Sliding Mode Control of Switching Power Converters

Techniques and Implementation

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Preface

As the characteristics of power sources and electrical/electronic loads become more widely varied, nonlinear, and unpredictable, the control of the power converters that provide the necessary power processing functions will play a crucial role in optimizing performance and maintaining the needed robustness under various operating conditions. Conventional control approaches based on small-signal linear techniques are found to be incapable of achieving the necessary regulation, dynamic response, and stability requirements needed for these systems. Much research effort has been devoted to the development of advanced control methods that are able to address the complex requirements of power conversion systems. In particular, modern control theories such as sliding mode control, fuzzy control, adaptive control, etc., have been applied to the control of these systems, and their feasibility has been studied. Among them, sliding mode control has been most widely investigated and has demonstrated to be a highly promising solution for both current and future generations of power converters.

Following the trend of this development and taking advantage of the mature theoretical framework already being laid out on the subject, it is timely to present a complete exposition of the development of sliding mode controllers for power converters. This book presents an in-depth and thorough account of how such kind of controllers can be practically engineered to suit the purpose of controlling power converters. The dissemination of such knowledge is now timely and necessary, especially since the electronic industry is moving toward using renewable energy sources and widely varying loads, which can only be adequately supported by power converters using nonlinear controllers.

We developed this book with the following objectives in mind. First, we aim to offer a comprehensive overview of the principles and methods in the application of sliding mode control to power converter systems for the general readership. Second, for the more advanced readers, we aim to provide a systematic exposition of the mathematical machineries and design principles relevant to the construction of sliding mode controllers, and building upon that, to introduce and impart new practical approaches of designing such controllers. Our third objective is to demonstrate the practical implementation of sliding mode controllers based on analog circuits and to present their supporting design rules. Our final objective is to promote an appreciation of nonlinear control in general by presenting it from a practical perspective and using terminology that is familiar to the engineers.

In a nutshell, *Sliding Mode Control of Power Converters: Techniques and*

Implementation will be a guide to understanding the sliding mode control principle, its application to power converters, and the practical realization of sliding mode controllers. By combining theory with application and relating mathematical concepts and models to their industrial targets, this book will be equally accessible to readers with analog circuit design, power electronics, or control engineering backgrounds. We believe that this book will be of interest to students and professionals alike in the field of electrical and electronic engineering. At the same time, we believe that our approach to the modeling and implementation of sliding mode controllers for power converters will help power electronics and IC industry professionals design effective and high-performance controllers for power converters.

The book is organized as follows. We will begin in Chapter 1 with a discussion on the basic principles and theory of sliding mode control to familiarize readers with the core terminology and background of sliding mode control. This is followed by Chapter 2, in which we will give a review on the basics of power converters and their control. A short discussion on the common types of control techniques available and the current progress of the research work on the control of power converters are also provided. Next, in Chapter 3, we move on to address the important concepts, operating principles, and properties of the sliding mode controller that are relevant to the application of power converters. Here, we will also provide a detailed review of the state-of-the-art research work and some common practices in the development of sliding mode controllers for power converters.

Then, in Chapter 4, the practical design process of sliding mode controllers based on hysteresis modulation for the power converters is described. In Chapter 5, the problem of switching frequency variation in traditional sliding mode control, due to the deviation of operating conditions, and the effectiveness of applying adaptive control solutions in sliding mode control in alleviating the problem, will be thoroughly covered. Chapter 6 introduces a practical technique for implementing sliding mode control with fixed frequency for power converters operating in continuous conduction mode. Then, the idea of implementing fixed-frequency sliding mode controllers using equivalent control is further explored in Chapter 7. This includes the derivation of the system models and sliding mode control laws for the discontinuous conduction mode converter counterparts. In Chapter 8, we extend our discussion to the design and practical circuit implementation of the pulse-width-modulation-based sliding mode controllers.

Up to this stage of the book, our discussions have been focused on the design and implementation of sliding mode controllers using the output voltage of the converters as the control variable for constructing the sliding manifold. For Chapters 9 to 11, the design and implementation of the sliding mode controllers are extended to cover power converters with non-conventional sliding manifolds that are constructed nonlinearly from the current error and voltage error. In Chapter 9, the design and implementation of sliding mode controllers based on current error and voltage error will be discussed. In Chapter 10, the discussion will be focused on how a reduced-state nonlinear sliding manifold may be used for the control of a high-order converter like the Ćuk converter. In Chapter 11, a non-conventional type of sliding mode controller based on a double-integral sliding surface for improving the steady-state regulation is discussed.

For the completion of this book, we must give our sincere gratitude to a number of people, institutions, and organizations. First, we would like to thank all our friends and colleagues in the Department of Electronic and Information Engineering at Hong Kong Polytechnic University, and the members of the Applied Nonlinear Systems Research Group, for their friendship, encouragement, and inspiration. Special thanks are due to Prof. Luis Martínez-Salamero, Universidad Rovira i Virgili, Tarragona, Spain, who is not only a great friend to us, but is also an important collaborator of some of our research work in this area. Luis is by far the most knowledgeable person in sliding mode control applications in power electronics that the authors personally know. We would also like to take this opportunity to extend our gratitude to Prof. Ashoka Bhat, Dr. Martin Chow, Prof. Adrian Ioinovici, Dr. Joe Liu, Dr. Franki Poon, Dr. Siu Chung Wong, and Prof. Xinbo Ruan, who are all experts in different areas of power electronics, and whom the authors have worked with and learned a great deal from. Next, we would also like to thank the staff of CRC Press, especially Ms. Leong Li Ming and Ms. Amy Blalock, for their professional and enthusiastic support of this project. The completion of this research work would not be possible without the financial support of the Hong Kong Research Grant Council and the Research Committee of Hong Kong Polytechnic University. Last, but not least, we must thank our families for their support and understanding throughout the course of our academic careers.

