THE STEADY-STATE AND DYNAMIC CHARACTERISTICS OF FOURTH ORDER CURRENT-SOURCE RESONANT POWER CONVERTERS

by

SARAVAN AYYAPPA KANCHUBOTLA, B.E

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SARAVAN AYYAPPA KANCHUBOTLA

Department of Electrical and Computer Engineering

APPROVED:

Bill M.Diong, Ph.D., Chair

Darrell C. Schroder, Ph.D.

Ryan B. Wicker, Ph.D.

Charles H. Ambler, Ph.D.
Dean of the Graduate School

Dedicated to

my parents
Lakshmi Narasimham Kanchibhotla & Padma Suryanarayana Melarkode

and

my sister
Sai Kanchibhotla

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Abstract

High-frequency resonant converters possess several advantageous properties that make them well suited for high power density applications, such as on aerospace vehicles. A comparison of high frequency resonant converter topologies with four energy storage elements is presented. It first describes how all possible circuit topologies for such converters under current-source and voltage/current-sink conditions can be individually characterized. The analytical results obtained regarding the converter's main steady state characteristics (including input-output transfer function, DC gain, high-frequency-gain slope, input impedance, resonant frequencies, load invariant gains and load invariant frequencies) are then summarized for easy reference. This summary provides valuable insight about which of these converters offer possible advantages (in terms of steady-state characteristics) over other fourth-order and lower-order resonant converters; two converters were identified for in-depth investigation.

This thesis then presents the detailed results for the Γ-CL//-LC current-source resonant inverter circuit and CLLC current-source resonant inverter circuit. These include analytical results on its steady-state characteristics (including input impedance, resonant frequency, input-output transfer function, individual component voltage and current stresses, and efficiency). In addition, samples of analytically derived design charts, simulation results and experimental results are shown.

This thesis then presents results regarding the dynamic characteristics of the Γ-CL//-LC current-source resonant DC/DC converter and CLLC current-source DC/DC resonant converter. An approximation technique is employed based on the extended describing function concept, to derive a small-signal model of these resonant DC/DC converters. By this method, one can obtain the frequency responses of the output voltage to frequency control, to duty-ratio control, and to source and load perturbations, useful for dynamic response studies and for control design of these converters. Analytical results derived via the proposed procedure for design examples are presented along with corresponding simulation and test results.

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Chapter 1

Introduction

Electronic systems have undergone a drastic improvement and increase in usage in the past few decades. We depend on these systems because of their assistance to us in every mode of life. Modern devices on which we depend such as computers, cell phones and other devices not only have made our lives more convenient, but also have changed our human society. Computers make our jobs easier, quicker and more efficient; we can communicate with people all around the world using wireless telecommunication systems. There has been a greater need in the automobile industry to use these systems to achieve a cleaner and quieter environment by powering vehicles with electricity.

Because of the widespread use of electronic systems, the processing and storage of electrical energy have become much more important issues to present-day society. There has been a lot of research going on to improve such processing and storage. For the power processor, we try to improve it by making it lighter, smaller and more efficient. Then we can reduce the size and weight of electronic products and get better performance. Today's engineers face difficult choice about which of the available technologies can achieve this. The technology represented by high-frequency resonant converters is one excellent method to achieve this.

1.1 Need for higher order resonant converters

High frequency resonant converters possess several advantageous properties that make them well suited for high power density applications. Until recently, only the class of resonant converters with 2 energy-storage elements had been seriously investigated and, along the way, a few drawbacks of these converters have been also identified. However, there is now evidence in the literature [1,4] that some of these drawbacks (including poor load regulation and poor transient response) can be overcome by the judicious addition of more energy-storage elements to these converters. Detailed investigations of a few particular four-element resonant converters and their advantages have also been described [1,5,6], but many more such converters have yet to be discussed in literature, raising the issue of which ones to focus attention on. In addition, since there are many more fourth-order resonant converters, design engineers will be faced with a more challenging task of selecting the appropriate topology to use for satisfying a given set of design requirements.

1.2 Thesis overview

In order to have better understanding of these resonant converters, we have to study their steady state and dynamic characteristics. This thesis focuses on those resonant power converters that use four energy storage elements. The analysis of steady state characteristics of these resonant power converters includes the current gain, which is the ratio of the output current and the input current; and the efficiency of the converter. The dynamic characteristics refer to the system's output response to system input changes.

We use small-signal techniques to model this dynamic behavior of the system. Then we can analyze the system's dynamic behavior to determine how to improve them and also apply the results to control design to achieve better stability and performance. Thus this analysis of fourth-order resonant DC-DC converters will help design engineers make use of these novel converters to satisfy their design requirements.

