ELECTRIC POWER CONVERSION SYSTEM SYNTHESIS – THEORY AND PRACTICE

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Keywords: Power electronics, circuit synthesis, quasi-resonant converters, DC-DC converters, soft-switching, zero-current switching, zero-voltage switching

Contents

Summary

There has been an evolution in the process of electrical power conversion in the last decades. Bulky mechanical systems involving rotating masses have been replaced by more compact and efficient static systems employing silicon switches in various power conversion processes. This evolution has also been echoed, more so recently, by a gradual change in the nature of power consumption. Today, the rapidly increasing utilization of electronically powered products ranging from computer-based systems to life supporting medical equipment that invariably require DC (Direct Current) power sources, is creating the need for efficient alternating current-direct current (AC-DC) and direct current-direct current (DC-DC) power conversions. These modern switching power converters, aided by improved design techniques and semiconductor technology, are a far cry from their conventional counterparts. Basic concepts of power converters are reviewed, then in more details the principles of the resonant type converters are discussed, as a key power conversion unit for tomorrow's electronically powered

products. They operate at higher efficiency by means of switching the current or voltage when they are approaching zero value, thus have the advantages of very low switching losses, avoidance of high voltage or high current stress on the components, and much reduced thermal stress and electromagnetic interference. A case study on the design and synthesis of a DC-DC resonant power converter, operating at a very high resonance frequency and efficiency, illustrates the synthesis procedure and suggests practical applications. The chapter concludes with remarks on the increasingly important role these power converters play as the provider and custodian of energy utilization in a global context, where higher performance, reliability and efficiency of power supplies are needed at affordable costs for every community in the world.

1. Introduction

Power consumption is closely associated with human needs and associated activities. It is generally believed that the infrastructure of the generation of electricity, the main type of various power sources, is an invariably reliable indicator of how developed an economy is. A nation's capacity to produce products and services to satisfy the needs of its population and overseas customers, measured as gross national product (GNP), relies critically on this form of power. Whilst a nation's electrical power consumption has been well known to be closely associated with its wealth and its GNP, the rapidly changing nature of power conversion process which provides the power for consumption is perhaps less apparent. Over the last decades, power conversion has evolved from an essentially 'copper and iron' technology to one which heavily depends on the 'silicon' technology.

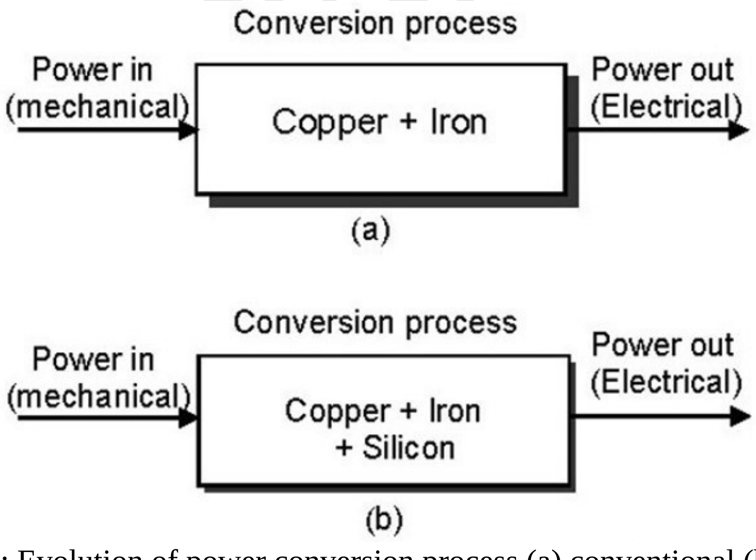

Figure 1: Evolution of power conversion process (a) conventional (b) modern

Figure 1 depicts such an evolution, in which the 'copper and iron' in the conventional conversion process refers to the exclusive use of large rotating electrical machines which essentially consist of copper windings wound on to the iron rotor and/or stator. The copper which carries the electrical current and the iron in which the magnetic field is formed, are the fundamental elements enabling the conversion of power. Thus the rotating 'iron and copper' serve as the crucial medium of power conversion. Iron and copper are also key components for the power transformers, which are essentially non rotating electrical machines used to step up or step down voltage levels for efficient distribution and convenient usage of electrical power. The second part of Figure 1 shows silicon added in the modern conversion process. The silicon technology, which refers generically to semiconductor technology, has emerged in the form of solid state electronics since its invention in the 1950's.

