1
Introduction

1.1 INTRODUCTION TO POWER PROCESSING

The field of power electronics is concerned with the processing of electrical power using electronic devices [1–7]. The key element is the *switching converter,* illustrated in Fig. 1.1. In general, a switching converter contains power input and control input ports, and a power output port. The raw input power is processed as specified by the control input, yielding the conditioned output power. One of several basic functions can be performed [2]. In a *dc–dc converter,* the dc input voltage is converted to a dc output voltage having a larger or smaller magnitude, possibly with opposite polarity or with isolation of the input and output ground references. In an ac–dc *rectifier,* an ac input voltage is rectified, producing a dc output voltage. The dc output voltage and/or ac input current waveform may be controlled. The inverse process, dc–ac *inversion,* involves transforming a dc input voltage into an ac output voltage of controllable magnitude and frequency. Ac–ac *cycloconversion* involves converting an ac input voltage to a given ac output voltage of controllable magnitude and frequency.

Control is invariably required. It is nearly always desired to produce a well-regulated output

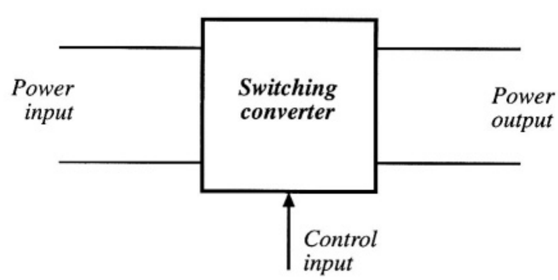


Fig. 1.1 The switching converter, a basic power processing block.

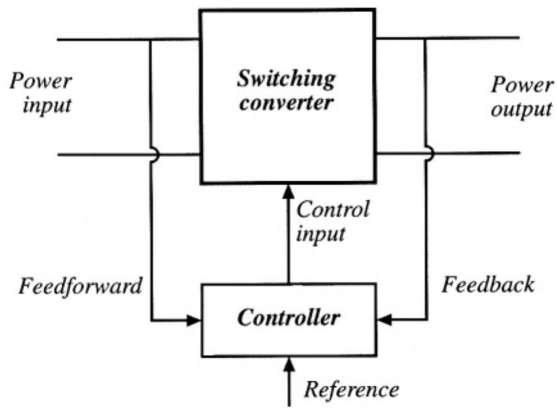


Fig. 1.2 A controller is generally required.

voltage, in the presence of variations in the input voltage and load current. As illustrated in Fig. 1.2, a controller block is an integral part of any power processing system.

High efficiency is essential in any power processing application. The primary reason for this is usually not the desire to save money on one's electric bills, nor to conserve energy, in spite of the nobility of such pursuits. Rather, high efficiency converters are necessary because construction of low-efficiency converters, producing substantial output power, is impractical. The efficiency of a converter having output power P_{out} and input power P_{in} is

$$\eta = \frac{P_{out}}{P_{in}} \tag{1.1}$$

The power lost in the converter is

$$P_{loss} = P_{in} - P_{out} = P_{out}\left(\frac{1}{\eta} - 1\right) \tag{1.2}$$

Equation (1.2) is plotted in Fig. 1.3. In a converter that has an efficiency of 50%, power P_{loss} is dissipated by the converter elements and this is equal to the output power, P_{out}. This power is converted into heat, which must be removed from the converter. If the output power is substantial, then so is the loss power. This leads to a large and expensive cooling system, it causes the electronic elements within the converter to operate at high temperature, and it reduces the system reliability. Indeed, at high output powers, it may be impossible to adequately cool the converter elements using current technology.

Increasing the efficiency is the key to obtaining higher output powers. For example, if the converter efficiency is 90%, then the converter loss power is equal to only 11%

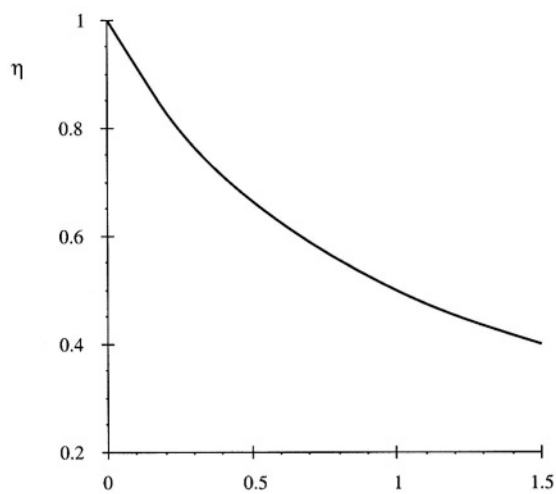


Fig. 1.3 Converter power loss vs. efficiency.

