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Introduction

Power electronic converters are used in myriad applications. Some of these are adjustable speed motor drive systems, high-voltage direct current (HVDC) power transmission, flexible alternating current transmission systems (FACTS), power conditioning custom power devices, and microgrids. Several power electronic installations use traditional thyristor-based naturally commutated power converters, which have been in use for over half a century. However, with the advent of high-power insulated-gate bipolar transistors (IGBTs), voltage source converters (VSCs) have become increasingly popular in almost all the applications mentioned above.

With the present-day concerns about climate change and its effects on the well-being of all living creatures of our planet, an increased amount of renewable energy sources has been integrated with modern power systems. Traditionally, power is generated through large turbo alternators that are rotated at a fixed speed. Note that the system frequency is directly related to the generator speed ($n = 120\,f/P$, n is the generator speed in rpm, f is the frequency in Hz, and P is the number of poles). Usually, these turbogenerators have large inertia that help in maintaining synchronism during faults or transient disturbances. Renewable generators, on the other hand, provide low inertia and are often integrated through power electronic converters and therefore cannot maintain system frequency. Special control strategies are therefore adopted for the integration of renewable generators.

Renewable energy, as the name signifies, is a form of energy that is replenished constantly. For example, our sun is an abundant source of energy, and it shines throughout the year in all parts of the world. Similarly, wind blows all the time, while its speed depends on the time of day and the terrain. These two are the most prominent types of renewable energy that are used for electricity generation. An excellent resource for renewable energy is the book by Masters [1].

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The other forms of renewable energy sources are water (e.g. hydro, wave, and tidal), geothermal, etc. Out of these, hydro and geothermal plants are location dependent. Hydropower is the production of electrical power using the gravitational force of falling or flowing water, where electricity is produced by placing a turbine generator in the path of the flowing water. For this, catchment areas, water heights, and a continuous flow of water are required. Usually, hydro plants are placed in mountainous terrains. Hydropower is the most common form of renewable energy, which accounts for about 16% of the world's electricity generation. The total installed capacity of hydropower in 2020 is 1330 GW [2].

A powerful form of natural energy is generated by the gravitation of the moon and the sun, which causes low and high tides almost twice per day. The movement of the rising and falling sea level alters the potential energy of water that can be converted into electricity by the operation of a power plant. To use this energy, a dam wall is created to enclose a certain amount of seawater in an artificial bay serving the purpose of a reservoir, just like a hydropower plant. When the tide rises, the water enters the reservoir through a turbine which produces electric energy until the seawater inside the reservoir is almost as high as the outside water level. At low tide, the reverse process occurs and the water inside the reservoir exits into the sea through the turbine. Note that these two separate processes are not continuous as there is a pause of about two hours between these two. The tidal power has tremendous potential; however, it is still in the experimental stage of development due to the excessive cost involved. Other forms of waterpower that are also in the experimental stage are ocean current and wave power plants.

Geothermal energy comes from the core of our earth. The center of the earth is 6400 km below the surface. Since the temperature there is about 4200 °C, it is hot enough to melt rock into magma. The molten rock forms the outer core. The heat from the core rises to the earth's mantle, which is the layer that surrounds the core. It is this energy that powers volcanoes, geysers, and hot springs. In a geothermal plant, water is pumped into the earth's mantle and the resultant steam that rises is used for electricity generation using steam turbines. Geothermal plants, however, have a finite lifetime. The energy production ceases when the mantle at the location of the plant cools down due to the continuous extraction of heat energy.

There are two possible ways of generating solar power: through photovoltaic (PV) array and through concentrated solar power (CSP), which is also known as solar thermal power. In CSP, power is generated using mirrors and lenses to concentrate sunlight over a large area onto a receiver. The concentrated light then produces heat energy, which drives steam turbines to produce electricity using thermal generators. It is to be noted that water is not the only source that can be used for heat extraction from CSP: molten nitrite salt and hydrides are also considered for their higher heat retention properties. Spain is the leading country in CSP installation, followed by the United States.

Most of the technologies mentioned above use rotary generators to produce energy without any requirement of power electronic converters. This, however, is not the case for solar PV and wind generators as they require power electronic converters. A PV array produces power at DC voltage, which is then boosted through a DC-DC converter. The DC-DC converter is also often used for maximum power point tracking. The DC-DC converter output is converted into AC through a VSC for grid connection.

There are several types of wind turbines. These are [3]:

- Type 1: Fixed speed in which a squirrel-cage, self-excited induction generator is directly connected to the grid through a transformer. The turbine speed is synchronized with the grid frequency and is therefore (nearly) fixed.
- Type 2: Limited variable speed in which a wound rotor induction generator is connected directly to the grid through a transformer. The generator contains a variable resistor in the rotor circuit, which can control the rotor current quickly to keep the power constant, even during grid or wind disturbance.
- Type 3: Variable speed with partial power electronic conversion using doubly fed induction generator (DFIG). In this, there are a pair of VSCs that are connected back-to-back on the DC side through a capacitor. The grid side converter exchanges power with the grid and holds the DC bus voltage, while the rotor side converter can almost instantaneously control the magnitude and angle of rotor current. The major advantage of the DFIG is that it can bring about a large control of power in the stator circuit while using converters that have a much smaller rating than the machine.
- Type 4: Variable speed with full power electronic conversion in which a permanent magnet synchronous generator is connected to the grid through full-rated back-to-back converters. The turbine, in this case, is allowed to rotate at its optimal aerodynamic speed harnessing maximum power. Also, the need of a bulky gearbox is eliminated since the machine speed is separated from the grid frequency. The turbine side converter converts the generator voltage into DC and the grid side inverter injects power to the grid at rated or prevailing grid frequency.

Recently, several offshore windfarms have been installed. The power from these plants is supplied to the mainland through either submarine DC cables at high voltage or through multiterminal HVDC systems. All of these employ VSCs for power conversion.