However, it was only since the 1980s that the rapid developments in the power semiconductor technology have started to make significant impacts on power conversion. More recently, developments in microelectronics, albeit another form of silicon technology, have made inroads into improvement in power conversion systems. Micro-controllers and digital signal processors (DSPs) are commonly used as the control and switching units in solid state power converters. Thus, the silicon in Figure 1 refers to both power and micro-electronic devices. It is envisaged that future power systems depend critically on the key developments in these devices.

It should be noted that the period of evolution of a power conversion system that was characterized solely by rotating iron and copper masses into one that incorporates key static silicon components, as depicted in Figure 1, has been echoed by a gradually changing nature of power consumption. However, such a relationship between power conversion and power consumption is complex. It has been argued that the 'virgin land' of iron and copper would have been preserved had there not been a surge of thirst for quality and quantity of electrical power at affordable costs. Yet such a surge of thirst would not have been materialized had there not been a stimulus in the form of rapid advances in the silicon technology. This demand-pull-technology-push interplay has fuelled the rapid increase of research and commercial interests in electrical power.

The electrical power, when processed by power electronics, is suitable for many applications which have previously been prohibitively costly or technically impossible. These applications include DC regulated power supplies, electrochemical processes, electronic welding, variable speed motor drives, induction heating, power supplies for accelerators in nuclear fusion and space satellites, and heating and lighting control. The process is two-fold. First it involves the control of a power semiconductor device operated in switching or linear mode. Operating a power device in switching mode lends itself to digital and microprocessor control, and results in higher efficiency when compared to linear mode because of the negligible device losses in fully-on or fully-off states. Switching mode has a penalty of harmonic ripples in the load and source sides which are absent in linear mode operations. As high switching frequency is essential for high efficiency, noise and electromagnetic radiation are undesirable by-products. Despite these shortcomings switching mode is predominately used in electronically processed power conversions. Secondly, at a level higher than the turning on and off of the power devices, the processing involves conversion which is either one or combination of four main types: DC-to-AC, AC-to-DC, DC-to-DC and AC-to-AC. In more recent power electronics systems, the processing in the control of power devices and the conversion are coordinated seamlessly by means of powerful microprocessors or DSPs. These systems essentially consist of two types of semiconductors, the power semiconductor devices that can be considered as the 'muscle' of the system, and the microelectronic control chips that resemble the 'brain'. Both semiconductors are operated in digital form, one manipulating power up to gigawatts, and the other handling power at levels of a fraction of a milliwatt. Although situated at the extreme ends of the power scale, the two semiconductors when closely coordinated will yield efficiency, size and cost advantages for modern power conversion technology.

2. Rapid Increase in Electronically Powered Applications

Utilization of today's electronically powered products, ranging from mobile phones and mobility aids to personal computers and power supplies for space satellites, is rapidly increasing the need for DC-DC power supplies. These electronically powered products typically run on DC power instead of AC, which is found in electrical outlets or sockets. The voltages that AC power sources provide are not appropriate for end products and must be altered to DC voltages and currents in order for these end products to function. The mobility requirement of these electronically powered products such as portable laptops, powered wheelchairs and electric vehicles, implies that a highly efficient DC power supply is highly desirable. Mobility will be more restricted with less efficient systems when recharge is required more often. Environmental concern is also a key factor for more efficient power conversion.