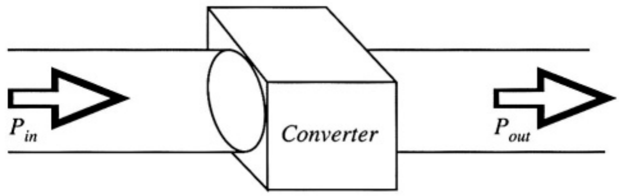


Fig. 1.4 A goal of current converter technology is to construct converters of small size and weight, which process substantial power at high efficiency.

of the output power. Efficiency is a good measure of the success of a given converter technology. Figure 1.4 illustrates a converter that processes a large amount of power, with very high efficiency. Since very little power is lost, the converter elements can be packaged with high density, leading to a converter of small size and weight, and of low temperature rise.

How can we build a circuit that changes the voltage, yet dissipates negligible power? The various conventional circuit elements are illustrated in Fig. 1.5. The available circuit elements fall broadly into the classes of resistive elements, capacitive elements, magnetic devices including inductors and transformers, semiconductor devices operated in the linear mode (for example, as class *A* or class *B* amplifiers), and semiconductor devices operated in the switched mode (such as in logic devices where transistors operate in either saturation or cutoff). In conventional signal processing applications, where efficiency is not the primary concern, magnetic devices are usually avoided wherever possible, because of their large size and the difficulty of incorporating them into integrated circuits. In contrast, capacitors and magnetic devices are important elements of switching converters, because ideally they do not consume power. It is the resistive element, as well as the linear-mode semiconductor device, that is avoided [2]. Switched-mode semiconductor devices are also employed. When a semiconductor device operates in the off state, its current is zero and hence its power dissipation is zero. When the semiconductor device operates in the on (saturated) state, its voltage drop is small and hence its power dissipation is also small. In either event, the power dissipated by the semiconductor device is low. So capacitive and inductive elements, as well as switched-mode semiconductor devices, are available for synthesis of high-efficiency converters.

Let us now consider how to construct the simple dc-dc converter example illustrated in Fig. 1.6. The input voltage V_g is 100 V. It is desired to supply 50 V to an effective 5 Ω load, such that the dc load current is 10 A.

Introductory circuits textbooks describe a low-efficiency method to perform the required function: the voltage divider circuit illustrated in Fig. 1.7(a). The dc–dc converter then consists simply of a

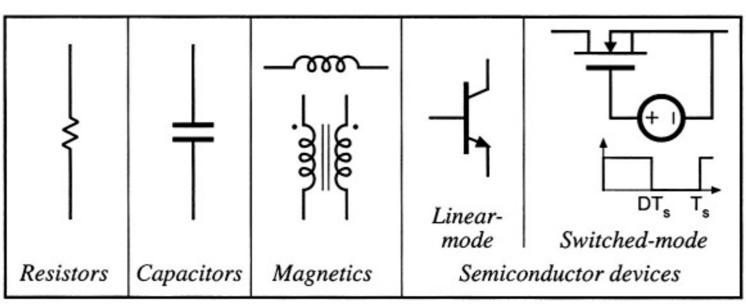


Fig. 1.5 Devices available to the circuit designer [2].

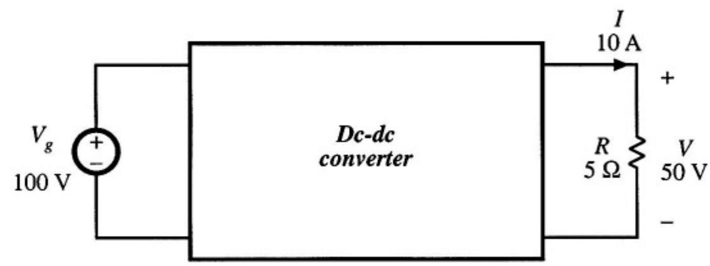


Fig. 1.6 A simple power processing example: construction of a 500 W dc–dc converter.