There are several smaller generators that are deployed in power distribution systems, though not all of them necessarily use renewable energy. The most prevalent among these are the rooftop solar PV systems, which generate power with an output DC voltage level. These are then converted into AC through DC-AC power converters. There are others such as wind, fuel cells, and microturbines that use power electronic converters. Collectively these generators are called distributed generators (or DGs) because they are distributed throughout power distributions systems and are placed close to where the energy is consumed. Many of the renewable sources (e.g. solar and wind), however, are intermittent in nature. Therefore, storage systems are required to maintain continuity of the power flow. The DGs, together with the energy storage systems, are usually called distributed energy resources (or DERs). The most common energy storage such as battery energy storage systems (BESS) require power converters for converting DC voltage into AC.

From the above discussion, it is evident that power electronic converters play a very crucial role in the modern-day operation of power systems. Therefore, the control of these converters is also very crucial for the smooth and stable operation of power systems. Section 1.1 presents a brief introduction to power electronics.

1.1 Introduction to Power Electronics

Power electronics essentially is power processing. It is the application of electronics, control, and signal processing to adjust, regulate, or control electrical energy. Power electronics consists of power and electronic circuitry. In the power circuitry, DC or AC energy sources are converted to regulate or adjust voltage or current waveforms in the form of DC or AC with specific amplitude or frequency suitable for different applications. Figure 1.1 shows a schematic diagram of a power electronics system, which consists of an input source, a power converter, a load, and a controller.

The input source can be DC (e.g. BESS, solar PV, fuel cell, etc.) or an AC (e.g. grid, wind turbine, etc.). In some applications, the DC source can be in the form of

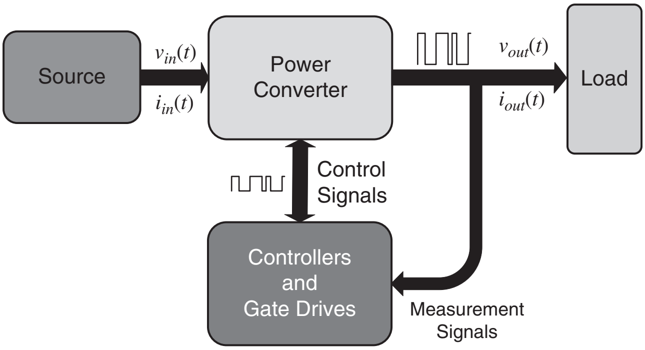


Figure 1.1 Schematic diagram of a power electronic circuit.

capacitors that can store energy. Furthermore, in an AC system, the input can be single- or three-phase. The loads can be either AC or DC. They can operate at either high or low voltage, where the frequency can be variable in the case of AC applications. For example, in home applications, power electronics is used in battery chargers (cell phones, laptops/desktops), electric motors, and induction cooking devices among others.

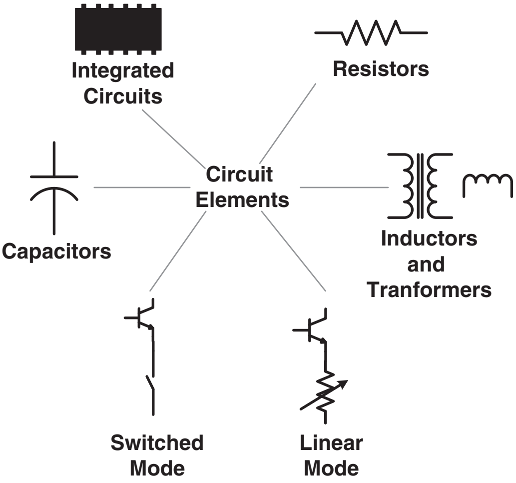
The power converter consists of semiconductor switching devices and passive elements, such as magnetic devices and capacitors. The semiconductor switching devices, such as MOSFETs (metal oxide silicon field effect transistor) or IGBTs, can operate at high voltage and current ratings that are suitable for different applications.

The controller unit consists of (i) measuring devices including input and output voltage and current signals to monitor and protect the system, (ii) a microcontroller with signal processing capability, and (iii) digital and analog electronic circuits. The controller synthesizes signals in the form of pulses suitable for the power converter to convert the input energy suitable for a load. The interface between the controller and the power converter is through gate drives, which take the control signals based on a pulse pattern and turn the semiconductor switches on and off at high voltage and current amplitudes.

Overall, the main aim of modern power electronic systems is to convert and deliver input power with maximum efficiency, high quality, minimum cost, and weight, in an integrated and high-power density circuit.

The main components used in the controller and the gate drive units are shown in Figure 1.2. As the voltage and current ratings of the controller and gate drives

Figure 1.2 The main active and passive components used in controllers and gate drive units.



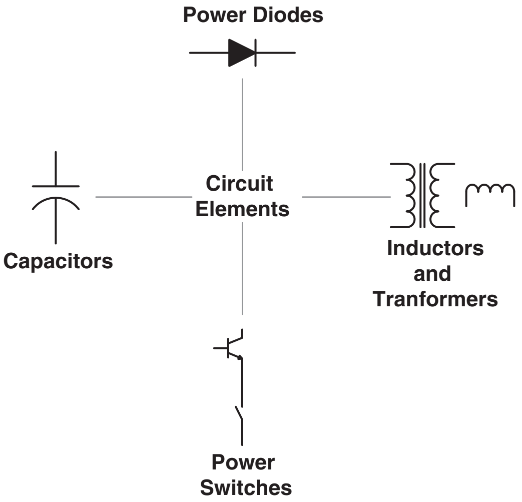


Figure 1.3 The main active and passive components used in power converters.

are very low compared to the power converters, resistors, and operational amplifiers (OPAMPS), linear mode switches are used in these units without any loss due to their high efficiency. On the other hand, their circuitry and design are very complex as the total power electronics system needs to be monitored and controlled through these units.

The power converter consists of four main components, as shown in Figure 1.3. Resistors and power switches in linear mode are not used in the power converters, because they incur significant losses when currents pass through these components. The energy conversion is usually based on a pulse width modulation (PWM) method where a desired signal is generated by pulse patterns at higher frequencies. The switching devices chop the input voltage or current (at high voltage and/or current rating) based on the control signals synthesized by the controller. Thus, the major issues of the power electronics system are (i) the generation harmonics and high-frequency noises which should be controlled and mitigated using filters and (ii) conduction and switching losses.

