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Introduction

In the last few decades, the use of power converters and high-performance adjustable speed drives has gained an increased presence in a wide range of applications, mainly due to improved performance and higher efficiency, which lead to increased production rates. In this way, power converters and drives have become an enabling technology in most industrial sectors, with many applications in a wide variety of systems. Conversion and control of electrical energy using power electronics is a very important topic today, considering the increasing energy demands and new requirements in terms of power quality and efficiency. In order to fulfill these demands new semiconductor devices, topologies, and control schemes are being developed.

This chapter presents a basic introduction and useful references for readers who are not familiar with power converters, motor drives, and their applications. The most common applications that involve the use of power converters are presented, and a general scheme for a drive system is explained. The power converter topologies found in industry are introduced according to a simple classification. A brief introduction to control schemes for power converters, the basic concepts behind them and the digital implementation technologies used today, are discussed.

This chapter provides the necessary context, including a brief motivation for the use of predictive control, to understand the contents of this book.

1.1 Applications of Power Converters and Drives

Power converters and drives are used in diverse sectors, ranging from industrial to residential applications [1, 2]. Several application examples for different sectors are shown in Figure 1.1, where a diagram of the system configuration is shown as an example for each group, marked with $*$.

From the drive applications used in industry, pumps and fans are those that account for most of the energy consumption, with power ratings up to several megawatts. The use of adjustable speed drives can bring important benefits to these kinds of systems in terms of performance and efficiency. Many interesting applications of high-power drives can be found in the mining industry, for example, in downhill belt conveyors. A block diagram of one of these systems is shown in Figure 1.1, where three-level converters with active

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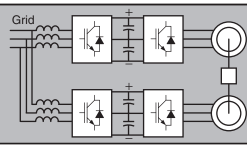
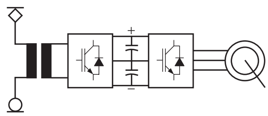
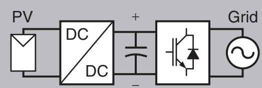
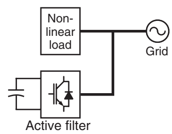
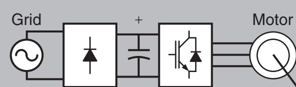
Sector	Application examples	System diagram*
Industrial	Pumps Fans Conveyors* Shovels Rectifiers	
Transportation	Electric vehicles Hybrid vehicles Trains* Ships Aircraft	
Renewable energies	Wind energy Photovoltaic energy*	
Power systems	Active filters* Distributed generation Energy storage STATCOM	
Residential	Air conditioners Home appliances*	

Figure 1.1 Power converter applications

front-end rectifiers are used for regenerative operation, that is, power flowing from the motors to the grid [3, 4].

Common applications of drives can be found in transportation, where electric motors are used for traction and propulsion. In electric trains, the power is transferred from the overhead lines to the motors using a power converter like the one shown in the figure. This converter generates the required voltages for controlling the torque and speed of the electric motor. High-power drives can be found in ships, where diesel engines are used as generators and the propulsion is generated by electric motors. Newer applications in transportation can be found in electric and hybrid vehicles, and in aircraft.

The use of power converters in renewable energy conversion systems has been constantly increasing in recent years, mainly due to growing energy demands and environmental concerns. Among the different renewable energy sources, photovoltaic (PV) generation systems are a very interesting example of power converter applications because it is not possible to deliver power from the PV panel to the grid without a converter. An example of a power converter for a PV system is shown in Figure 1.1, composed of a DC–DC converter for optimal operation of the panel and an inverter for injection of sinusoidal currents to the grid. The use of power converters and drives in wind generation systems allows optimization of the amount of energy extracted from the wind and compliance with the new grid regulations that impose restrictions on the power quality and performance of the system [5].

The use of power converters can help to improve the quality and stability of the grid. Some examples of power converters with applications in power systems are active filters, converters for distributed generation, energy storage systems, static VAR compensators (STATCOM), and others. A diagram of an active filter application is also shown in Figure 1.1, where the power converter generates the required currents for compensating the distorted currents generated by a nonlinear load. In this way, distortion of the grid voltage is avoided.

Low-power drives and converters offer many possibilities in residential applications. The use of adjustable speed drives can increase the efficiency of systems like air conditioners and other home appliances [1, 6].

1.2 Types of Power Converters

There are many types of power converters and drive systems, and every application requires different specifications that define the most appropriate topology and control scheme to be used. A general scheme for a drive system and a simple classification of the different types of power converters are presented next.

