Feature

# Suppressing Electromagnetic Interference in Direct Current Converters

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## Abstract

Since James Clerk Maxwell established the electromagnetic field theory in 1865, multifarious electrical and electronic products have been invented, designed, produced, and widely deployed, such as wireless communication devices, electrical machines and motors. This has profoundly changed our world and our lives. Now we cannot live without electrical products anymore and, thus, we are surrounded with electromagnetic fields generated. On the other side, especially in the past few decades, the rapid development and wide deployment of electrical products have caused lots of troubles, among which the most prominent one is electromagnetic interference (EMI), which may impact other




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devices' performance and harm human beings' health. Therefore, fighting EMI has become a stringent, difficult problem faced by engineers and scientists. The sources of EMI include natural sources, like atmospheric charge/discharge phenomena and extraterrestrial radiation, and man-made sources, like power lines, auto ignition, radio frequency interference, and radiation hazards, to name just a few. As important components, direct current (DC-DC) converters are embedded and employed in various electrical devices, thus forming main sources of EMI. Some measures, such as filters and electromagnetic shielding, have been taken to suppress EMI, but these methods have various drawbacks with respect to cost, volume, weight, and efficiency. Therefore, new theories and methodologies are desired to cope with the EMI problem, and chaos theory is a candidate due to the continuous spectrum feature of chaos. This paper aims to provide an overview on the state of the art of traditional EMI suppression technologies, and to introduce the use of chaos theory and chaos control to reduce EMI, as well as to motivate more efforts in theoretical research and engineering practice.

## 1. Introduction

During the period from 1855 to 1873, Scottish theoretical physicist and mathematician James Clerk Maxwell (13 June 1831–5 November 1879) established the classical electromagnetic theory, by synthesizing all previously unrelated observations, experiments, and equations of electricity, magnetism, and even optics into a consistent theory. His work in electromagnetism has been called the "second great unification in physics", which laid a foundation of the electrical era, after the first one carried out by Isaac Newton (4 January 1643–31 March 1727), whose classic mechanics inaugurated the era of machines.

In 1888, German physicist Heinrich Rudolf Hertz (22 February 1857–1 January 1894) was the first to experimentally verify the existence of electromagnetic waves. This discovery opened the way for the development of radio, television, and radar, leading to a booming time of developing various radio technologies, such as telegraph (1894), AM radio broadcast (1906), naval radio (1911), radio telephone (1916), shortwave communication (1921), fax (1923), television (1928), microwave communication (1933), and radar (1935). More recently, with the rapid development of microelectronic techniques and (very) large scale integration technology, various electrical and electronic devices have been invented, designed, and produced, which pervaded into all aspects of our life, as well as proved beneficial for our daily life. However, electrical and electronic devices inevitably emit electromagnetic impulses and harmful harmonics, which may form EMI. This, in turn, may impact other devices' performance and harm human beings' health.

For instance, we may have already experienced that it is difficult to listen to the radio or watch TV when someone is using a vacuum cleaner in the next room, because the vacuum cleaner causes significant interference with the radio signal.

During the years 1984 to 2000, Health Canada's Medical Devices Bureau received thirty-six reports of medical-device malfunctions due to EMI [21, 51], among which four cases were caused by mobile telephones, two were malfunctioning implantable cardiac pacemakers impacted by electronic article surveillance (EAS) systems, and one case was premature failure of a pacemaker [21, 51]. Further two cases were an electrically powered wheelchair suddenly veering due to radio and microwave transmissions, and an infant apnea monitor failing to alarm because of the ambient electromagnetic fields [55, 48].

In the late 1980s, five crashes of Blackhawk helicopters shortly after coming into service happened due to EMI from very strong radar and radio transmitters with electronic flight control systems [26]. Besides, recent events regarding cellular telephones include that of a Northwest Airlines flight being diverted because of a suspicious cellular telephone used by a passenger, and of a British Airways flight having to return to Heathrow Airport 90 minutes after take-off, because nobody confessed using a cellular telephone even though crew members heard a telephone ring causing considerable fear among passengers and crew and resulting in severe flight delays. The reason for prohibiting the use of cellular telephones on board of airplanes is the possibility of EMI generated by cellular telephones to interfere with aircraft communication and navigation.

Such negative examples caused by EMI can be given without number, although EMI can intentionally be utilized for, as a positive example, radio jamming, as in some forms of electronic warfare. With the rapid development and wide deployment of electrical and electronic products, EMI has been becoming an increasingly serious and stringent problem faced by scientists and engineers. The EMI problem involves EMI receivers/victims, which are disturbed by EMI, and EMI sources. The sources of EMI include natural ones, like atmospheric charge/discharge phenomena and extraterrestrial radiation, and man-made ones, like power lines, auto ignition, radio frequency interference (RFI), and radiation hazards (RADHAZ), as shown in Fig. 1.