Figure 1.4 shows four different configurations of power converters that can convert energy from DC or AC sources to adjustable and regulated DC or AC current or voltage waveforms suitable for different loads. Figure 1.4a shows a DC-DC converter that has an input DC voltage source (e.g. battery or PV). The output voltage can be adjusted (increased or decreased) during the operation, as in a DC motor control or regulated power supplies. In Figure 1.4b, the energy from an AC source (fixed or variable amplitude or frequency), can be changed into an AC signal with adjustable amplitude and frequency, as in variable speed motor drive systems, or with regulated amplitude and frequency, as in grid-connected renewable energy

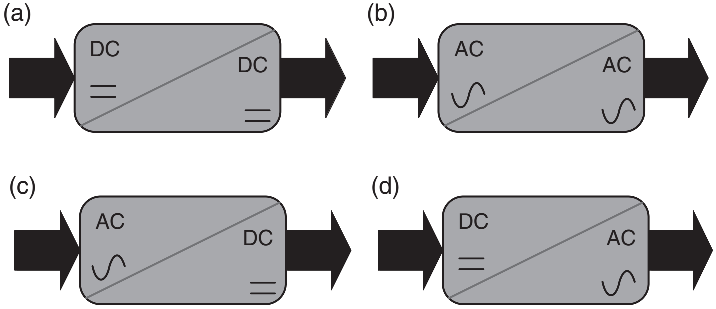


Figure 1.4 Four different configurations of power converters: (a) DC-DC, (b) AC-AC, (c) AC-DC, and (d) DC-AC.

systems. Figure 1.4c shows a power converter can transfer the energy from an AC source (e.g. grid or wind generator) to an adjustable or regulated DC signal (e.g. DC grids, power supply). The input source can be either a single-phase or a three-phase for low- or high-power applications. In the last configuration, shown in Figure 1.4d, a DC source is connected to a power converter and the output AC signal amplitude and frequency can be adjustable (e.g. induction heating and welding) or regulated (e.g. uninterruptable power supply or controllable AC sources).

1.2 Power Converter Modes of Operation

While designing a power converter, its modes of operation should be determined according to the system operation and the load characteristics. The instantaneous values of the load current $i_{out}(t)$ and voltage $v_{out}(t)$ can either be positive or negative in amplitude. These values represent four modes of operation for the power converter, as shown in Figure 1.5. The converter topology will be different when it

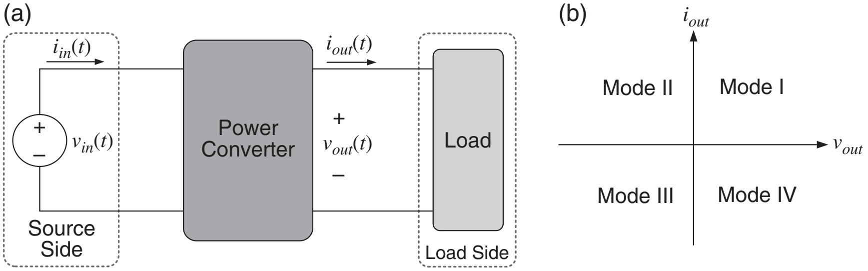


Figure 1.5 (a) Power converter supplying a load and (b) four quadrants of operation.

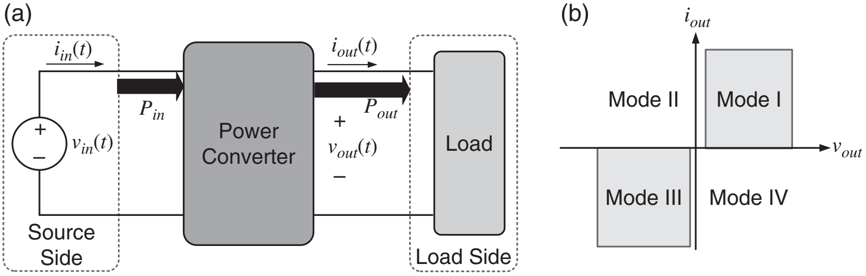


Figure 1.6 (a) Power converter in unidirectional power flow and (b) two modes of operation.

operates in one, two, or four quadrants. These conditions and operating modes are explained in this section.

Figure 1.6 shows a power converter with a unidirectional power flow in which the power is controlled and processed from the input side and transferred to the output side. The converter may operate either in quadrant I (when both voltage and current values are positive) or in quadrant III (when both voltage and current values are negative), or both these quadrants.

A power converter with a bidirectional power flow can operate in four different quadrants and the power can be transferred from the source to the load (consumption) or from the load to the source (regeneration). The converter may operate in any quadrant, based on the instantaneous voltage and current values and the load operating modes, as shown in Figure 1.7. The operating modes of a power converter with different topologies and semiconductor switches (type and configuration) will be explained in the following section.

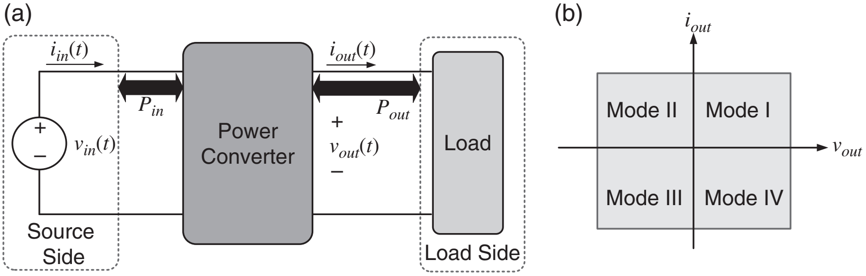


Figure 1.7 (a) Power converter in bidirectional power flow and (b) four modes of operation.