Finally, it is our pleasure to dedicate this book to all those who have been passionately involved in the work on sliding mode control and the control of power electronics.

Siew-Chong Tan
Yuk-Ming Lai
Chi Kong Tse

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Introduction to Sliding Mode Control

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1.1 Introduction

The earliest published works that introduced the concept of sliding mode (SM) control can be traced back to the 1930s, and the earliest forms of SM control realization were successfully applied for ship-course control and the control of DC generators [102]. In fact, the development of the theory and applications of SM control were first initiated by Russian engineers, and in the 1950s, the theoretical framework that later facilitated the widespread applications of SM control was reported in the Russian literature [21, 101, 102]. The work was subsequently disseminated outside Russia in English written manuscripts by Itkis (1976) and Utkin (1977) [21]. Since then, the SM control theory has aroused a lot of interests from control theoreticians and practicing engineers around the world.

In simplest terms, the SM control is a kind of nonlinear control which has been developed primarily for the control of variable structure systems [21, 68, 85, 101, 102]. Technically, it consists of a time-varying state-feedback discontinuous control law that switches at a high frequency from one continuous structure to another according to the present position of the state variables in the state space, the objective being to force the dynamics of the system under control to follow exactly what is desired and pre-determined.

The main advantage of a system with SM control characteristics is that it has guaranteed stability and robustness against parameter uncertainties [102]. Moreover, being a control method that has a high degree of flexibility in its design choices, the SM control method is relatively easy to implement as compared to other nonlinear control methods. Such properties make SM control highly suitable for applications in nonlinear systems, accounting for their wide utilization in industrial applications, e.g., electrical drivers, automotive control, furnace control, etc. [21].

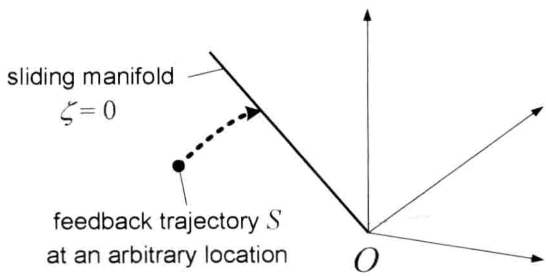
In this book, we are concerned with a particular class of variable structure engineering systems, known as power electronics converters. The aim of this introductory chapter is to introduce the basic concepts and mathematical background of SM control that are necessary for understanding the discussions covered in the following chapters.

1.2 General Theory

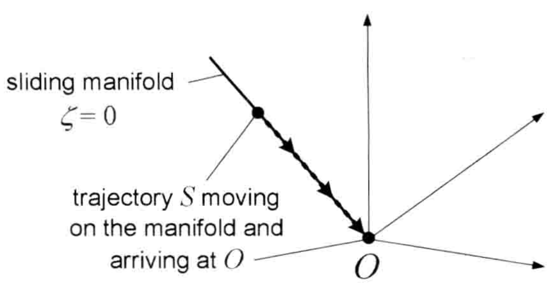
Let us start by considering a system in a three-dimensional space. Imagine that there exists a plane in this space. On this plane, there is a point O, which we call the equilibrium point. This equilibrium point represents a stable attractor where any trajectory that touches it will settle upon it. It is also a point which we would like to drive the trajectory of our system to.

Next, we consider that the system's controlled trajectory is arbitrarily located in space and is far away from the plane. Without any control action, the trajectory will move according to the natural characteristics of the system. However, when a control action is given, the trajectory can be altered in a "preferred way." The direction in which the trajectory moves is dependent on the type of control action given. A series of different control actions may be given to the system such that regardless of its initial condition, the controlled trajectory will first move toward the plane, and upon reaching the plane, will slide along the plane toward and eventually settle upon O.

A control such as this is known as SM control. The plane which guides the trajectory is called the sliding plane or sliding surface, or more generally, the sliding manifold. The control actions required for performing the SM control



(a) Reaching phase



(b) Sliding phase

FIGURE 1.1
Graphical representations of SM control process: (a) Reaching phase—illustrating trajectory S moving toward the sliding manifold irrespective of its initial condition; and (b) Sliding phase—illustrating trajectory S moving on the sliding manifold and stopping at the origin O.

will involve very fast switching between different control functions. The sectors of the space in which the trajectory can be made to perform SM control is called the sliding regimes.

With all these terminologies explained, let us put the definition of SM control in a more formal sense. For any given system, if a sliding regime exists and the sliding manifold $\zeta = 0$ possesses a stable equilibrium point O, when operated in sliding mode, the feedback tracking trajectory S, regardless of its location, will be driven toward the sliding manifold, and upon hitting the manifold, it will induce the control of the system to switch alternately between two or more discrete control functions U_1, U_2, ..., etc., at an infinite frequency, such that the system's trajectory will be trapped precisely on the sliding manifold such that $S = \zeta = 0$, and eventually the trajectory will be directed toward the desired equilibrium point O.