1.3 Topic and scope

This thesis is divided into six chapters including this introductory chapter. In the next chapter, we will introduce the concept of resonant converters. In chapter 3, fourth order current-source resonant converter steady-state characteristics are discussed and derived, to help identify which of these converters should be pursued for further detailed study.

Chapter 4 and chapter 5 deal with those particular resonant converters. In these chapters, the steady-state characteristics of each of these converters are derived and the small signal dynamic models of these converters are described.

Finally, the conclusions of this thesis and suggestions for future work are given in chapter 6.

Chapter 2

High-Frequency Resonant Power Converters

2.1 Introduction

In order to achieve power supplies with faster transient response, smaller size and lighter weight, interest in high frequency DC-DC resonant converters has been steadily increasing since the early 1980's. Because of the reduced switching losses due to sinusoidal behavior of resonant converters it is possible to operate such converters at high frequencies to reduce the size of their reactive components. Consequently, several of today's resonant DC-DC converters have their operating frequencies in the megahertz range [2]-[3]. With the exception of a few topologies, the majority of existing topologies, whether full-bridge, half-bridge or single ended quasi-resonant are of the second-order resonant tank type i.e.; the resonant tank circuit consists of only two energy storage elements.

Compared with conventional second-order resonant converters, higher-order converters have been shown to possess more desirable characteristics. The previous analysis of the LCC type [13]-[14] and LLC type [15] resonant converters show that

these converters exhibit better control characteristics than the conventional converters. In addition, by using higher order resonant tanks, the designer has the choice of utilizing parasitic capacitances and inductances, which always exist in the converter circuit, especially when operating at very high frequency. As a result, depending on the topology used, the parasitic reactance can turn into an asset rather than being a liability [16]. Moreover, the diversity in resonant topologies gives the designer flexibility to choose the topology that most suits the application. However, the drawback is that since these converters are high-order non-linear systems, their analysis becomes more difficult.

This chapter introduces resonant converters and resonant topologies, with those topologies having four energy storage elements as our main interest.

2.2 Generalized block diagram of DC-DC resonant power converter

In general, DC-DC resonant converters may be illustrated by a simplified block diagram as shown in Figure 2.1.

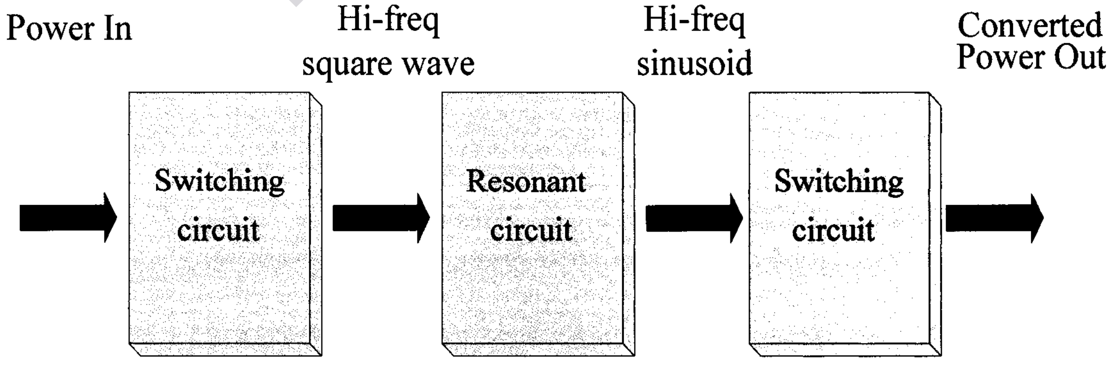

Figure 2.1: Simplified general DC-DC resonant power converter block diagram

The DC input, which can be either voltage or current source, is first processed by either half- bridge or full- bridge switching networks [1]. The AC storage tank consists of a frequency selective network whose function is to store and buffer energy transferred from the source to the load. The DC output voltage sink or current sink are typically implemented by using half or full-wave rectifier circuits in order to rectify and couple the resonant current or voltage from the resonant tank to the output circuit. The output circuit consists either a series inductor or a parallel capacitor with the load resistance in order to give constant voltage controlled current sink or constant current controlled voltage sink, respectively.

Generalized half bridge and full bridge voltage driven resonant converter circuits are shown in Figure 2.2 (a) and 2.2(b) respectively.