1.3 Power Converter Topologies

Several different topologies are utilized in energy conversion systems. The most common systems are shown in Figure 1.8 and are classified as:

- Low-frequency (at grid frequency 50 or 60 Hz) power converters such as diode rectifiers or controlled rectifiers with slow power switches, such as diodes or silicon-controlled rectifiers (SCR). These converters rectify AC signals (single-phase or a three-phase) to a DC form. These are shown in Figure 1.8a–d.
- High-frequency (at a switching frequency in kHz range) power converters are based on fast semiconductor switching devices such as MOSFETs or IGBTs. These converters are controlled based on PWM signals (modulated signals) and are used in different DC-DC or DC-AC energy conversion systems. The size of passive components utilized in these converters can be reduced if the switching frequency of the PWM signal is increased. This is shown in Figure 1.8e.
- A cascaded topology is based on a combination of a few low- and high-frequency power converters. For example, in Figure 1.8f, two power converters are in

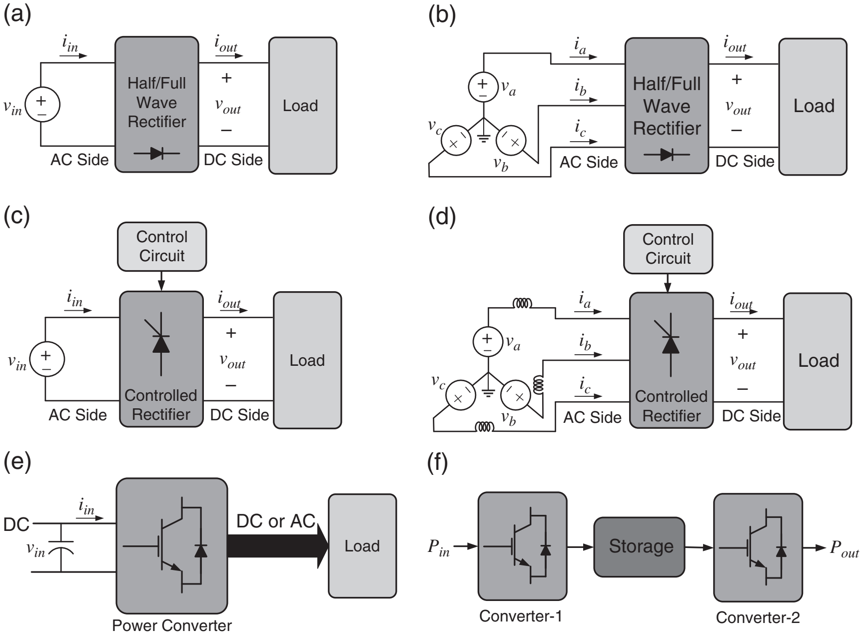


Figure 1.8 Power converter topologies: (a) and (b) low-frequency diode rectifiers, (c) and (d) lower frequency-controlled rectifier, (e) high frequency power converters, and (f) cascade power converter.

cascade with a storage element to convert an AC signal into a DC form and then the resulting DC signal back into an AC signal with adjusted or regulated amplitude and frequency. This is also called back-to-back (B2B) connection.

1.4 Harmonics and Filters

Harmonics and high-frequency noises are the two main aspects of power converters which have a negative impact on the quality and efficiency of the overall system. These phenomena are caused due to low- or high-frequency switching transients of the semiconductor switches in power converters. For example, to change a DC voltage to a desired level that is suitable for a load, a pulse train is applied to a DC-DC converter with a controlled duty cycle in such a way that the average voltage over each switching cycle can be controlled, as shown in Figure 1.9. The DC-DC converter is shown in Figure 1.9a. For the converter, the duty cycle is generated by comparing a reference signal (v_{ref}) with a sawtooth signal (v_{st}) and a gate signal is generated, as shown in Figure 1.9b. It is to be noted

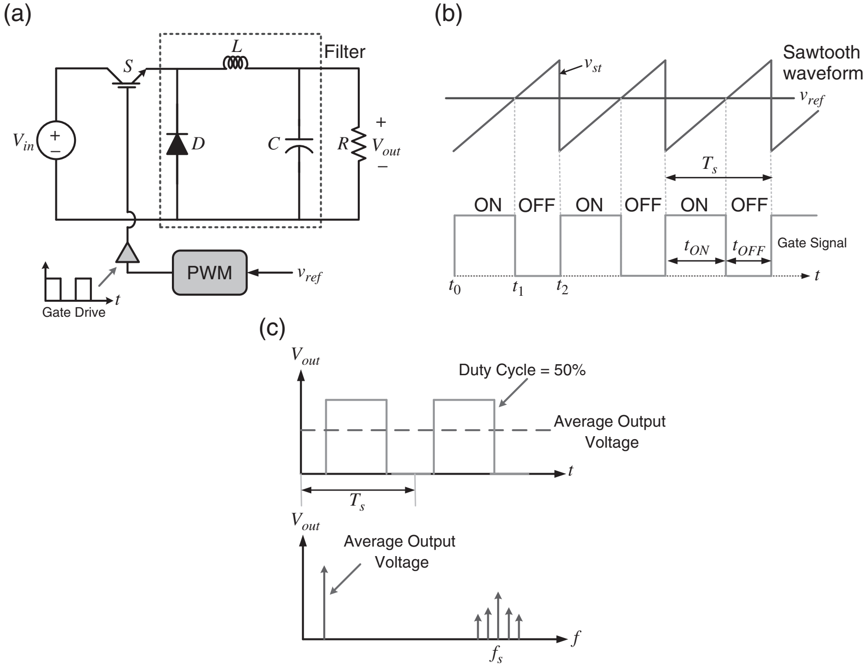


Figure 1.9 (a) A DC-DC converter, (b) its modulated signal, and (c) the output signal in time and frequency domain.

that the cycle time is $T_s = t_{ON} + t_{OFF}$. The switching frequency is $f_s = 1/T_s$, and the percentage duty cycle is defined as $d = (t_{ON}/T_s) \times 100\%$.

Let us assume that the duty cycle is controlled at 50% and the converter is designed such that the average value of the output voltage (V_{out}) for this duty ratio is 50% of the DC value (V_{in}). Although the pulse train is synthesized to control the average value of the output voltage, the proposed pulse waveform has harmonics, as shown in Figure 1.9c. This signal in time domain is not suitable for interfacing with electronic systems and the high-frequency harmonics should be filtered using an LC filter, as shown in Figure 1.9a.

Figure 1.10a shows a single-phase AC-DC converter where the input voltage is supplied from a low-voltage grid. The line current is not sinusoidal, and it is distorted due to the diode rectifier operation and its DC link filter (capacitor). The current harmonic amplitudes must be reduced according to international standardizations. There are several active or passive methods to mitigate current harmonics at the grid side.

