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Power electronics converters: Past, present and future

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ABSTRACT

The development of power electronics in the past century and the current state of the art of power electronics converters are briefly reviewed, before giving an insight into the deficiencies of the conventional current-source and voltage-source converters and into the superiority of impedance-source converters and, then, proposing a design methodology for impedance-source converters aimed to replace the traditional tedious, manual and experience-dependent design methods. Some examples for their deployment in renewable-energy applications are discussed, and the direction into which power electronic converters will develop in the future is indicated.

1. Introduction

In ancient times, thunder, lightning and electric fish [1] were the natural phenomena related to electricity. They were treated as myths, but not as energy until the discovery of electrostatic phenomena by Thales of Miletus in 640–540 BCE [2,3]. Much later in 1752, B. Franklin discovered electricity [4], and in 1820 H.C. Örsted revealed electromagnetism [5]. Since then, a series of great discoveries on the principles of electricity and magnetism has been achieved by Volta, Coulomb, Gauß, Henry, Faraday and others, leading to many inventions such as batteries (1800), generators (1831), electric motors (1831), telegraphs (1837) and telephones (1876), to name just a few. In the early 19th century electricity has been established as a scientific discipline, and in the late 19th century the greatest progress has been witnessed in electrical engineering [6].

In 1882, the first power grid, which was a direct-current (DC) distribution system invented by T. Edison, was set up in New York to provide 110 V DC power supplying over 1000 bulbs in a short distance. At that time, the problem was how to transfer energy at a low loss from power plants to customers over a long distance through transmission lines [7]. It is now well known that electricity must be transmitted at high voltages and in the form of alternating current (AC), because DC voltage could not be increased or decreased by DC systems at that time [8]. In 1885, L. Gaulard and J.D. Gibbs developed a device named transformer, which can increase or decrease the electrical voltage of AC systems. Thereafter, G. Westinghouse applied transformers in AC distribution systems to transmit electricity efficiently over long distances, which has promoted the development of electrical engineering [5].

Transformers played a vital rôle in electricity transmission, especially in energy conversion between different voltages. Transformers can, however, only increase or decrease AC voltage (AC-AC) at the same frequency. Moreover, energy loss in transformers, magnetic radiations, huge volume and high cost of copper limited their wider use [9]. In practical applications, electric energy was expected to be converted from one form to another, for instance, between AC and DC, or just to different voltages or frequencies, or some combinations of those — demands that cannot be fully met by transformers. Therefore, novel techniques were required to solve those problems. With the development of semiconductor switches, power electronics has come into being [10].

Power electronics refers to electric power, electronics and control systems. Electric power deals with static and rotating power equipment for generation, transmission and distribution of electric power; while electronics is concerned with solid-state semiconductor power devices and circuits together with control systems for power conversion specified to meet the desired control objectives. Power electronics is one of the main technologies to realise energy conversion with high efficiency. It is known that about 70% of electric energy is converted by power electronics devices before it reaches the consumer. Nowadays, power electronics has become a fundamental technology critical for the development of energy conservation, especially for renewable energy [11].

The history of power electronics is linked to the breakthrough and the evolution of power-semiconductor devices. The first power electronics device was the mercury arc rectifier developed in 1900, followed by other power devices, like metal-tank rectifier, grid-controlled vacuum tube rectifier, ignitron, phanotron, thyratron and magnetic amplifier,

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developed and deployed gradually for power-control applications until the 1950s. The second electronics revolution began in 1958 with the development of the commercial-grade thyristor by the General Electric company (GE), indicating the beginning of a new era of power electronics. From 1975 to 1995, more turn-off power-semiconductor elements have been developed and implemented, which have vastly improved modern electronics. Included here are improved bipolar transistors (with fine structures, and also shorter switching times), metal-oxide-semiconductor field-effect transistors (MOSFETs), gate turn-off thyristors (GTOs) and insulated-gate bipolar transistors (IGBTs). Correspondingly, many different types of power-semiconductor devices and power-conversion techniques have been proposed and designed. The power electronics revolution has endowed us with the ability to convert, shape and control electrical power [10].

With the development of semiconductor devices, different kinds of control strategies have also been developed to realise specified purposes. For instance, high-accuracy and high-frequency control methods based on single-chip solutions like Digital Signal Processors, Field Programmable Gate Arrays or Complex Programmable Logic Devices are applied to meet desired requirements and to gain better control of loads; more accurate mathematical methods to model power converters enable gaining better output features, reducing energy losses and increasing efficiency; and improved control algorithms are utilised to improve efficiency and robustness, to reduce complexity and to achieve better output features.