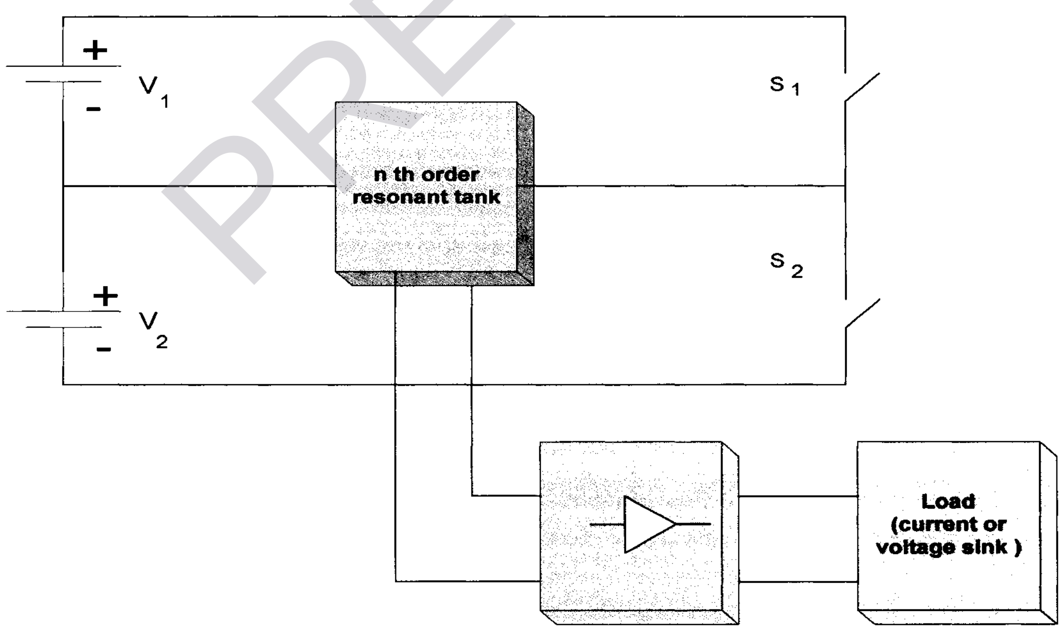

Figure 2.2(a): Generalized (Half-Bridge) voltage driven DC-DC resonant converter

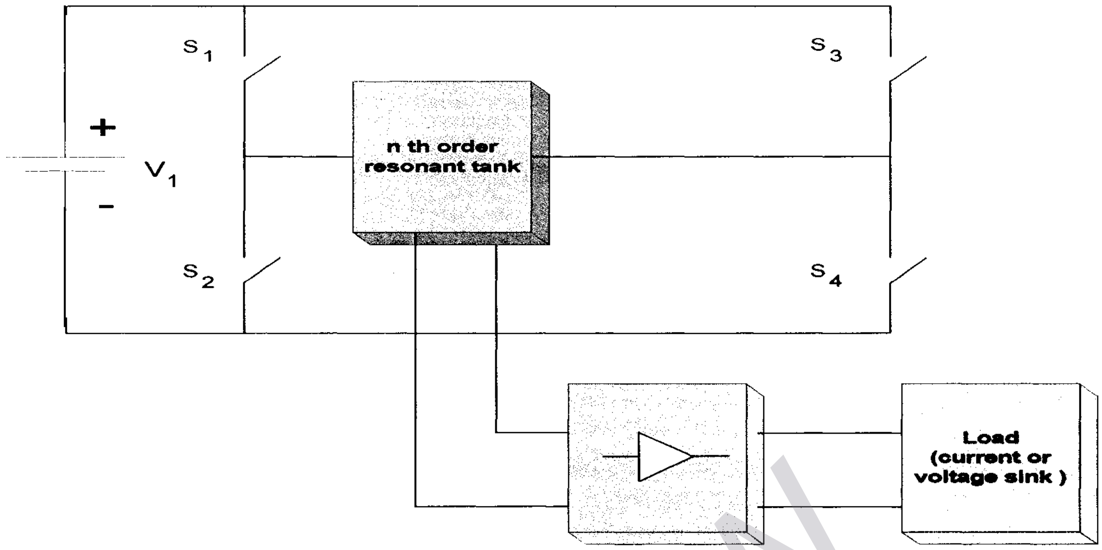

Figure 2.2(b): Generalized (Full-Bridge) voltage driven DC-DC resonant converter

Figure 2.3(a) and 2.3(b) shows the generalized half bridge and full bridge current driven DC-DC resonant converters.