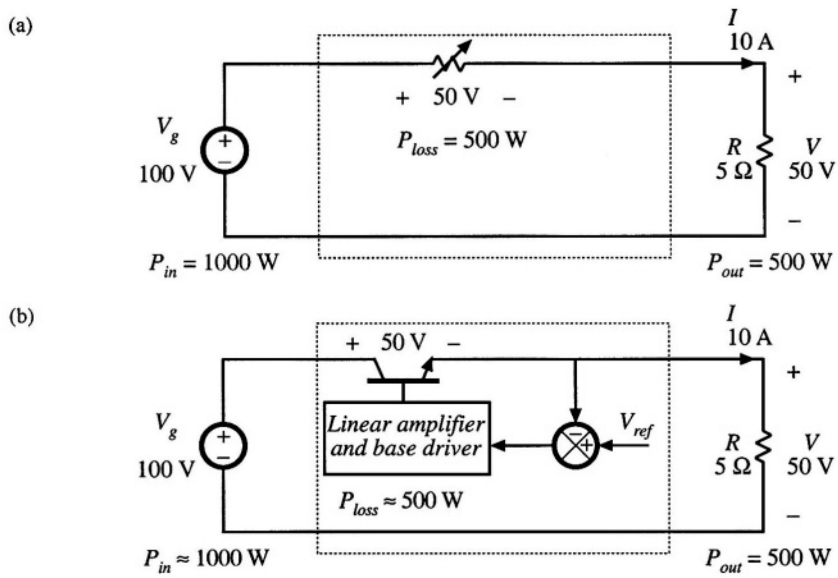


Fig. 1.7 Changing the dc voltage via dissipative means: (a) voltage divider, (b) series pass regulator.

variable resistor, whose value is adjusted such that the required output voltage is obtained. The load current flows through the variable resistor. For the specified voltage and current levels, the power P_{loss} dissipated in the variable resistor equals the load power P_{out} = 500 W. The source V_g supplies power P_{in} = 1000 W. Figure 1.7(b) illustrates a more practical implementation known as the linear series-pass regulator. The variable resistor of Fig. 1.7(a) is replaced by a linear-mode power transistor, whose base current is controlled by a feedback system such that the desired output voltage is obtained. The power dissipated by the linear-mode transistor of Fig. 1.7(b) is approximately the same as the 500 W lost by the variable resistor in Fig. 1.7(a). Series-pass linear regulators generally find modern application only at low power levels of a few watts.

Figure 1.8 illustrates another approach. A single-pole double-throw (SPDT) switch is connected as shown. The switch output voltage $v_s(t)$ is equal to the converter input voltage V_g when the switch is in position 1, and is equal to zero when the switch is in position 2. The switch position is varied periodically, as illustrated in Fig. 1.9, such that $v_s(t)$ is a rectangular waveform having frequency f_s and period $T_s = 1/f_s$. The duty cycle D is defined as the fraction of time in which the switch occupies position 1. Hence, $0 \le D \le 1$. In practice, the SPDT switch is realized using switched-mode semiconductor devices,

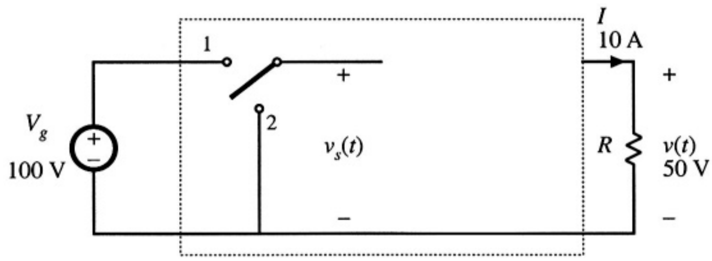


Fig. 1.8 Insertion of SPDT switch which changes the dc component of the voltage.

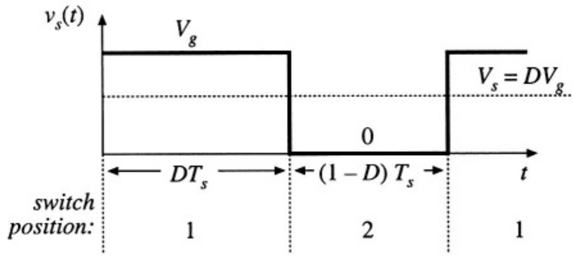


Fig. 1.9 Switch output voltage waveform $v_s(t)$.

which are controlled such that the SPDT switching function is attained.