From the technical aspect, this creates a direct relationship and interest between DC-DC power conversion and electronic circuit design. Numerous circuit design topologies are possible to achieve the conversion at varying degrees of functionality, complexity and efficiency. Power supply and circuit design researchers are faced with a challenging task that demands good knowledge of several disciplines. These circuits are highly non-linear and very difficult to stabilize. From a control engineering viewpoint, the circuits may not often be easy to control as their transfer functions in Laplace transform have real and complex poles in the right-half of the s-plane, and are prone to ‘chaos’ – a circuit phenomenon that is a subject of much research interest. Magnetically they are complex and call for consideration of proximity and eddy current effects. In the manufacture aspects, they often require planar construction to achieve the performance and size specifications. The enforcement of electromagnetic compatibility (EMC) compliance in electronics equipment also poses further challenges in understanding the complex mechanism of electromagnetic interference in electronic equipment operating at high frequency.

From a market viewpoint, the expected rapid growth in these products means increased revenues for the lucrative DC-DC converter market. Market trends currently affecting the DC-DC converter industry include a converter design shift to smaller, lower profile converters that provide higher power density and efficiency. Coping with this trend has become one of the top industry challenges as compromises for size affect the performance and converter reliability. Frost & Sullivan, a market research agent in power converters, identifies and segments the world DC-DC converter industry into three ranges: low (1W to 100W), medium (101W to 500W), and high (greater than 500W). The key opportunities for growth in this market are the IT industry, which includes data communications and computer products, and the telecommunications industry. It is interesting to note that power converters with distributed power architectures are becoming essential as IT systems are more likely to be networked in the future. The distributed architecture of the IT system will mean that the computer and the converter will form an integral unit or node in the whole network. It should also be noted that the increased functionality of future mobile products also means that they draw more power, and hence the more urgent need for highly efficient DC-DC converters. Apart from the IT industry, high power DC-DC converters will play an important role in tomorrow’s automotive industry that will become more ‘electrified’ with the introduction of the 42V system and increasing popularity of electric vehicles.

3. Switched Power Converters

The motivation for switched power converters rests on the fact that the costs of silicon-based power and control devices are steadily falling, whilst those for the passive bulky power elements such as inductors (built with iron and copper) are essentially constant. The basic switched power converter essentially consists of a switching circuit, inductors and capacitors. The switching circuit operates at high frequency and transfers energy from input to output in discrete packets, through the inductor and capacitor. Practical converters use feedback circuitry to regulate the energy transfer to maintain a constant voltage within the load limits of the circuit. Transformers may also be used to isolate input from the output. The basic circuit can be configured to step up (boost), step down (buck), or invert output voltage with respect to input voltage. The key reason to impress switching signals rather than to operate on linear mode for the power semiconductor is efficiency, for, linear regulators, can only step down, and efficiency is equivalent to the output voltage divided by the input voltage. On the other hand, switching DC-DC converters operate by passing energy in discrete packets over a low-resistance switch, so they can step up, step down, and invert. In addition, they offer higher efficiency than linear regulators. Using a transformer also allows the output voltage to be electrically isolated from the input voltage. One key disadvantage of the switching converters is the generated electromagnetic radiation. This, along with the stresses imposed on the components created by the rapid changes of voltage, calls for continued research and development efforts in this field. The introduction of quasi-resonant converters (QRC) or simply resonant converters (RC) in the late 1980’s, gave rise to a new class of power converters with high efficiency and low electromagnetic radiation and component stresses.

3.1. Primitive DC-DC Converter

A primitive version of the DC-DC converter will be the best to illustrate its fundamental power conversion mechanism. This mechanism is indeed basic to all switching power converters. The conversion mechanism, shown in Figure 2, involves two steps – the charging stage and discharging stage.

In the charging stage on the left of Figure 2, the circuit is assumed at steady state. Since the switch is open, the voltage across the capacitor is equal to the input voltage. The closing of the switch initiates the charging stage. Energy is transferred from the input source to the inductor while the diode prevents the capacitor from discharging to ground.

The charging current profile will be linear, being at a rate that is proportional to the input voltage divided by the inductance, as illustrated in Figure 1. During the charging stage, the inductor serves as a temporary energy store, storing energy equal to one-half the inductance times the square of the peak current for the duration shown.

The discharge phase starts when the switch opens following the charging stage. Since current flow in an inductor must be continuous, the voltage across the inductor changes instantaneously to a value needed to maintain current flow, thus making the diode forward-biased.

