Introduction

The present-day soul searching over modern society's dependency on oil has resulted in considerable attention being given to alternative, renewable energy sources; this has emphasized how important electrical energy will be in the future, and its potential for reducing environmental impact.

This is particularly true for electrical energy conversion, a field that has seen continual progress over the last 30 years. The primary reasons for this have been the development of power switches operating at increasingly higher speeds and ever-increasing power levels. At the same time digital systems, able to act as controllers for power electronics, have opened up new possibilities both in terms of ease of use and increased performance.

Thus static converters and their accompanying controllers have become critical to modern power conversion devices. This fact has rapidly led controller designers to pay close attention to the electrical output from static converters (voltages and currents) since these have a direct effect on the quality of the higher-level control variables such as torque and velocity (in the case of an actuator) or active and reactive power flows (in the case of a generator connected to the grid).

This observation has naturally led designers to organize their controllers in a hierarchical manner. The lowest level is known as the current and/or voltage controller. This inner-loop controller ensures that electrical quantities output from the converter are correctly regulated, thus ensuring a high quality of energy transfer between the source upstream of the converter and its downstream load. The next highest level accompanies the inner loop controller. This second level is often referred to as “algorithmic control” because it is generally implemented in a microprocessor (DSP, RISC, etc.). This more sophisticated element of the control focuses on controlling the variables directly relevant to the final application (speed of a motor, etc.). The resultant servo loops are known as outer-loop controllers and their control quantities act as references to the inner-loop controllers.

The current-voltage control of static converters is an important technical consideration since it is crucial to the correct functioning of the entire energy conversion system.

The dynamic characteristics that are required span over a considerable range and the specifications are continually being tightened in response to technological advances. Thus, a great deal of research effort has been devoted to this topic, both in universities and in industry, and we will attempt to summarize that work in this book, discussing not only the reference algorithms but also the current trends in innovation within this field.

In this book on current and voltage control of static converters, we will focus on the following two central themes:

– Chapters 1 to 9 focus on pulse width modulation (PWM) techniques that enable a static converter to continuously generate variable output voltages in response to binary orders sent to the static converter, with both the output amplitude and frequency being controllable in terms of instantaneous mean values;

– Chapters 10 to 16 focus on electric current control techniques.

In order to better introduce PWM techniques, we should recall a few important characteristics of electronic power devices. These are high-efficiency devices since they only operate in fully blocking states (zero current) or fully conducting states (zero voltage). The transition from a blocking state to a conducting state, and vice versa, occurs in response to a switching action.

However, this switching method of energy conversion can only produce a limited number of different voltage levels, in other words, it is a quantized process. Consequently, in order to achieve acceptable accuracy for the amplitudes and frequencies of the resultant voltage waveforms we must modulate the duration of the voltage pulses applied to the gates of the power switches.

The modulation will be more effective when its associated frequency is higher. However, this modulation frequency can only be increased up to a certain limit beyond which it leads to unacceptably high switching losses in the power switches. Another factor limiting increases in switching frequency is associated with an increase in conducted and radiated interference, which can cause damage to equipment near the static converter: this is a problem of electromagnetic compatibility.

Thus, this inevitable compromise between an increase in the modulation frequency and the drawbacks associated with this increase has led researchers to develop a wide range of modulation techniques.

The quality criteria commonly specified for a PWM system include minimization of the total harmonic distortion of the electric current, maximization of the linear range of the fundamental harmonic voltage, minimization of torque harmonics (in the case of motor control), reduction of losses within the static converter, and minimization of the common mode voltage that is produced.

The aim of the first nine chapters of this book is to highlight the wide variety of PWM techniques that are available. Focus will be on the case of the voltage source inverter because of its importance in industrial applications.

Chapters 1 and 2 can be treated as reference chapters. They discuss in depth the two main families of PWM strategies: carrier-based PWM strategies and space vector PWM strategies. In both these cases we will study a two-level voltage inverter intended to feed a three-phase inductive load such as an electric motor. We will emphasize the conceptual similarities between these two approaches despite their different implementations. The degree of freedom introduced by the addition of a zero-sequence component to the modulated voltage enables us to meet a range of challenges (e.g. maximization of the linear range and limitation of losses).

Chapter 3 considers overmodulation of three-phase voltage inverters, a very important mode of operation in case of variable speed drive applications. We will discuss modulation strategies for when the required voltage is close to or greater than the maximum possible value, with the main objective to maximize the total power while restricting the effects of low frequency harmonic components.

Chapter 4 discusses high-power systems for which the modulation frequency is necessarily restricted. The idea here is to work with modulation frequencies that are synchronized with the fundamental harmonic, and to optimize the harmonic content of the modulated voltage waveforms by careful choice of the exact switching times. We will consider the case of a three-level inverter as well. We will also present an original configuration for a multi-level power supply using active filtering based on two, two-level inverters (one supplying the requisite power and the other operating as an active filter). This construction enables the harmonic content of the power supply to be optimized.

Chapter 5 describes the Delta-Sigma modulation strategy. The main advantages of this modulation are its robustness, the possibility of reducing the ratio between the switching frequency and the modulation frequency, and the possibility of operating with either variable or fixed switching frequency.

Chapter 6 considers stochastic modulation methods. The main advantage is that they can broaden the spectrum of the modulated signals, thus reducing electromagnetic and acoustic interference. The latter will be the subject of a detailed study at the end of the chapter.

Chapter 7 continues from the previous chapter. It focuses on analyzing conducted electromagnetic interference produced by the modulated voltages output from a voltage source inverter driving an electric motor.