Based on the above discussion, a general block diagram of a power electronics system is shown in Figure 1.11, where two filters – one at the grid side and the

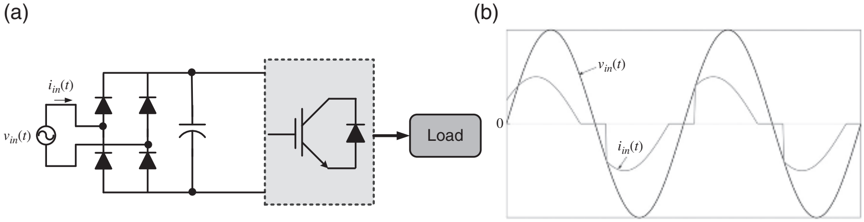


Figure 1.10 (a) A diode rectifier connected to a DC-AC converter and (b) voltage and current waveforms of the diode rectifier.

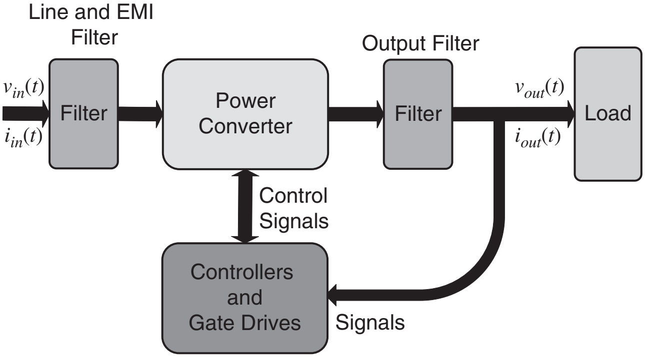


Figure 1.11 A general block diagram of a power electronic system with different filters.

other one at the load side – are utilized to mitigate low- and high-frequency harmonics. The grid side filter consists of two different types of filters: harmonics and electromagnetic interference (EMI) filters. A harmonic filter is designed to mitigate low-order harmonics below the order of 40th or 50th harmonics depending on standardization limits. The EMI filter is designed for high-frequency harmonics, mainly above 150 kHz to suppress conducted emission noise.

1.5 Power Converter Operating Conditions, Modelling, and Control

Power electronics systems are nonlinear as there are several semiconductor switching devices which are turned on and off thereby splitting a power converter circuitry into sub-circuitries. The system might have more subsystems when the inductor current is not continuous during the operation. Figure 1.12 shows all operating conditions of a DC-DC converter, which can operate in either a continuous conduction mode (CCM) or a discontinuous conduction mode (DCM). The steady state analysis is used to design a power converter under different load conditions. This includes the selection of passive and active elements, switching frequency, losses, and quality analysis. The system can be simplified when internal parasitic and stray components are neglected, including the voltage drops across the diodes or switches, the internal resistance of magnetic elements, or the stray inductance of the interconnections.

Dynamic behavior of a power converter takes place when a change occurs in the reference signal or input voltage or the load. This includes the startup condition when a power converter is turned on, as shown in Figure 1.13. In this case, the instantaneous value of the inductor current is increased from zero. The inductor current at the beginning and at the end of each switching cycle is not the same.

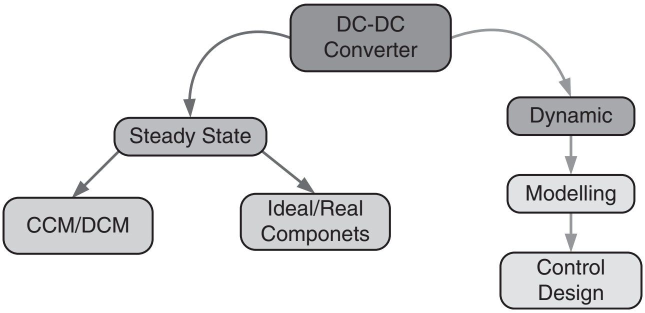


Figure 1.12 Operating conditions of DC-DC converters.

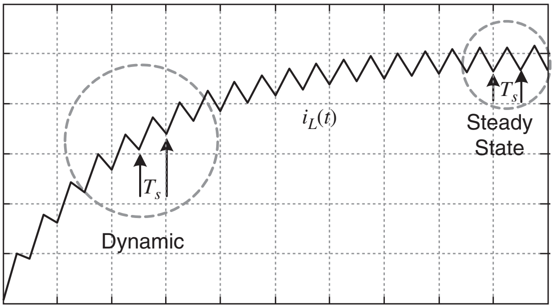


Figure 1.13 The time domain behavior of inductor current of a DC-DC converter.

However, when it reaches a steady state after several switching cycles, the inductor current at the beginning and the end of each switching cycle is the same. Thus, the dynamic behavior of a power converter, i.e. reaching the steady state value with minimum transient time, error, and overshoot, can be improved using a proper control system.

The general approach of designing a controller is to find the transfer function of a system. Most power electronics systems are nonlinear with discrete operating modes. For example, Figure 1.14a shows a buck or step-down DC-DC converter operating in CCM where the current through the inductor is always continuous. When the switch is turned "ON" or "OFF," the converter circuitry is changed into two different equivalent circuits, as shown in Figure 1.14b,c. As the power converter is switched on in the frequency range of kHz, it has different subsystems

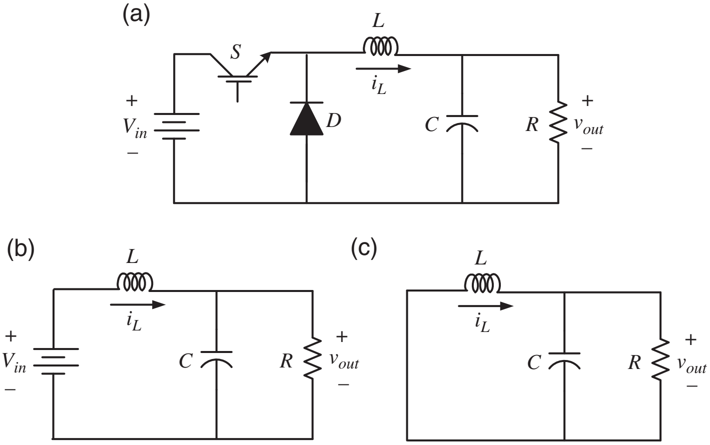


Figure 1.14 (a) A buck converter, (b) when the switch is turned ON, and (c) when the switch is turned OFF.

that cannot be modeled and analyzed based on conventional control theory. Thus, small signal modeling, averaging approach, and linearization techniques are required to model a power converter as a continuous system. In this book, different power converters based on the averaging method and stability analysis of power converters are studied at the device and system levels. Discrete modeling is a helpful step to recognize the delays in control.