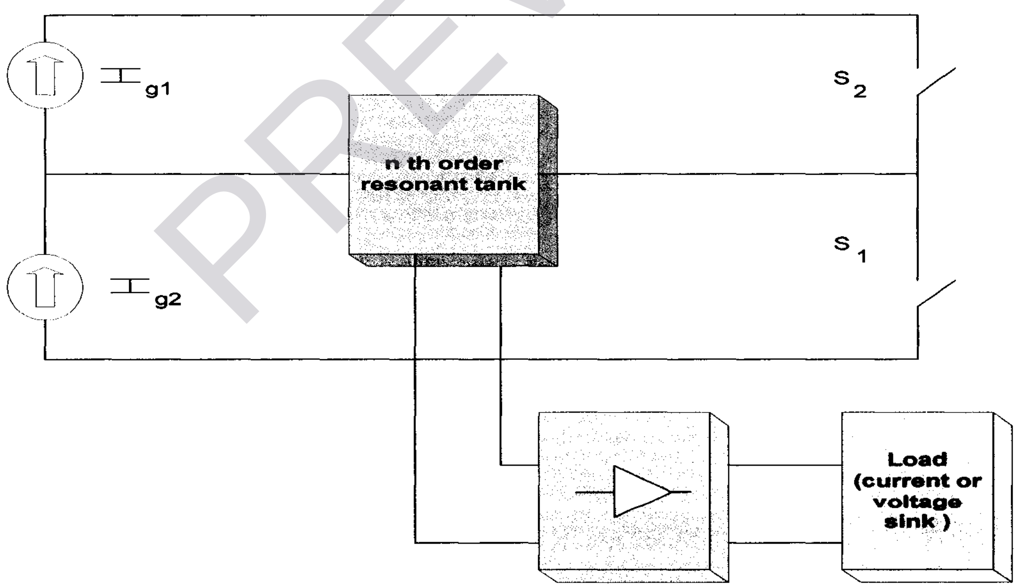

Figure 2.3(a): Generalized (Half-Bridge) current driven DC-DC resonant converter

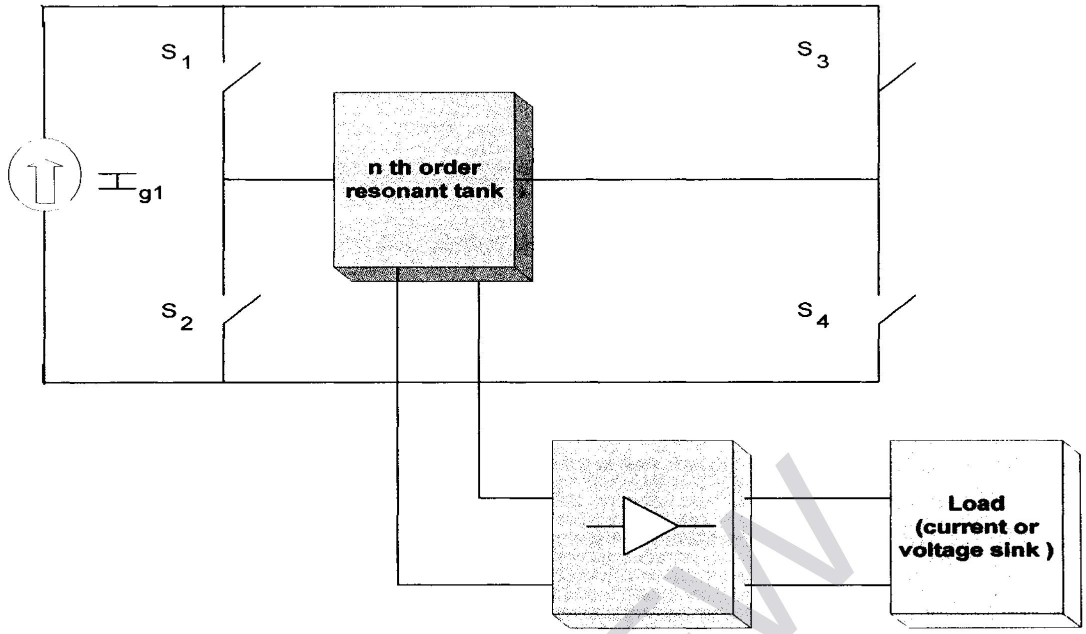

Figure 2.3(b): Generalized (Full-Bridge) current driven DC-DC resonant converter

Each of the commutational networks of these converters consists of a lossless (ideally) ideal frequency selective resonant tank. We define the order of the converter by the order of its commutational network. Practically, current and voltage sources and loads are implemented using non-dissipative components. These include semiconductor switches, capacitors and inductors.

2.2.1 Voltage Sources And Current Sources (Input switching circuit)

There are two types of power sources that can be connected to power converters. They are voltage sources and current sources. In general, they comprise a DC voltage source and some non-dissipative components such as capacitors and inductors. As shown in Figure 2.4, a DC voltage is placed in parallel with a capacitor to form a voltage source. Because there will be a pulsating input current caused by the high frequency switching of