Chapters 8 and 9 offer an introduction to the study of modulation strategies for energy conversion devices where the power delivery is distributed. There is a strong interest, presently, in designing energy conversion structures with multiple windings or multiple levels. These structures are inevitably more complex than a traditional three-phase motor driven by a two-level inverter. Indeed, such structures enable fault-tolerant architectures to be developed, exploiting the redundancies present in such a system; they can also be used to distribute between multiple components the power that the device must deliver, thus reducing the stress on the power switches and increasing the lifetime of the equipment.

Chapter 8 introduces an extension of the space vector PWM technique to multiphase systems through a formalism based on linear algebra.

Chapter 9 provides a generic discussion of PWM applied to common multilevel converter topologies. In particular, we show how redundancies in the voltage levels can be exploited to optimize additional objectives such as voltage balancing across flying capacitors.

Chapters 10 to 16 are devoted to current regulation techniques. It seems worthwhile recalling the main reasons that have led designers to integrate this type of regulation in a fairly systematic manner into the design of inner-loop control systems for static converters. The main objectives are to ensure accurate control of the instantaneous current waveforms to protect the static converter from any potential current surges, to reject disturbances caused by the load, to be robust with regard to parametric variations and to nonlinearities within the converter, and also to offer excellent control dynamics. From a quantitative point of view these criteria result in a minimal static error, maximize the bandwidth, and offer an optimized modulation depth and a minimum level of distortion.

These fundamental requirements for current regulation are often accompanied, where possible, with additional regulation requirements such as control over the switching frequency in the case of hysteresis-based control, balancing of intermediate voltages in the case of a multicell converter, etc.

As we will see in this part of the book, current control structures are also tightly integrated with the applications with which they are associated. It is for this reason that we have included a range of studied examples although we make no claims of being exhaustive. These examples will of course include the combination of a voltage inverter and motor, a very popular case and one that has seen the greatest range of experimental work in terms of current control. Nevertheless, the current control techniques that are brought together in this volume are also relevant to other types of applications such as high performance *power-in-the-loop* emulation, the generation of electrical energy both for the electrical grid and for isolated networks, DC/DC power delivery, and high-power applications based on multilevel converters.

In terms of their operating principles, current regulation methods for static converters can be divided into two main families:

– direct control, also known as amplitude control, for which the outputs of the current regulators directly control the associated static converter. These control strategies are exclusively nonlinear. Their main advantage is that they ensure excellent system dynamics along with a high robustness in the face of parametric variations and model uncertainties. Their main drawbacks are variation in switching frequency and the emergence of limit cycles at steady state;

– indirect control, also known as PWM control, for which the outputs of the current regulators act as inputs to a PWM modulator (Chapters 1 to 9). These control strategies may be either linear or nonlinear and offer the possibility of controlling the converter in a very accurate manner and at a fixed frequency, thus avoiding any risk of limit cycles appearing. However, the dynamics that can be achieved using such methods are generally not up to the standard of those obtained using direct command.

Chapters 10 to 12 discuss a single application: current control for a synchronous motor supplied by a three-phase voltage inverter. For this application, control of the current is equivalent to control of the torque. Chapter 10 discusses indirect control using a PI controller in a rotating reference frame. The quantities being controlled are constant at steady state, which makes servo control of those quantities easier. This first control method is linear and will be treated as a reference method since it is so widely used in industry.

Chapter 11 discusses direct and indirect predictive control, the principle of which involves calculating the most suitable voltage vector to apply in each sampling period. This control strategy is relatively demanding in terms of computation time but can be implemented in a highly parallel manner. It is therefore very well suited to implementation in an FPGA (Field Programmable Gate Array).

Chapter 12 describes direct and indirect sliding mode control. The design principle behind these two sliding mode control methods is described in detail and their contrasting strengths in terms of dynamics and precision are clearly demonstrated.

Chapter 13 discusses hysteresis-based control. The aim is to explain the fundamentals of this type of control using theoretical tools developed for the study of nonlinear systems. Without focusing on any specific application, this chapter offers a different perspective on the qualities of this direct control method focusing on the concept of modulated hysteresis control, which combines the excellent dynamic performance of hysteresis control with guaranteed fixed frequency operation.

Chapter 14 discusses current and voltage control using a self-oscillating regulator, known as SOCC (self-oscillating current control) and SOVC (self-oscillating voltage control). This innovative direct control technique is protected by patents. It relies on self-oscillation within the control loop, a property that guarantees fixed frequency operation at the same time as promising excellent performance in terms of dynamics and robustness. Here, the application area is for *power-in-the-loop* emulation of electrical loads.

Chapter 15 introduces the principle of resonant control at fixed frequency. This type of control makes it possible to introduce an infinite gain at a precisely known frequency, which results both in elimination of any tracking error and rejection of any disturbance at this specific frequency. This control strategy, which is a sensitive form of regulation, is very promising since it is ideally suited to distributed energy generation networks. Here the authors demonstrate the qualities of these resonant regulators through an example of control of a wind turbine able to operate both on a power grid and on an isolated network. This is an indirect, linear type of control.

Finally, Chapter 16 presents a *state of the art* for current control of multi-cell converters. The number of degrees of freedom available in such conversion structures is useful for studies into multi-objective current control (both tracking of commanded current references and balancing of internal voltages). The application area here is for high-power equipment. We also show how the principle control paradigms presented earlier can be adapted to the case of multilevel converters.

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