1.6 Control of Power Electronic Systems

In this section, the concept of feedback control is briefly discussed and the application of control on a simple power electronic circuit introduced. Our discussion starts with the advantage of feedback control.

1.6.1 Open-loop Versus Closed-loop Control

Consider a first-order system given by the differential equation

$$\dot{y}(t) + \alpha y(t) = u(t) \tag{1.1}$$

where $y(t)$ is the output, $u(t)$ is the input, and α is a scalar. Assume that the system is at rest, i.e. $y(t)|_{t \leq 0} = 0$ and a control input $u(t) = K \times u_s$ is applied at time $t = 0$, where u_s is a unit step and K is a scalar constant. Then the system response will be given by

$$y(t) = \frac{K}{\alpha}(1 - e^{-\alpha t}), \quad t \geq 0 \tag{1.2}$$

If $\alpha > 0$, the exponential term will tend toward zero as $t \rightarrow \infty$. Therefore, the steady state value of $y(t)$ as $t \rightarrow \infty$ will be K/α. If, on the other hand, $\alpha < 0$, the output will tend toward infinity as time progresses, resulting in an unstable system. The schematic diagram of the open-loop system is shown in Figure 1.15a.

The main aim of a control system is to follow a reference input $y_r(t)$ asymptotically. To achieve this, a negative feedback of the output is used to form the control law as

$$u(t) = K\left\{y_{ref}(t) - y(t)\right\} = Ke(t) \tag{1.3}$$

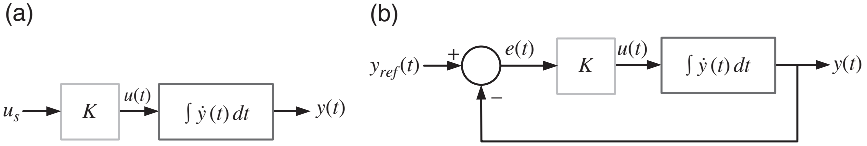


Figure 1.15 (a) Open-loop control system and (b) feedback control system.

where $e(t)$ is defined as the tracking error. Substituting (1.3) in (1.1) and assuming $u(t) = Ke(t)$, we have

$$\dot{y}(t) + (K + \alpha)y(t) = Ky_{ref}(t) \tag{1.4}$$

The closed-loop system is shown in Figure 1.15b. Let us assume that the reference input is a unit step. Then, the output is given by

$$y(t) = \frac{K}{K + \alpha}\left(1 - e^{-(K+\alpha)t}\right), \quad t \geq 0 \tag{1.5}$$

The closed-loop system will remain stable (bounded) so long as $K + \alpha > 0$. If $\alpha > 0$, then the system will be stable for positive values of K. On the other hand, if α is negative, K should be greater than $|\alpha|$. This is one of the advantages of the feedback control. Another important aspect of the feedback is reference tracking, where the output $y(t)$ needs to be close to the reference input $y_{ref}(t)$ in the steady state, which can only be achieved if the system is stable. In that case, the steady state tracking error is defined from (1.5) as

$$e_{ss}(t) = \{y_r(t) - y_r(t)\}|_{t\to\infty} = \frac{K}{K + \alpha} \tag{1.6}$$

The steady state error can be minimized by choosing a large value of K.

Figure 1.16 shows the behavior of the open- and closed-loop systems for $|\alpha| = 0.5$. For the open-loop system, it is assumed that $\alpha > 0$ and $K = 1$. This is shown in

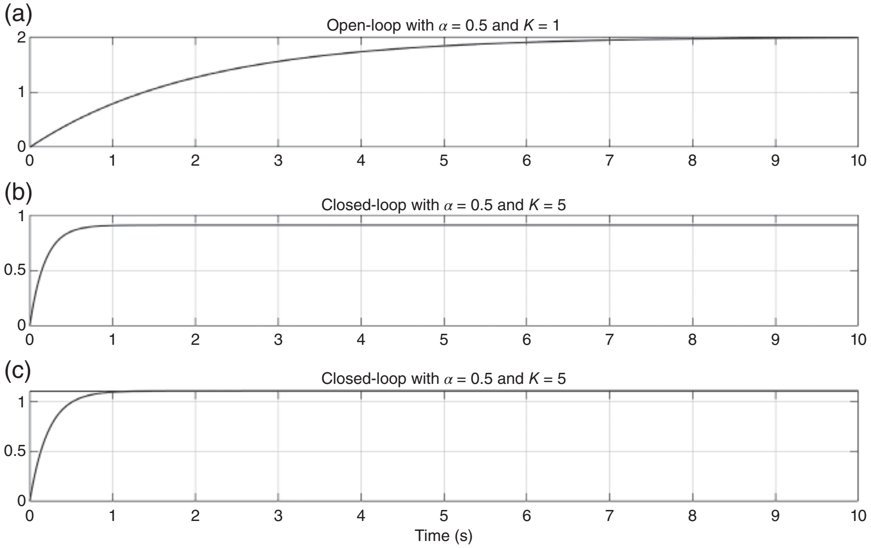


Figure 1.16 (a) Open-loop control system, feedback control system (b) with $\alpha > 0$ and (c) with $\alpha < 0$.

Figure 1.16a, where the output reaches its steady state value of 2. The closed-loop response for $\alpha > 0$ is shown in Figure 1.16b, while Figure 1.16c shows the closed-loop response for $\alpha < 0$. The value of the gain for both these cases is chosen as $K = 5$. Even though the open-loop system is unstable for $\alpha < 0$, the closed-loop system is stable in Figure 1.16c since $K + \alpha > 0$.