If a suitably large capacitor is used, then its output voltage V_{OUT} will remain relatively constant throughout the discharging phase. Since voltage across the switch remains at a diode drop above V_{OUT}, the voltage impressed across the inductor will stay constant, resulting in a linear current profile with slope opposite to that of the charge phase.

It should be noted that the discharging phase of the inductor is the charging stage of the capacitor, denoting a changeover of the energy in a 'tamed' manner. These charging and discharging cycles, when modulated and controlled, can in fact produce a range of regulated $V_{OUT,}$ within the breakdown tolerance of the L and C components.

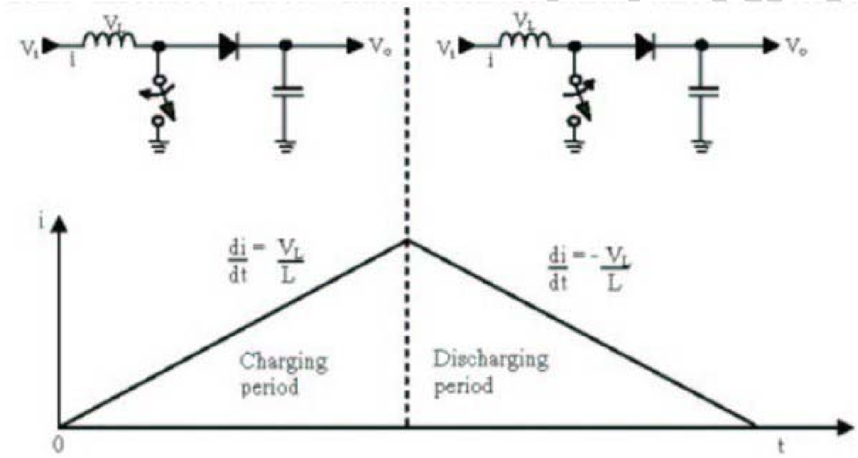

Figure 2: Fundamental conversion mechanism in DC-DC converters (a) Charging stage (b) Discharging stage

3.2. Unified Model

Inspection of the circuit in Figure 2 shows that the components can be grouped into two units. First, the switch and the diode work in co-ordination to guide the timing and direction of power flow. Second, the inductor and the capacitor act in pair as carrier for the power flow, from input to output.

The first unit, together with the associated part for the switching signals, is an active circuit; whilst the second unit consists of essentially passive components. It must be noted that the 'power switch and the diode' unit lies at the heart of modern power converter design, and is often regarded as the 'atomic unit' for switched power converters. A unified model that reflects these observations is shown in Figure 3. The voltage across terminals 1 and 2 (v_{12}) and the current through terminal 3 (i_3) represent the effects due to external components connected.