The switch changes the dc component of the voltage. Recall from Fourier analysis that the dc component of a periodic waveform is equal to its average value. Hence, the dc component of $v_s(t)$ is

$$V_s = \frac{1}{T_s}\int_0^{T_s} v_s(t)dt = DV_g \tag{1.3}$$

Thus, the switch changes the dc voltage, by a factor equal to the duty cycle D. To convert the input voltage $V_g = 100$ V into the desired output voltage of $V = 50$ V, a duty cycle of $D = 0.5$ is required.

Again, the power dissipated by the switch is ideally zero. When the switch contacts are closed, then their voltage is zero and hence the power dissipation is zero. When the switch contacts are open, then the current is zero and again the power dissipation is zero. So we have succeeded in changing the dc voltage component, using a device that is ideally lossless.

In addition to the desired dc component V_s, the switch output voltage waveform $v_s(t)$ also contains undesirable harmonics of the switching frequency. In most applications, these harmonics must be removed, such that the output voltage $v(t)$ is essentially equal to the dc component $V = V_s$. A low-pass filter can be employed for this purpose. Figure 1.10 illustrates the introduction of a single-section L–C low-pass filter. If the filter corner frequency f_0 is sufficiently less than the switching frequency f_s, then the filter essentially passes only the dc component of $v_s(t)$. To the extent that the switch, inductor, and capacitor elements are ideal, the efficiency of this dc–dc converter can approach 100%.

In Fig. 1.11, a control system is introduced for regulation of the output voltage. Since the output voltage is a function of the switch duty cycle, a control system can be constructed that varies the duty cycle to cause the output voltage to follow a given reference. Figure 1.11 also illustrates a typical way in which the SPDT switch is realized using switched-mode semiconductor devices. The converter power stage developed in Figs. 1.8 to 1.11 is called the *buck converter,* because it reduces the dc voltage.

Converters can be constructed that perform other power processing functions. For example, Fig.

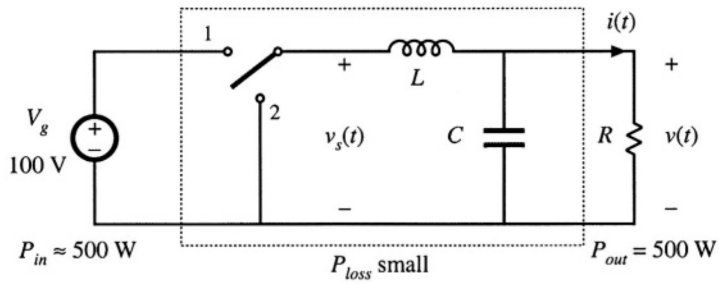


Fig. 1.10 Addition of L–C low-pass filter, for removal of switching harmonics.

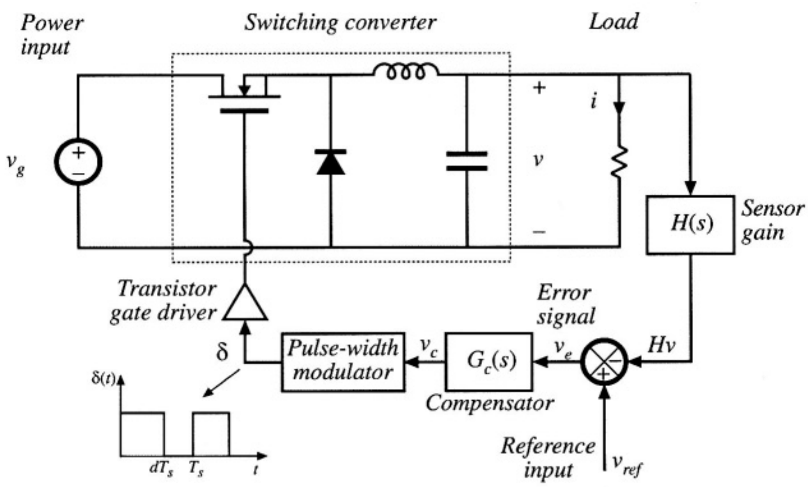
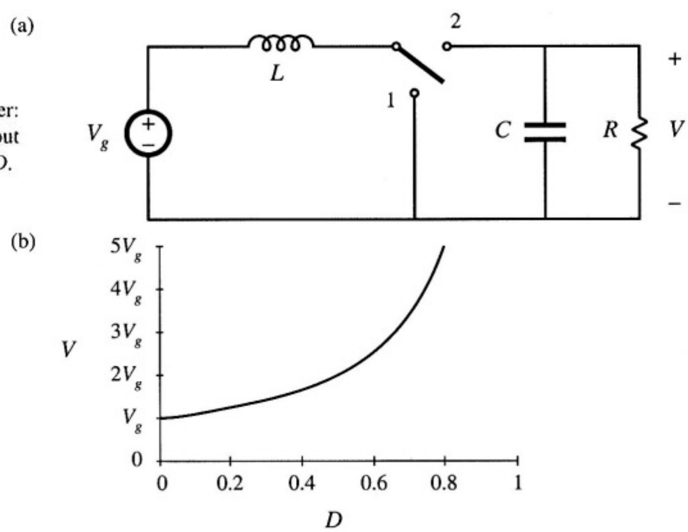