The natural sources have their own inevitability of existence, for instance, as electricity in the atmosphere accumulates to some extent that an electrical discharge (the bolt of lightning) occurs within clouds or between clouds and the ground. Therefore, we can do nothing against the natural sources of EMI. Nevertheless, for the man-made EMI sources, we should do. As important components, DC-DC converters are widely embedded and employed in various electrical and electronic appliances, and release

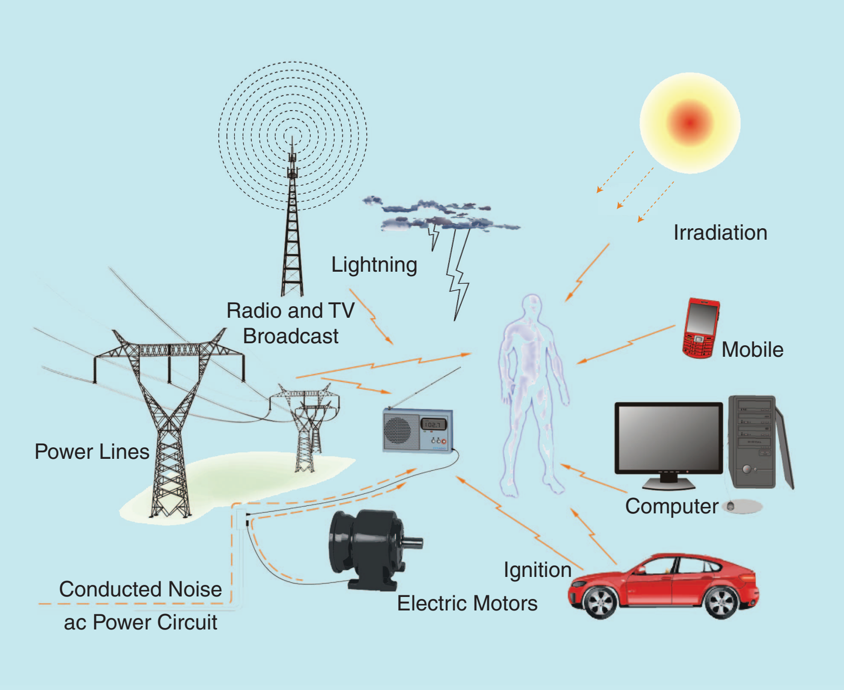


**Figure 1.** Typical electromagnetic environment.

to EMI, can thus be suppressed, implying the reduction of EMI. A prominent advantage of using chaos control methodology is that the system design can focus on the circuit itself without the need to append exogenous circuits like filters and shielding, thus reducing cost, weight, and space.

This paper aims to provide an overview on the state of the art of traditional EMI suppression technologies, and to introduce the way how to use chaos theory and chaos control to reduce EMI, as well as to motivate more efforts in theoretical research and engineering practice.

## 2. Electromagnetic Interference (EMI)

Roughly speaking, EMI is an undesirable disturbance that affects an electrical circuit due to either electromagnetic emissions and, thus, form main sources of EMI. Therefore, controlling EMI in DC-DC converters is of great significance for cleaning the entire EMI environment. For this purpose, some measures, such as filters and electromagnetic shielding, have been employed to suppress EMI, but these methods have considerable drawbacks in cost, volume, weight, and efficiency. New theories and methodologies are, thus, desired to cope with the EMI problem and, fortunately, the newly developed chaos theory is a good candidate for it. The reason is that the continuous spectrum feature of chaos can be employed to fight EMI by spreading the spectra of the output signals over the whole frequency band. The peaks, which appear at the multiples of the fundamental frequency and lead

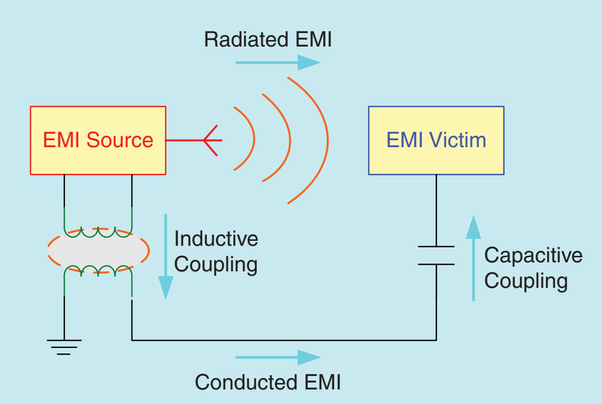


**Figure 2.** EMI coupling modes.

electromagnetic conduction or electromagnetic radiation emitted from an external source. The disturbance may interrupt, obstruct, or even degrade or limit the effective performance of the circuit.