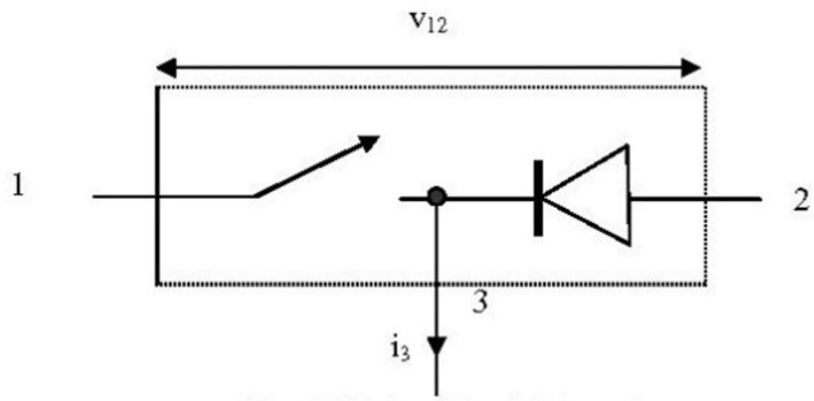

Figure 3: Unified model for switched converters

From the earlier discussions we know that there are different forms of DC-DC converters. The most commonly known ones are the Buck, Boost, Buck-Boost, and Cuk converters. Let us now apply this unified model to these converters. The Buck is similar to the primitive DC-DC converter described and the output voltage is always lower than the input voltage by a factor determined by the switching ON-OFF ratio. The Boost can have an output voltage higher than that of the input voltage, and is also determined by the switching ON-OFF ratio. The Buck-Boost combines the features of the both and the output voltage can be lower or higher than the input voltage. The Cuk converter, named after its inventor, is also a combination of the Buck and Boost. These four converters can be easily synthesized by connecting different external capacitors and inductors to the terminals of the unified model. Figure 4 illustrates the construction of these converters using the unified model. The analysis of the operation of these converters can be followed in the same way as discussed in the previous section since they all share the 'atomic switching unit'.

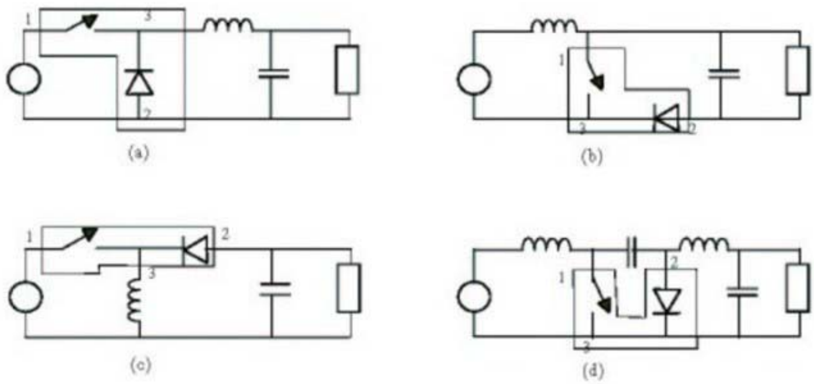

Figure 4: Synthesis of the main converters using the Unified Model (a) Buck (b) Boost (c) Buck-Boost (d) Cuk

4. Resonant Converters

The DC-DC converters discussed so far employ a switching regime commonly known as 'hard switching', in which the power semiconductor device turns itself on or off when neither the voltage across its gates nor current flowing through it is zero. The consequence of hard-switching is two fold. There are higher switching losses due to simultaneous non-zero voltage and current. The switching frequency is restricted. In contrast, resonant converters employ the 'soft switching' regime in which switching of the power semiconductor occurs only when either the voltage or current is zero. Since silicon produces static devices that have very small energy storage capacity, a 100% silicon solution is not possible for medium or high power level conversion. Storage devices such as inductors and capacitors, which are essentially comprised of iron, copper and dielectric materials, store energy in the form of magnetic and electrical fields are necessary. Resonance provides the optimum condition when maximum energy can be stored for a given resonance frequency. At resonance, the sizes for capacitors and inductors are also at minimum for a given power transfer. The 'silicon solution' of passive power circuit components is a combination of 'iron, copper, and dielectric' such that resonance provides the condition for optimum power conversion.

The resonant converter consists of a resonance circuit, which is usually composed of circuit capacitance and inductance, together with load impedance. Soft-switching of the power devices takes place when the voltage or current is approaching zero. Thus, simultaneous transitions of voltage and current are avoided, resulting in minimum switching losses. For energy conversion process using resonance, there are three distinct periods that can always be identified. First, energy charging is linear (at constant rate) from one element while that of the other element is zero. Second, resonance occurs between the two elements. Third, energy discharge from one element is at constant rate while that of the other element is zero.

4.1 Elementary Resonant Switch

The unified model described in the Section 3 can be further developed to an elementary resonant switch by the inclusion of an inductor and capacitor (LC). This switch constitutes the most basic unit for the synthesis of any resonant converters. However, the concept of duality gives rise to two types of elementary resonant switching circuits - the zero-current (ZC) and zero-voltage (ZV) types. Figure 5 shows the ZC and ZV switches in which each includes an LC resonant network as its integral part. The ZC switch with an arrow in Figure 5(a) denotes bi-directional voltage, unidirectional current operation. The ZV switch in Figure 5(b) denotes bi-directional current, unidirectional voltage operation. A more complete description of the switches is given later in Section 4.2.3. The LC circuits shown are generic and there are several permutations of connection possible. It must be noted that the inductor and capacitor used for resonance may not be the same as the filter inductor and capacitor described in Section 3. Usually they are much smaller. However, it is also possible to use the filter inductor and capacitor as part of the resonance circuit.