1.2.1 Generic Drive System

A block diagram and a picture of a real drive system are shown in Figure 1.2. The main components of the system are the line-side transformer, the rectifier, the DC link, the inverter, the electrical machine, and the control unit. Depending on the system requirements, the rectifier can be a diode rectifier or an active front-end rectifier. The DC link is composed of capacitors or inductors, depending on the topology of the inverter and rectifier, whose purpose is to store energy and decouple the operation of the inverter and rectifier. The inverter modulates the DC link voltage (or current) and generates a voltage whose fundamental component can be adjusted in amplitude, frequency, and phase, in order to control the torque and speed of the machine. The control unit samples voltage and current measurements of the most important variables and generates the gate drive signals for the power semiconductor devices.

As can be observed in Figure 1.2, the drive system requires several additional elements for proper operation, such as transformers, input and output passive filters, and a cooling system for the switching devices.

1.2.2 Classification of Power Converters

Power converters are composed of power semiconductor switches and passive components. They can be classified according to several criteria. A very simple and useful classification considers the type of conversion from input to output that the system

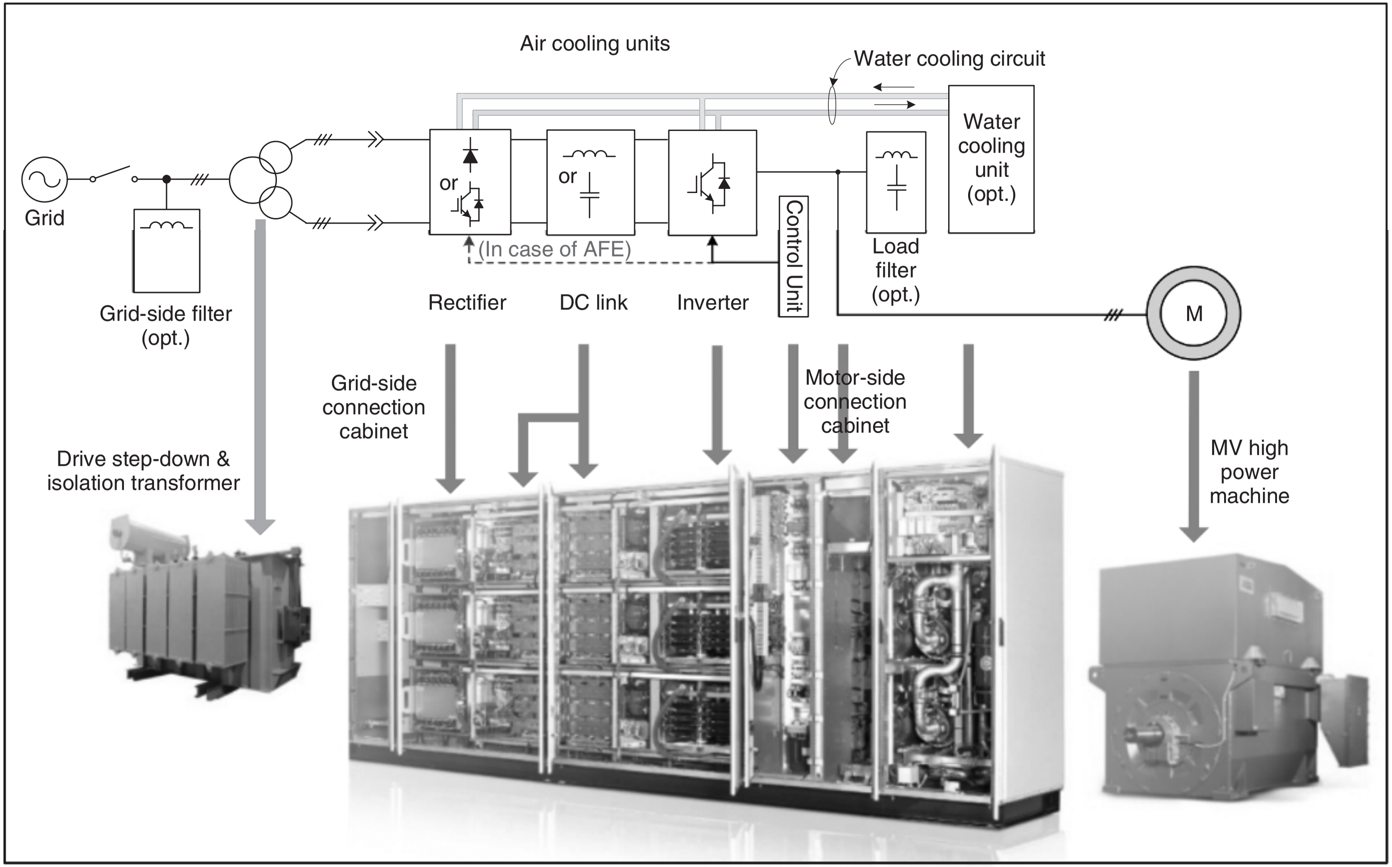


Figure 1.2 General motor drive system (AFE = Active Front-End)

performs, in terms of alternating current (AC) and direct current (DC). This leads to four main types of power converters:

AC–DC Conversion from AC to regulated or unregulated DC voltage or current.