Fig. 1.11 Addition of control system to regulate the output voltage.

Fig. 1.12 The boost converter: (a) ideal converter circuit, (b) output voltage V vs. transistor duty cycle D.



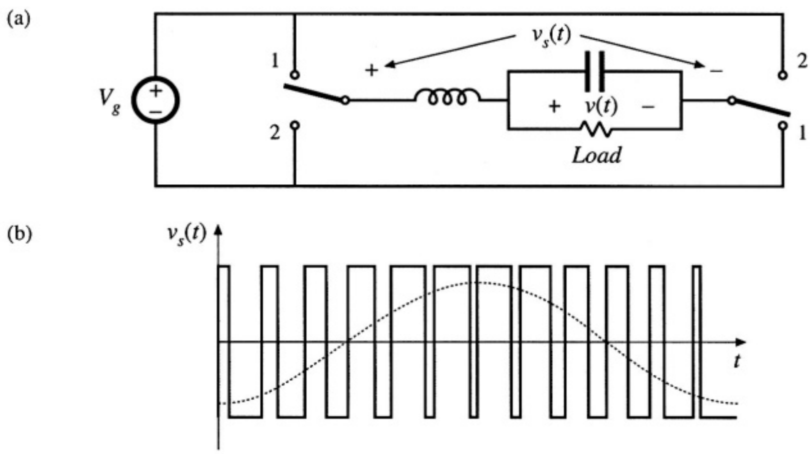


Fig. 1.13 A bridge-type dc-1øac inverter: (a) ideal inverter circuit, (b) typical pulse-width-modulated switch voltage waveform $v_s(t)$, and its low-frequency component.

1.12 illustrates a circuit known as the *boost converter,* in which the positions of the inductor and SPDT switch are interchanged. This converter is capable of producing output voltages that are greater in magnitude than the input voltage. In general, any given input voltage can be converted into any desired output voltage, using a converter containing switching devices embedded within a network of reactive elements.

Figure 1.13(a) illustrates a simple dc–1øac inverter circuit. As illustrated in Fig. 1.13(b), the switch duty cycle is modulated sinusoidally. This causes the switch output voltage $v_s(t)$ to contain a low-frequency sinusoidal component. The *L–C* filter cutoff frequency f_0 is selected to pass the desired low-frequency components of $v_s(t)$, but to attenuate the high-frequency switching harmonics. The controller modulates the duty cycle such that the desired output frequency and voltage magnitude are obtained.

1.2 SEVERAL APPLICATIONS OF POWER ELECTRONICS

The power levels encountered in high-efficiency switching converters range from (1) less than one watt, in dc–dc converters within battery-operated portable equipment, to (2) tens, hundreds, or thousands of watts in power supplies for computers and office equipment, to (3) kilowatts to Megawatts, in variable-speed motor drives, to (4) roughly 1000 Megawatts in the rectifiers and inverters that interface dc transmission lines to the ac utility power system. The converter systems of several applications are illustrated in this section.