1.6.2 Nonlinear Systems

Consider the following system

$$\dot{y}(t) + \alpha y^2(t) = \sin(\theta) \tag{1.7}$$

This is obviously a nonlinear system. Even though there is a vast amount of literature dealing with the stability and control of nonlinear systems, usually linear controllers are designed by linearizing the system around an operating point. For linearization, Taylor series expansion is performed around an operating point, where the second- and the higher-order terms are neglected. This aspect is discussed later in the book. However, we present a simple method here.

Let us assume that the system operates under a steady state operating point of y_0 and θ_0 such that (1.7) can be written as

$$\dot{y}_0(t) + \alpha y_0^2(t) = \sin(\theta_0) \tag{1.8}$$

Let us also assume that the system is perturbed with small increments such that

$$y(t) = y_0(t) + \Delta y(t) \text{ and } \theta = \theta_0 + \Delta\theta$$

The substitution of the above two equations in (1.7) yields

$$\dot{y}_0(t) + \Delta\dot{y}(t) + \alpha\{y_0(t) + \Delta y(t)\}^2 = \sin(\theta_0 + \Delta\theta) \tag{1.9}$$

Since the increments $\Delta y(t)$ and $\Delta\theta$ are very small, the following assumptions can be made

$$\Delta y^2(t) \approx 0, \ \sin(\Delta\theta) = \Delta\theta, \text{ and } \cos(\Delta\theta) = 1$$

Substituting these in (1.9), we have

$$\dot{y}_0(t) + \Delta\dot{y}(t) + \alpha y_0^2(t) + 2\alpha y_0(t)\Delta y(t) = \sin(\theta_0) + \cos(\theta_0)\Delta\theta \tag{1.10}$$

The following linearized model is obtained by subtracting (1.8) from (1.10)

$$\Delta\dot{y}(t) + 2\alpha y_0(t)\Delta y(t) = \cos(\theta_0)\Delta\theta \tag{1.11}$$

To determine the steady state condition, the first step is to choose a value of θ_0. Once the system attains the steady state, the derivative of the output in (1.8) will be zero, i.e. $\dot{y}_0(t) = 0$, and therefore, the steady state of the output is obtained as $y_0 = \sqrt{\sin(\theta_0)/\alpha}$. For example, if $\alpha = 2$, then the steady state values for $\theta_0 = 10°$, $\theta_0 = 20°$, and $\theta_0 = 30°$ are 0.2947, 0.4135, and 0.5 respectively. Starting from

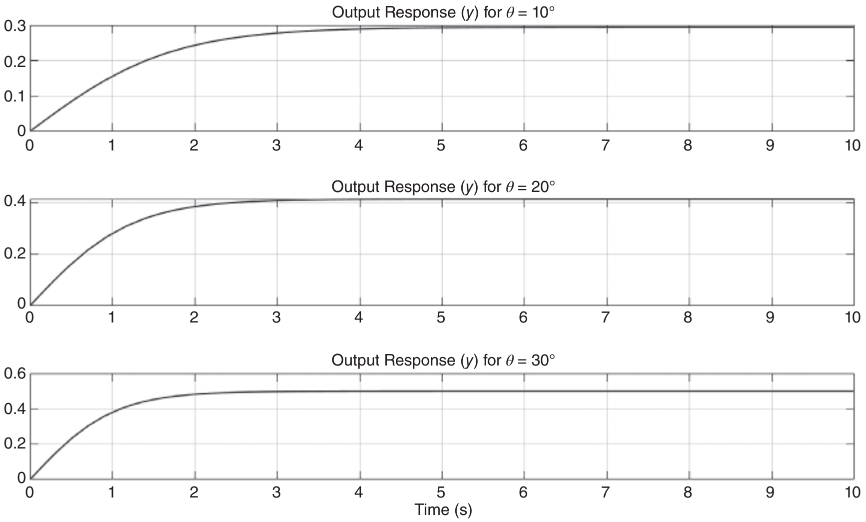


Figure 1.17 The response of the nonlinear system with three different values of θ_0.

$y(t)|_{t=0} = 0$, the response of the system with these values of θ_0 are shown in Figure 1.17. It can be seen that the output attains these values in the steady state.

1.6.3 Piecewise Linear Systems

Consider the buck converter model shown in Figure 1.14a. From Figure 1.14b, the following equations are obtained when the switch is ON.

$$\begin{aligned}\frac{dv_{out}}{dt} &= -\frac{1}{RC}v_{out} + \frac{1}{C}i_L\\ \frac{di_L}{dt} &= -\frac{1}{L}v_{out} + \frac{1}{L}V_{in}\end{aligned} \tag{1.12}$$

On the other hand, when the switch is OFF, the following equations describe the system

$$\begin{aligned}\frac{dv_{out}}{dt} &= -\frac{1}{RC}v_{out} + \frac{1}{C}i_L\\ \frac{di_L}{dt} &= -\frac{1}{L}v_{out}\end{aligned} \tag{1.13}$$

Both these sets of equations are linear. However, the behavior of the circuit is controlled by the duty ratio or duty cycle shown in Figure 1.9c. This is best described in terms of the state space description of the system, which is explained in Chapter 5.

Let us define a state vector as $\mathbf{x} = [v_{out} \;\; i_L]^T$. Then (1.12) and (1.13) can be written respectively as

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}V_{in} \tag{1.14}$$

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} \tag{1.15}$$

where

$$\mathbf{A} = \begin{bmatrix} -1/RC & 1/C \\ -1/L & 0 \end{bmatrix}, \qquad \mathbf{B} = \begin{bmatrix} 0 \\ 1/L \end{bmatrix}$$

Now assume that the switch closes at t_0, opens at t_1, and subsequently closes at t_2, as shown in Figure 1.9b. In the steady state, the duty ratio D is constant, and therefore

$$t_1 - t_0 = DT_s, \quad t_2 - t_1 = (1-D)T_s \tag{1.16}$$

where D is the duty ratio and T_s is the cycle time. Then the solutions of (1.14) and (1.15) respectively are

$$\mathbf{x}(t_1) = \int_{t_0}^{t_1} (\mathbf{A}\mathbf{x} + \mathbf{B}V_{in})dt + \mathbf{x}(t_0) = \int_{0}^{DT_s} (\mathbf{A}\mathbf{x} + \mathbf{B}V_{in})dt + \mathbf{x}(t_0) \tag{1.17}$$

$$\mathbf{x}(t_2) = \int_{t_1}^{t_2} \mathbf{A}\mathbf{x}dt + \mathbf{x}(t_1) = \int_{0}^{(1-D)T_s} \mathbf{A}\mathbf{x}dt + \mathbf{x}(t_1) \tag{1.18}$$