DC–DC Conversion from a DC input voltage to a DC output voltage, providing regulation of the output voltage and isolation (optional).

DC–AC Conversion from a DC voltage or current to an AC voltage or current with controlled (variable) amplitude, frequency, and phase.

AC–AC Conversion from an AC voltage with fixed magnitude and frequency to an AC voltage with controlled (variable) amplitude and frequency.

Each one of these types includes several subcategories, as depicted in Figure 1.3. Some examples of different types of power converters will be described and analyzed in this book.

1.3 Control of Power Converters and Drives

Control schemes for power converters and drives have been constantly evolving according to the development of new semiconductor devices and the introduction of new control platforms. While diode rectifiers operate without any control, analog control circuits were introduced for regulating the firing angle of thyristors. With the introduction of power transistors with faster switching frequencies, analog control circuits have been used from the beginning and later were replaced by digital control platforms with the possibility of implementing more advanced control schemes.

1.3.1 Power Converter Control in the Past

In thyristor-based rectifiers the average value of the output voltage can be adjusted by regulating the angle of the firing pulses in relation to the grid voltage. The control circuit for this power converter must detect the zero crossings of the grid voltage and generate the firing pulses according to the desired angle. Figure 1.4 shows the operation of a single-phase thyristor rectifier with a resistive–inductive load. It can be seen that the firing angle α modifies the waveform of the output voltage and, consequently, the average output voltage.

Thyristors switch at fundamental frequency, because their turn-off instant is line dependent and cannot be controlled. However, with the introduction of power transistors like the insulated-gate bipolar transistor (IGBT), hard switching or controlled turn-off is possible, allowing higher switching frequencies. A simple example of a power converter with only one switch is the buck converter. It generates an output voltage whose average value is between zero and the input voltage. This desired voltage is obtained by adjusting the duty cycle of the switch. A simple control for this converter consists of comparing the reference voltage to a triangular waveform. If the reference is higher that the triangular signal, then the switch is turned on, otherwise the switch is turned off. The power circuit and important waveforms are shown in Figure 1.5.