Power electronics converters fall into four categories, i.e. AC-DC, AC-AC, DC-DC and DC-AC converters, and they have been invented for and found a wide spectrum of applications in, for instance, transportation (electric/hybrid electric vehicles, electric locomotives, electric trucks), utilities (line transformers, generating systems, grid interfaces for alternative energy resources like solar panels, wind turbines and fuel cells, energy storage), industry/commerce (motor drive systems, electric machinery and tools, process control, factory automation), consumer products (air conditioners/heat pumps, appliances, computers, lighting, telecommunication equipment, un-interruptible power supplies, battery chargers) or medicine. Especially in the area of renewable energy applications, power electronics converters play a more important rôle, which enable DC micro-grids to realise high-efficient usage of renewable energy, and stable interfaces between energy storage systems and renewable energy resources [12,13], as well electrification of distant villages and rural areas [14]; high-voltage direct current (HVDC) systems can be also enabled to replace some long-range transmission AC transmission systems [15]; aircraft power supplies with special requirements can be realised by specific power converters [16]; to list just a few. Thus, power electronics has established itself as a scientific discipline [17].

With the rapid development of modern industry, power electronics is facing severe problems, namely how to meet the requirements of the load; how to improve the efficiency and reliability of power-semiconductor devices; how to design converters with smaller volume, less weight and lower cost; how to reduce the number of power switches and, thus, the design complexity of converters and how to improve the robustness of entire systems; and how to minimise negative influences on other equipment in electric power systems and on the electromagnetic environment [18].

Facing these challenges, some advances have been witnessed with respect to semiconductor switches of power converters, for example, integrated gate-commutated thyristors (IGCT) were invented to have lower conduction loss compared to the traditional high-capacity switches. Accordingly, control strategies were also improved [19].

To design a new power electronics converter, one can, on one hand, develop a new control strategy; on the other hand, one can design a novel power converter topology, so as to achieve specific outputs, simpler control, higher efficiency, less complexity, lower weight, minimal cost and better robustness. In fact, a control strategy is specified for a certain topology, and the topology determines the control system. Therefore, it is of great significance to coin optimal power-converter topologies to fulfill the requirements of various applications.

Owing to a converter's input source being either a voltage source or a current source, various traditional converters fall into two categories: voltage-source and current-source converters. It is, however, known that voltage-source converters suffer from shoot-through problems, the applicability to capacitive loads only, and limited output-voltage gains; while current-source converters have open-circuit problems, are applicable to inductive loads only, and have limited output-current gains [20].

In order to solve these problems, the Z-source converter was first proposed by Peng in 2002 [21], coupling an LC impedance-network (a two-port network with a combination of two basic linear energy-storage elements, i.e. L and C) with a DC source to form a novel source, named Z-source, which is a kind of impedance-source (Z stands for impedance) [22,23,27,24–26]. An impedance-source can be regarded as a general source, including the current and the voltage sources as two extreme cases, i.e. an impedance-source can be regarded as a current source when its equivalent impedance tends towards infinity, and as a voltage source when its equivalent impedance is equal to zero. The concept of the impedance-source provides a solution to the problems existing in the tractional converters and facilitates high efficiency of energy conversion [28–31].

Since 2002, many novel impedance-source converters with various topologies have been coined, such as quasi-Z-source converters, trans-Z-source converters, embedded-Z-source converters, which have been widely applied in wind energy [32], solar cells [33,34], motor drives [35,36], and vehicle systems [37–39]. However, the design of an impedance-source converter is still an art, lacking systematic design methodology, which hinders the extensive application of impedance-source converters in practice.

It is remarked that designing an impedance-source converter should be subject to the impedance-network matching, which instructs how an impedance-network can be matched to the sources, leading to a systematic design methodology, which will be discussed in detail in this paper.

The main part of this paper is organised as follows.

Past of power electronics converters: Section 1 expounds the history of the development of power electronics and power converters and, Section 2 gives preliminaries of traditional voltage- and current-source converters as well as Z-source converters.

Present of power electronics converters: A profound analysis of voltage- and current-source inverters is carried out in Section 3, and that of Z-source inverters in Section 4. The state-of-the-art of impedance-source converters together with typical examples are given in Section 5.

Future of power electronics converters: The impedance-network matching is clarified in Section 6, based on which a design methodology is proposed in Section 7. Some case studies for different industrial applications are presented in Section 8. Finally, Section 9 draws a conclusion and points out the direction that impedance-source converters should follow in the future.

2. Preliminaries

2.1. Voltage sources and current sources

A power converter processes an energy flow between two sources, i.e. generally between a generator and a load, as illustrated in Fig. 1. An ideal static converter is assumed to transmit electric energy between the two sources with 100% efficiency. The conversion efficiency is the main concern in designing a converter. In practice, power converter design therefore aims to improve efficiency.

There are two types of sources, namely voltage and current sources, any of which could be either a generator or a load.