In the steady state, we have $\mathbf{x}(t_2) = \mathbf{x}(t_0)$. Solutions of (1.17) and (1.18) will yield the description of the system between t_0 and t_2, which is dependent on the duty ratio, which appears in the exponential terms of the solutions of (1.17) and (1.18). Thus, even if the circuit is piecewise linear, the overall behavior of the circuit is nonlinear. Furthermore, the DC-DC converter is controlled by its duty ratio. Therefore, the system will have to be linearized for control design, as is discussed in Chapter 4 (Section 4.1.5) and Chapter 5 (Section 5.11.2).

1.7 Power Distribution Systems

Power systems' voltages and currents can be represented either though their instantaneous components or through their phasor components. The instantaneous voltage of the form $v(t) = V_m \sin(\omega t + \delta)$, where V_m is the voltage magnitude, ω is the angular frequency in rad/s, and δ is its phase angle. Phasor components represent the sinusoidal steady state, i.e. the voltage (or current) magnitude and its angle when the transients have died down and all the quantities in the system are in a pure sinusoidal state. For the instantaneous voltage given above, the phasor component is represented in polar of cartesian form as $V = \left(V_m/\sqrt{2}\right)e^{j\delta} = \left(V_m/\sqrt{2}\right)\left[\cos\delta + j\sin\delta\right]$. A diagram representing the phasors in a circuit is called the phasor diagram.

One of the main applications of power converters is in power distribution systems. These applications are discussed in Chapters 9 and 10 of this book. Consider, for example, the radial power system shown in Figure 1.18a. It contains a source V_S that supplies an RL load with the impedance of Z_L. Let us assume that the switch S is open. The phasor diagram of this system is shown in Figure 1.18b. The lagging load current (I) has two components: the real component (I_R) and the reactive component (I_Q). It is the real component that is doing any practical work, while the reactive component is present due to the load power factor. However, due to the reactive component, the current magnitude becomes larger. This causes more line voltage drop and larger $R|I|^2$ drop in the line that can lead to excessive heating in the conductors.

When switch S is closed, the capacitor, with a reactance of $-jX_C$, is connected in parallel with the load bus. This will draw a leading current I_C from the system, as

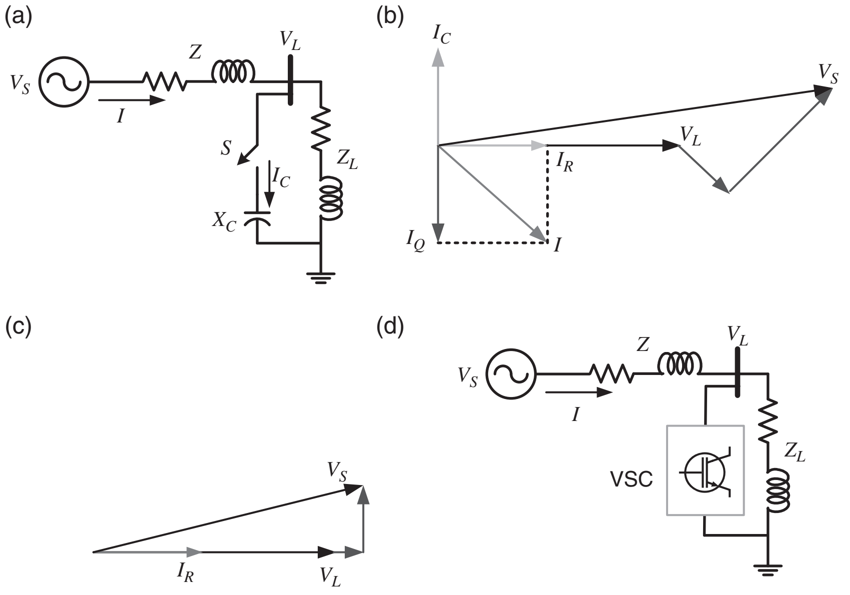


Figure 1.18 (a) A radial distribution system, (b) phasor diagram when the capacitor is not connected, (c) phasor diagram when the capacitor is connected, and (d) power factor correction through a VSC.

shown in Figure 1.18b. If this current is such that $I_C = I_Q$, then the source will only supply the current I_R. Then, the load and the capacitor will draw power from the source at unity power factor, as shown in Figure 11.18c.

The main problem with the above proposition is that the load may change, and therefore fixing the value of the capacitance with all load changes is not feasible. A better approach is to connect a VSC in shunt with the load bus. This VSC, through proper control, can not only correct the power factor but also provide harmonic compensation, balance the load bus voltage, and regulate the bus voltage [4].

A microgrid is a small, localized grid with its embedded control capability. It can operate along with the main utility grid or can also disconnect from the grid and work autonomously while supplying power to its local loads. Microgrids are supplied by their local generators with most of them harnessing power from renewable energy sources. Additionally, a microgrid may even contain battery storage systems. These power supply sources are collectively called DERs. Most of the DERs are connected to microgrids through VSCs and are required to supply power in the autonomous mode, while regulating its bus voltage and frequency. Therefore, converter control plays a significant role in the operation of microgrids. Since microgrids have local generators, they are very suitable for combined heat and power applications. Microgrids have tremendous potential for remote area power systems where power lines are not present or have very weak connections. Also, microgrids are being developed for university campuses, for commercial/community buildings, military usage, etc. Microgrids have even been conceptualized for space applications [5].

1.8 Concluding Remarks

In this chapter, a brief introduction to the book are presented. Topics mentioned in this chapter are elaborated in subsequent chapters. Specifically, several control analysis design principles are covered in detail. Furthermore, the control of both DC-DC and DC-AC converters is covered, along with the applications of these converters to power systems.

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