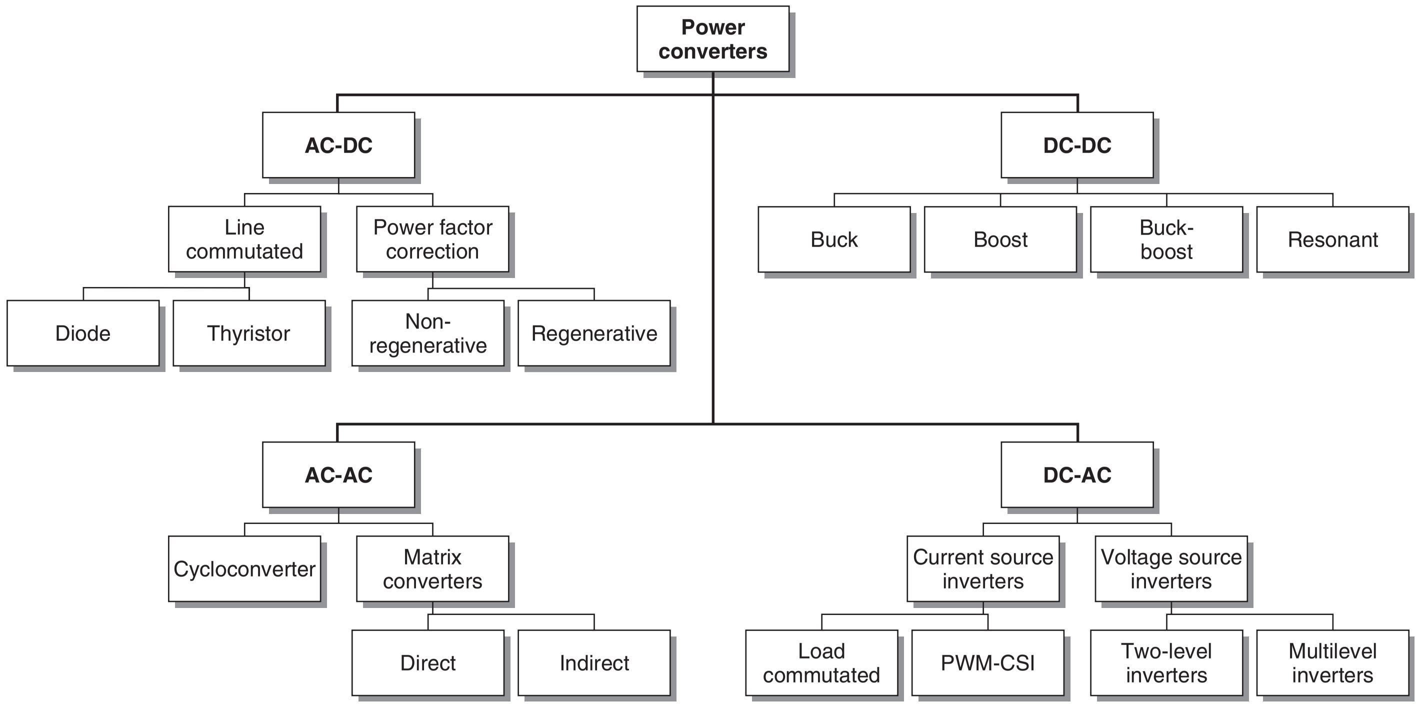


Figure 1.3 Power converter classification (PWM-CSI = Pulse Width-Modulated Current Source Inverter)