A power supply system for a laptop computer is illustrated in Fig. 1.14. A lithium battery powers the system, and several dc–dc converters change the battery voltage into the voltages required by the loads. A buck converter produces the low-voltage dc required by the microprocessor. A boost converter increases the battery voltage to the level needed by the disk drive. An inverter produces high-voltage high-frequency ac to drive lamps that light the display. A charger with transformer isolation converts the ac line voltage into dc to charge the battery. The converter switching frequencies are typically in the vicinity of several hundred kilohertz; this leads to substantial reductions in the size and weight of the reactive elements. *Power management* is used, to control sleep modes in which power consumption is reduced and battery life is extended. In a *distributed power system,* an intermediate dc voltage appears at the computer backplane. Each printed circuit card contains high-density dc–dc converters that produce

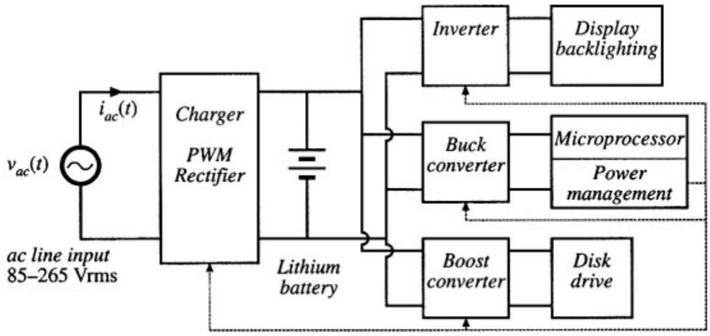


Fig. 1.14 A laptop computer power supply system.

locally-regulated low voltages. Commercial applications of power electronics include off-line power systems for computers, office and laboratory equipment, uninterruptable ac power supplies, and electronic ballasts for gas discharge lighting.

Figure 1.15 illustrates a power system of an earth-orbiting spacecraft. A solar array produces the main power bus voltage V_{bus}. DC–DC converters convert V_{bus} to the regulated voltages required by the spacecraft payloads. Battery charge/discharge controllers interface the main power bus to batteries; these controllers may also contain dc–dc converters. Aerospace applications of power electronics include the power systems of aircraft, spacecraft, and other aerospace vehicles.

Figure 1.16 illustrates an electric vehicle power and drive system. Batteries are charged by a converter that draws high power-factor sinusoidal current from a single-phase or three-phase ac line. The batteries supply power to variable-speed ac motors to propel the vehicle. The speeds of the ac motors are controlled by variation of the electrical input frequency. Inverters produce three-phase ac output voltages of variable frequency and variable magnitude, to control the speed of the ac motors and the vehicle. A dc–dc converter steps down the battery voltage to the lower dc levels required by the electronics of the system. Applications of motor drives include speed control of industrial processes, such as control of compressors, fans, and pumps; transportation applications such as electric vehicles, subways, and locomotives; and motion control applications in areas such as computer peripherals and industrial robots.

Power electronics also finds application in other diverse industries, including dc power supplies,

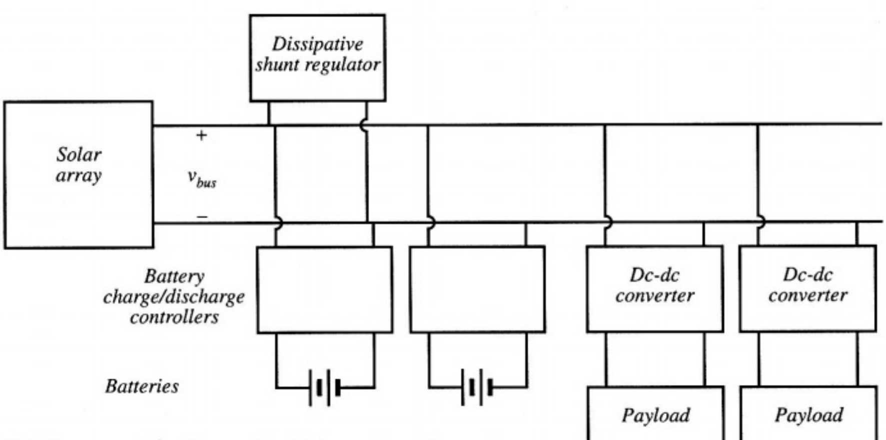


Fig. 1.15 Power system of an earth-orbiting spacecraft.

