

Complex Behavior in Switching Power Converters

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Invited Paper

Power electronics circuits are rich in nonlinear dynamics. Their operation is characterized by cyclic switching of circuit topologies, which gives rise to a variety of nonlinear behavior. This paper provides an overview of the chaotic dynamics and bifurcation scenarios observed in power converter circuits, emphasizing the salient features of the circuit operation and the modeling strategies. In particular, this paper surveys the key publications in this field, reviews the main modeling approaches, and discusses the salient bifurcation behaviors of power converters with particular emphasis on the disruption of standard bifurcation patterns by border collisions.

Keywords—Bifurcation, chaos, dc–dc converters, nonlinear dynamics, power electronics, switching power converters.

I. INTRODUCTION

Power electronics is a discipline spawned by real-life applications in industrial, commercial, residential, and aerospace environments. Much of its development evolves around some immediate needs for solving specific power conversion problems. In the past three decades, this branch of electrical and electronic engineering has undergone an intense development in many aspects of technology [1], including power devices, control methods, circuit design, computer-aided analysis, passive components, packaging techniques, etc. The principal focus in power electronics, as reflected from topics discussed in some key conferences [2], [3], is to fulfill the functional requirements of the application for which its circuits are used. Like many areas of engineering, power electronics is mainly motivated by practical applications and it often turns out that a particular circuit topology or system implementation has found widespread applications long before it has been thoroughly

analyzed. For instance, the widespread application of a simple switching converter may date back to more than three decades ago. However, good analytical models allowing better understanding and systematic circuit design were only developed in the late 1970s [4] and in-depth analytical characterization and modeling is still being actively pursued today. Despite their common occurrence in power electronics circuits, nonlinear phenomena have only recently received appropriate formal treatments.

In this paper, we review some of the nonlinear phenomena observed in typical power electronics systems. Our intention is to provide an overview of the recent research effort in the study of nonlinear phenomena in power converters, and to summarize the essential analytical approaches that can be used to perform a systematic study of the nonlinear behavior of such systems. The rest of the paper is outlined as follows. We begin in Section II with a brief overview of power electronics circuits, followed by a discussion of the benefits of studying chaotic dynamics in power electronics in Section II-C. A quick tour of some recent findings is presented in Section III. In Section IV, we present a discussion of the modeling methods for characterizing nonlinear behavior such as bifurcation and chaos in switching converter circuits. In Section V, we focus on the typical bifurcation scenarios observed in switching power converters, expounding their most relevant aspects from a practical viewpoint.

II. BRIEF OVERVIEW OF SWITCHING CONVERTERS OPERATION

The basic operation of any power electronics circuit involves toggling among a set of linear or nonlinear circuit topologies, under the control of a feedback system. As such, they can be regarded as *switched* or *piecewise-smooth* dynamical systems.

For example, in simple direct current–direct current (dc–dc) converters, such as the ones shown in Fig. 1, an inductor is “switched” between the input and the output through an appropriate switching element (labeled as *S*

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