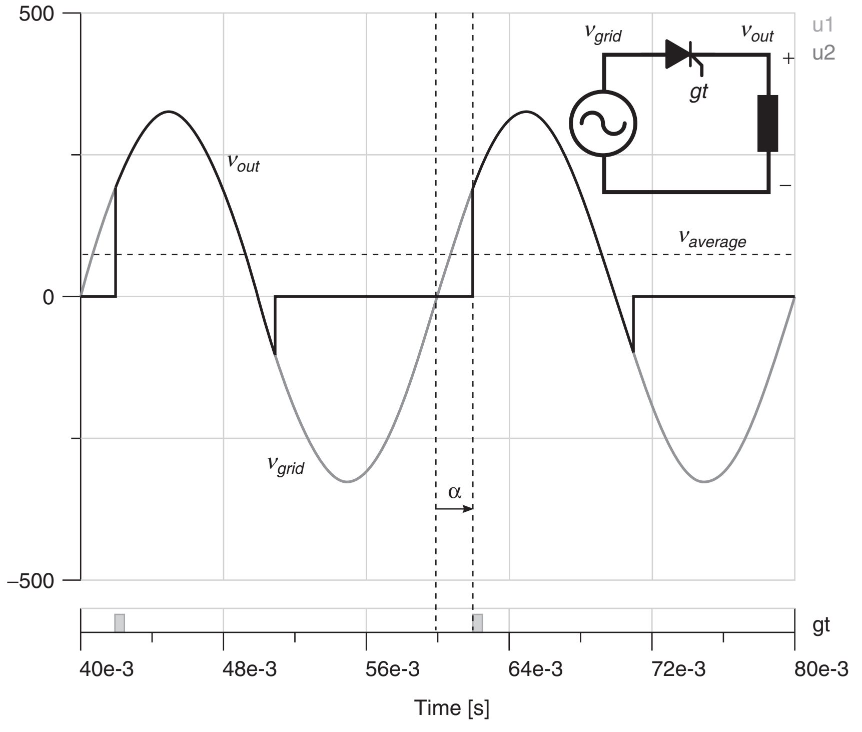


Figure 1.4 Operation of a single-phase thyristor rectifier

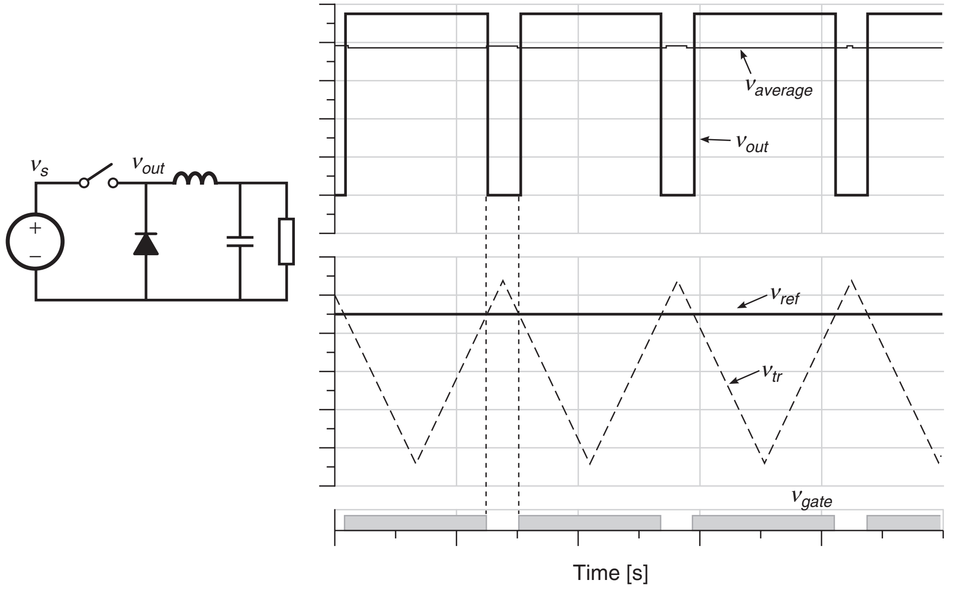


Figure 1.5 Operation of a buck converter

Implementation of these kinds of control schemes was realized completely in the 1960s using analog circuits composed of operational amplifiers and passive components. Later, digital circuits were introduced and worked in combination with the analog circuits. In recent decades, the use of microprocessors for the control of power electronic systems has become a common solution for fully digital control implementations. Modern microcontrollers and digital signal processors (DSPs) with high computational capabilities allow the implementation of more intelligent control schemes [7]. However, several concepts that were developed for the analog control circuits are replicated today in a digital way.

One of the fundamental concepts in analog control circuits for power converters is to control the time-average values of voltages or currents. These average values are calculated considering a base time that can be a fundamental cycle in the case of thyristor rectifiers, or the period of the triangular waveform in the case of modulated power converters. This idea allows the model of the converter to be approximated by a linear system and is the basis of most conventional control schemes used today. However, the nonlinear characteristics of the converter are neglected.

Another control scheme that has its origin in analog circuits is hysteresis control. More details about this type of controller will be given in the next chapter.

1.3.2 Power Converter Control Today

Several control methods have been proposed for the control of inverters and drives, the most commonly used ones being shown in Figure 1.6. Some of these are very well established and simple, such as the nonlinear hysteresis control, while newer control methods, which allow an improved behavior of the system, are generally more complex or need much more calculation power from the control platform.

Hysteresis control takes advantage of the nonlinear nature of the power converters and the switching states of the power semiconductors are determined by comparison of the measured variable to its reference, considering a given hysteresis width for the error.

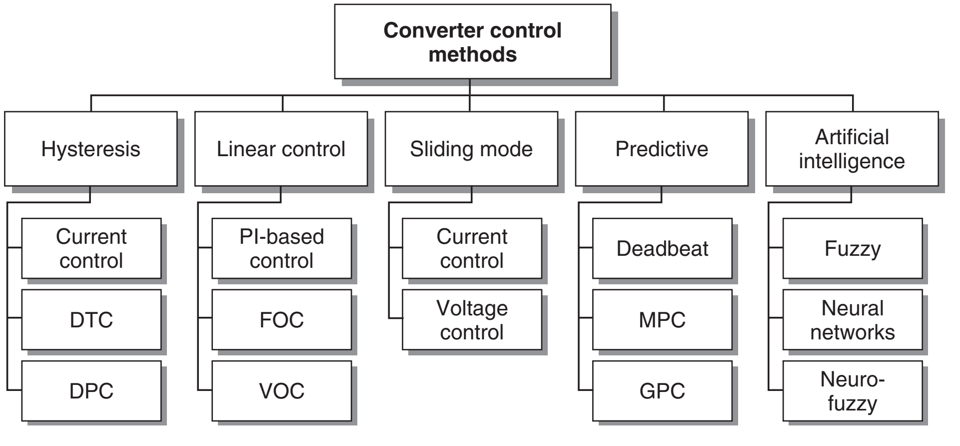


Figure 1.6 Different types of converter control schemes for power converters and drives (GPC = Generalized Predictive Control)

This control scheme can be used in simple applications such as current control, but also for more complex schemes such as direct torque control (DTC) [8] and direct power control (DPC) [9]. This control scheme has its origin in analog electronics, and in order to implement this control scheme in a digital platform, a very high sampling frequency is required. The hysteresis width and the nonlinearity of the system inherently introduce variable switching frequency, which can lead to resonance problems in some applications and generate a spread spectral content. This leads to the need for bulky and expensive filters. Some modifications have been proposed to control the switching frequency.

Given a modulation stage for the converter, any linear controller can be used with the power converters, the most common choice being the use of proportional–integral (PI) controllers. A well-known control method for drives, based on linear controllers, is field-oriented control (FOC) [10, 8]. Similar concepts can be also applied for grid-connected converters with voltage-oriented control (VOC) for the current [11]. The linear control scheme with a modulation stage often requires additional coordinate transformations. In addition, the fact that a linear control is applied to a nonlinear system can lead to uneven performance throughout the dynamic range. Moreover, today's digital implementation requires sampled data control schemes that are an approximation of the continuous-time linear controller. All this, together with the additional modulation stage, introduces several design steps and considerations for achieving a suitable control scheme, which can be very challenging for some power converters such as matrix, multilevel converters, etc. Furthermore, power converter systems are subject to several system constraints and technical requirements (total harmonic distortion (THD), maximum current, maximum switching frequency, etc.), which cannot be directly incorporated into linear controller design. In summary, classical control theory has been adapted over and over in order to use it in modern digitally controlled converters.