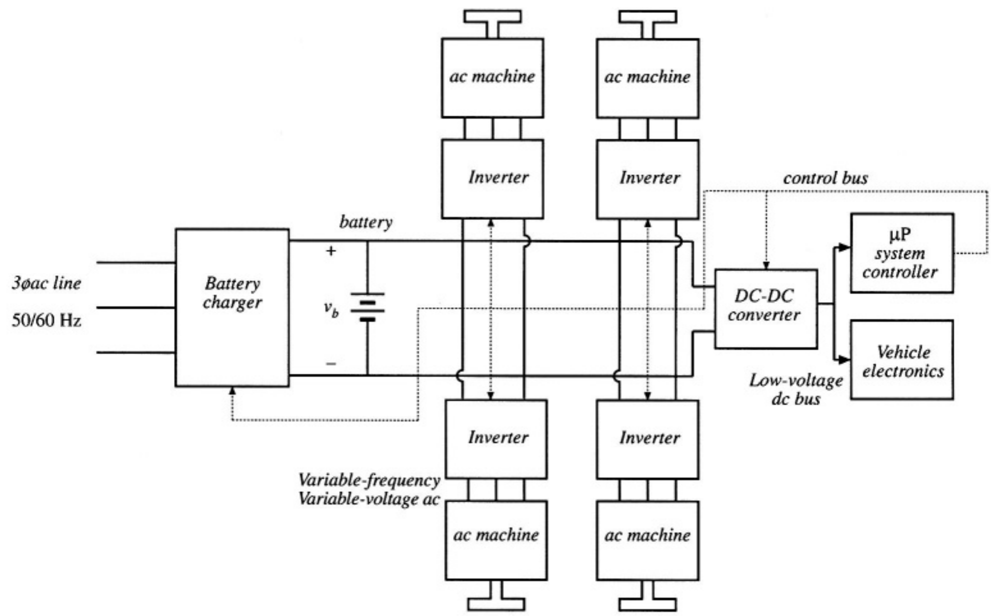


Fig. 1.16 An electric vehicle power and drive system.

uninterruptable power supplies, and battery chargers for the telecommunications industry; inverter systems for renewable energy generation applications such as wind and photovoltaic power; and utility power systems applications including high-voltage dc transmission and static *VAR* (reactive volt-ampere) compensators.

1.3 ELEMENTS OF POWER ELECTRONICS

One of the things that makes the power electronics field interesting is its incorporation of concepts from a diverse set of fields, including:

- analog circuits
- electronic devices
- control systems
- power systems
- magnetics
- electric machines
- numerical simulation

Thus, the practice of power electronics requires a broad electrical engineering background. In addition, there are fundamental concepts that are unique to the power electronics field, and that require specialized study.

The presence of high-frequency switching makes the understanding of switched-mode converters not straightforward. Hence, converter modeling is central to the study of power electronics. As introduced in Eq. (1.3), the dc component of a periodic waveform is equal to its average value. This ideal can be generalized, to predict the dc components of all converter waveforms via averaging. In Part I of this book, averaged equivalent circuit models of converters operating in steady state are derived. These models not only predict the basic ideal behavior of switched-mode converters, but also model efficiency and losses. Realization of the switching elements, using power semiconductor devices, is also discussed.

Design of the converter control system requires models of the converter dynamics. In Part II of this book, the averaging technique is extended, to describe low-frequency variations in the converter waveforms. Small-signal equivalent circuit models are developed, which predict the control-to-output and line-to-transfer functions, as well as other ac quantities of interest. These models are then employed to design converter control systems and to lend an understanding of the well-known current-programmed control technique.

The magnetic elements are key components of any switching converter. The design of high-power high-frequency magnetic devices having high efficiency and small size and weight is central to most converter technologies. High-frequency power magnetics design is discussed in Part III.

Pollution of the ac power system by rectifier harmonics is a growing problem. As a result, many converter systems now incorporate low-harmonic rectifiers, which draw sinusoidal currents from the utility system. These modern rectifiers are considerably more sophisticated than the conventional diode bridge: they may contain high-frequency switched-mode converters, with control systems that regulate the ac line current waveform. Modern rectifier technology is treated in Part IV.

Resonant converters employ quasi-sinusoidal waveforms, as opposed to the rectangular waveforms of the buck converter illustrated in Fig. 1.9. These resonant converters find application where high-frequency inverters and converters are needed. Resonant converters are modeled in Part V. Their loss mechanisms, including the processes of zero-voltage switching and zero-current switching, are discussed.

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