices based on wide bandgap materials such as SiC

and GaN are expected to revolutionize power electronics with their capabilities of higher voltage, lower losses, faster switching speed, higher temperature, and smaller size.

- *Power electronics converters.* More cost-effective and reliable converters will be developed as a result of better devices, passive components and circuit structures. Modular, distributed, and hybrid with non-power-electronics approaches are expected to result in greater benefits overall.
- *Enhanced functions.* Power electronics controllers can be designed to have multiple functions in the system. For example, wind and PV solar inverters can provide reactive power to the grid, in addition to transferring real energy. Today, power electronics controllers are mostly locally controlled. With better measurement and communication technologies, they may be controlled over a wide area for supporting the system-level functions.
- *New applications.* The new applications for future power systems include a DC grid based on multiterminal HVDC and energy storage. Critical technologies include cost-effective and efficient DC transformers and DC circuit breakers. Power electronics will play key roles in these technologies.

ACKNOWLEDGMENTS

This work (except the Energy and Environment sections) made use of the Engineering Research Center Shared Facilities supported by the Engineering Research Center Program of the National Science Foundation and DOE under NSF Award Number EEC-1041877, and the CURENT Industry Partnership Program. The authors would like to acknowledge the help and contribution of current and former CURENT students Shuoting Zhang, Zheyu Zhang, Yalong Li, and Xiaojie Shi.

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