With the development of more powerful microprocessors, new control schemes have been proposed. Some of the most important ones are fuzzy logic control, neural networks, sliding mode control, and predictive control.

Among these new control schemes, predictive control appears to be a very interesting alternative for the control of power converters and drives. Predictive control comprises a very wide family of controllers with very different approaches. The common ideas behind all predictive control are the use of a model of the system for calculating predictions of the future behavior of the controlled variables, and the use of an optimization criterion for selecting the proper actuation.

One of the best known predictive control schemes is deadbeat control, which uses a model of the system to calculate the voltage that makes the error zero in one sample time. Then the voltage is applied using a modulator. A different and very powerful predictive control strategy that has been applied quite recently to power electronics is model predictive control (MPC), which is the subject of this book.

1.3.3 Control Requirements and Challenges

Traditionally, control requirements were mainly associated with the dynamic performance and stability of the system. Currently, industry requires more demanding technical specifications and constraints, and in many cases it is subject to regulations and codes. Many of these requirements enforce operating limits and conditions that cannot be dealt with by the hardware only, but also need to be addressed by the control system. This shift in trend has driven the development of more advanced control methods.

The design of an industrial power electronic system can be seen as an optimization problem where several objectives must be fulfilled at the same time. Among these requirements, constraints, and control challenges, the following are especially important in power electronics:

- Provide the smallest possible error in the controlled variables, with fast dynamics for reference following and disturbance rejection.
- Operate the power switches in such a way that switching losses are minimized. This requirement leads to increased efficiency and better utilization of the semiconductor devices.
- Power converters are switched systems that inherently generate harmonic content. Usually this harmonic content is measured as THD. Many power converter systems have limitations and restrictions on the harmonic content introduced by the modulation stage. These limits are usually specified in standards that can change from one country to another.
- The electromagnetic compatibility (EMC) of the system must be considered, according to defined standards and regulations.
- In many systems, common-mode voltages must be minimized due to the harmful effects that they can produce. These voltages induce leakage currents that reduce the safety and lifetime of some systems.
- Good performance for a wide range of operating conditions. Due to the nonlinear nature of power converters, this is difficult to achieve when the controller has been adjusted for a single operating point of the linearized system model.
- Some converter topologies have their own inherent restrictions and constraints such as forbidden switching states, voltage balance issues, power unbalances, mitigation of resonances, and many other specific requirements.

1.3.4 Digital Control Platforms

Control strategies for power converters and drives have been the subject of ongoing research for several decades in power electronics. Classical linear controllers combined with modulation schemes and nonlinear controllers based on hysteresis bounds have become the most used schemes in industrial applications. Many of these concepts go back to research on analog hardware, which limited complexity. Modern digital control platforms like DSPs have become state of the art and have been widely accepted as industrial standards. The main digital control platforms used in industrial electronics are based on fixed-point processor, due to the high computational power and low cost. However, in the academic world, control platforms based on floating-point processor with high programming flexibility are more usually used. Recently, hardware and software solutions implemented in field programmable gate arrays (FPGAs) have received particular attention, mainly because of their ability to allow designers to build efficient and dedicated hardware architectures by means of flexible software. The main stream control platforms used in power electronics are summarized in Table 1.1. An example of the continuously increasing computational power of digital hardware is shown Figure 1.7.

Table 1.1 Examples of digital control platforms

DSP TMS320F2812	DSP TMS320C6713	dSPACE DS1104–DS1103	FPGA XC3S400
150 MHZ Fixed-point 150 MIPS	225 MHz Floating-point 1800 MIPS	350 MHz–1 GHz Floating-point 662–2500 MIPS	50 MHz Fixed-point –
			