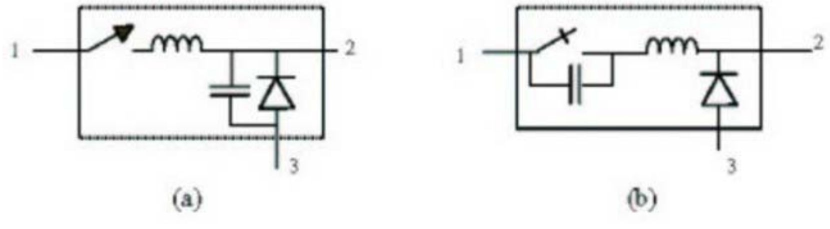

Figure 5: Elementary switching unit (a) Zero-current (b) Zero voltage

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Biographical Sketches

Patrick Chi-Kwong LUK was born in Hong Kong, 1960. He obtained his High Diploma from Hong Kong Polytechnic University in 1983, and MPhil from Sheffield University and PhD from University of Wales, Glamorgan in 1989 and 1992 respectively, all in electrical engineering. After a brief career as a sales engineer, then as an research assistant in Hong Kong Polytechnic University between 1984-86, Dr. Luk won an award to further study in the U.K. After his MPhil at Sheffield, Dr. Luk started his working career in the U.K. as research associate at Black Clawson International Ltd (UK), to which his doctoral work was related, from 1988-92. He then took academic positions in several UK institutions, before he joined Cranfield University in 2002, where he is senior lecturer on motor drives and power electronics. He is principal investigator for a number of research and consultancy projects embracing various aspects of power electronics systems, with current industrial concerns including the development of a switched reluctance drive for Mitsubishi Electric (UK). He has won a number of engineering awards and grants, including the British Council's Overseas Research Awards for his MPhil degree. His total research and other grants to date exceed £300k, mainly in power electronics systems, and more recently in digital signal processing applications from the Department of Trade and Industry, U.K. A Chartered Engineer and members of The IEE and IEEE, Dr. Luk is currently Associate Editor of the *IEEE Transactions on Power Electronics,* and is featured in *Who's Who in the World, Who's Who in Finance and Industry,* in *Marquis* 2000 and 2001 respectively. He has authored over 40 technical publications in motor control and power electronics. He is co-holder of two patents on switched reluctance motor.

Khalil EL KHAMLICHI DRISSI was born in Fez, Morocco, in 1965. He graduated as Engineer (1987) from "Centrale Lille". He received Master's (1987) and Doctoral degrees (1990) in Electrical Engineering, from the University of Sciences and Techniques of Lille-Flandres-Artois. He then joined the Engineering Sciences Institute (CUST) and he is currently associate professor in power electronics. From October 1990 to December 1995, he was a member of research team EPC (Power Electronics Laboratory at Clermont Ferrand), where he conducted research work on various aspects of power electronics, and in particular, power components, motor drives and harmonic active filtering. Since January 1995, he has been conducting research work at the LASMEA (Laboratory of Sciences and Materials for Electronics, and of Automatic Control), where he focuses his research work on electromagnetic compatibility (EMC) applied to power electronics and telecommunications. His other main interests are resonant and quasi-resonant converters, random modulation control of DC-DC and DC-AC converters, Multi conductor Transmission Lines (MTL) fault localization and numerical modeling of MTL network with Finite Difference Time Domain techniques. He has published over 40 papers in journals and symposiums in power electronics and EMC. He is IEEE Member in the EMC and Power Electronics Societies, URSI Member (International Union of Radio Science), EEA Member (Electronic, Electrotechnic and Automatic) and Secretary of SEE Auvergne (Electrotechnic and Electronic Society).