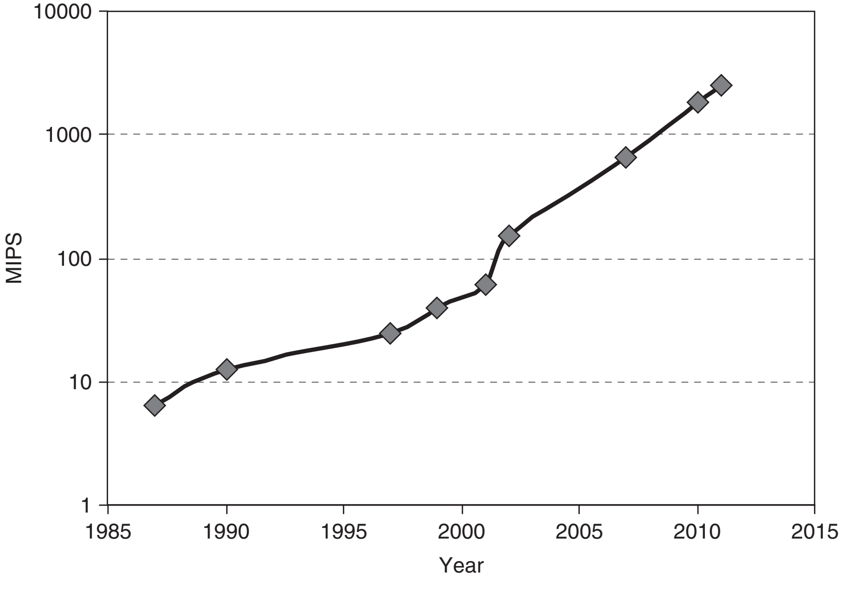


Figure 1.7 Evolution of the processing capabilities of digital hardware

This computational power is measured in terms of millions of instructions per second (MIPS). The high computational power of today's control platforms allows the implementation of new and generally more complex control techniques, for example, fuzzy, adaptive, sliding mode, and predictive control techniques.

1.4 Why Predictive Control is Particularly Suited for Power Electronics

Considering the increasing demands in performance and efficiency of power converters and drives, the development of new control schemes must take into account the real nature of these kinds of systems. Power converters and drives are nonlinear systems of a hybrid nature, including linear and nonlinear parts and a finite number of switching devices. The input signals for power electronic devices are discrete signals that command the turn-on and turn-off transitions of each device. Several constraints and restrictions need to be considered by the control, some of which are inherent to the system, like the maximum output voltage of the inverter, while others are imposed for security reasons, like current limitations to protect the converter and its loads.

Nowadays, practically all control strategies are implemented in digital control platforms running at discrete time steps. Design of any control system must take into account the model of the plant for ajusting the controller parameters, which in the case of power converters and drives is well known. As described in the previous section, control platforms offer an increasing computational capability and more calculation-demanding control algorithms are feasible today. This is the case for predictive control.

All these characteristics of the power converters and drives, as well as the characteristics of the control platforms used to form the control, converge in a natural way to the application of model predictive control, as summarized in Figure 1.8. The purpose of this book is to highlight the characteristics that lead to simple control schemes that possess a high potential for the control of power converters and drives.

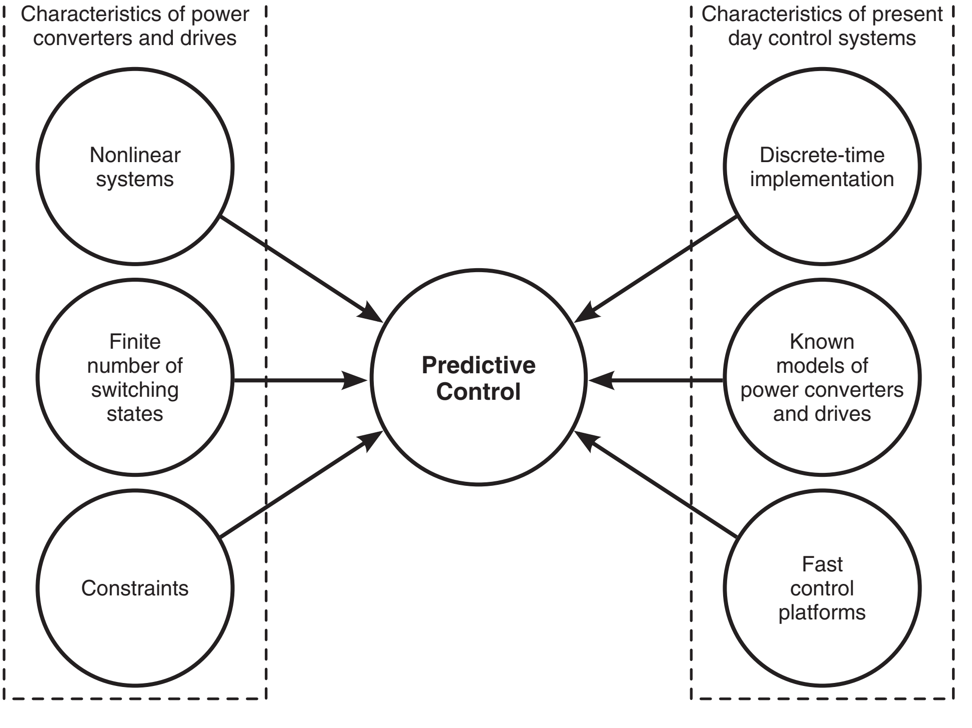


Figure 1.8 Characteristics of power converters and drives that make predictive control a natural solution

1.5 Contents of this Book

The book is organized in four parts. Basic information about power converters, drives, and the classical control schemes appears in the first part. A brief introduction to the basic theory behind model predictive control is also included in this first part. The second part includes several examples of the application of predictive control to different power converter topologies. The third part focuses on predictive control schemes for motor drives, considering induction machines and permanent magnet synchronous motors. The fourth part summarizes several design and implementation aspects that are not covered in the previous parts.

The contents of the subsequent chapters can be summarized as follows:

- Chapter 2 presents some of the most established control methods for current control and state-of-the-art control schemes for drives. These control schemes will be considered as a reference point for comparison of the predictive control schemes presented throughout the book.
- Chapter 3 contains the basic principles of model predictive control and the main considerations that are taken into account for its application to power converters and drives.
- Chapter 4 introduces the application of predictive control to power converters, considering one of the most common converters, the three-phase inverter.
- A three-level neutral-point clamped inverter is considered in Chapter 5. A predictive current control scheme that takes into account the special requirements imposed by this converter topology is presented.
- Different predictive control schemes for active front-end rectifiers are presented in Chapter 6, including current control and power control.
- The application of predictive control to a matrix converter is covered in Chapter 7. Control schemes for the input and output variables are presented.
- Predictive control schemes for induction machines are presented in Chapter 8. Current control and torque control schemes are considered.
- Chapter 9 presents current control and speed control for permanent magnet synchronous motors.
- Considerations on the formulation of an appropriate cost function are discussed in Chapter 10.
- Some guidelines on how to adjust the weighting factors of the cost function are presented in Chapter 11.
- The high number of calculations required by predictive control introduces time delays between the measurements and the actuation. A method to compensate this delay, and related topics, are included in Chapter 12.
- An empirical approach to assess the effect of model parameter errors in the performance of predictive control is presented in Chapter 13.

In the appendices to this book, information about how to implement MATLAB® simulations of predictive control schemes is given, considering three different examples. These examples will allow the reader to start implementing predictive control from proven simulations. In this way, it will be easier for the reader to understand the principles of predictive control and then adapt these schemes to different applications.

References

[1] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power electronics*, 3rd ed. John Wiley & Sons, Inc., 2003.

[2] B. Bose, "Energy, environment, and advances in power electronics," *IEEE Transactions on Power Electronics*, vol. 15, no. 4, pp. 688–701, July 2000.

[3] J. Rodríguez, J. Pontt, N. Becker, and A. Weinstein, "Regenerative drives in the megawatt range for high-performance downhill belt conveyors," *IEEE Transactions on Industry Applications*, vol. 38, no. 1, pp. 203–210, January/February 2002.

[4] J. Rodríguez, J. Pontt, G. Alzarnora *et al.*, "Novel 20-MW downhill conveyor system using three-level converters," *IEEE Transactions on Industry Applications*, vol. 49, no. 5, pp. 1093–1100, October 2002.

[5] "Grid code: High and extra high voltage," E.ON Netz GmbH, Bayreuth, Germany, Status: 1 April 2006.

[6] D. Ionel, "High-efficiency variable-speed electric motor drive technologies for energy savings in the US residential sector," in 12th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), pp. 1403–1414, May 2010.

[7] G.-A. Capolino, "Recent advances and applications of power electronics and motor drives–advanced and intelligent control techniques," in 34th Annual IEEE Conference on Industrial Electronics, IECON. pp. 37–39, November 2008.

[8] I. Takahashi and T. Noguchi, "A new quick response and high efficiency control strategy for an induction motor," *IEEE Transactions on Industry Applications*, vol. 22, no. 5, pp. 820–827, September 1986.

[9] T. Ohnishi, "Three phase PWM converter/inverter by means of instantaneous active and reactive power control," in Proceedings of the International Conference on Industrial Electronics, Control and Instrumentation, 1991. Proceedings. IECON '91. vol. 1, pp. 819–824, October–November 1991.

[10] F. Blaschke, "The principle of field-orientation applied to transvector closed-loop control system for rotating field machines," *Siemens Review*, vol. XXXIX, no. 5, pp. 217–219, 1972.

[11] M. Kazmierkowski and L. Malesani, "Current control techniques for three-phase voltage-source pwm converters: a survey," *IEEE Transactions on Industrial Electronics*, vol. 45, no. 5, pp. 691–703, October 1998.