An interference is produced by a source emitter and detected by a susceptible victim via a coupling path, as shown in Fig. 2 [44].

In terms of the frequency band, EMI is categorized into conducted and radiated EMIs by the way the electromagnetic field propagates, which can simply be illustrated in Fig. 2. Conducted EMI is caused by physical contact of conductors in contrast to radiated EMI, which is caused by induction (without physical contact of conductors), depending on the frequency of operation, just like water flowing through a pipe and light radiating from a lamp, respectively. That is to say, for lower frequencies EMI is emitted via conduction and, for higher frequencies, via radiation.

Normally having frequencies between 10 kHz and 30 MHz, conducted EMI can further be classified into common mode (CM) noise and differential mode (DM) noise in terms of different directions of conduction.

- **Common Mode Noise** is conducted through all lines in the same direction, and always exists between any power line and ground.
- **Differential Mode Noise** is conducted through all lines in inverse directions, and always exists between power lines.

Empirically, at frequencies below approximate 5 MHz, the noise currents tend to be predominantly DM, whereas at frequencies above 5 MHz, the noise currents tend to be predominantly CM [56].

Radiated EMI can contain electric and magnetic fields. The strength of the electric field is proportional to the circuit voltage, operation frequency, and "the effective length of the antenna". The strength of the magnetic field is proportional to the circuit current, operation frequency, and "the effective area of the antenna loop". Since circuit parameters and operation frequency are fixed in terms of a converter's operating characteristics, the only variable factor is the length of the power line, or the enclosed loop area of the power line's return path. Therefore, radiated EMI can be minimized by physically locating the noise-generating source as close to its source and load as possible. However, such a compact assembly is rarely possible for mechanical reasons.

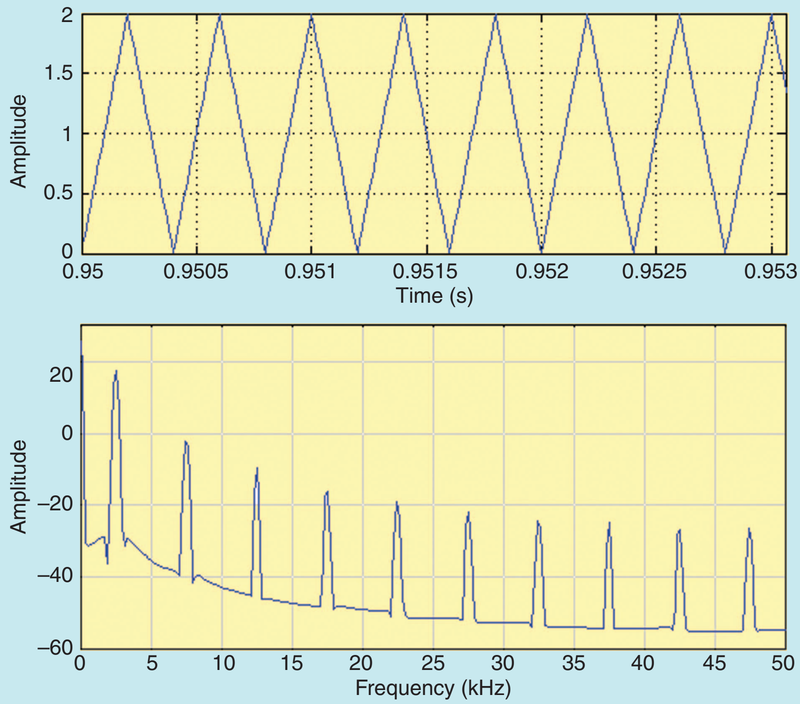



**Figure 3.** A triangle waveform and its power spectrum.

How do we observe EMI? Normally, EMI can be estimated and observed by measuring the power spectral density (PSD), which describes how the power of a signal or time series is distributed with frequency, as illustrated in Fig. 3.

Fig. 3 shows that a spectrum consists of the operation (or fundamental) frequency and its harmonics. As shown in the lower part of Fig. 3, *the large peaks located at the multiples of the fundamental frequency imply possible EMI.* In converters, if the harmful harmonics of input and output signals are not filtered, they can corrupt the power source and interfere with the operation of other equipment, which gives rise to serious problems of *electromagnetic compatibility (EMC).*

### 3. Electromagnetic Compatibility (EMC)

EMC refers to the ability of an apparatus to operate satisfactorily in its intended operating environment without causing EMI to other electronic equipment and, on the other hand, itself to be able to function well without being adversely affected by EMI from other equipments operating in the same environment. EMC requirements concern two basic concepts: emissions and susceptibility.

- **Emission** issue is related to the unwanted generation of electromagnetic energy, and to countermeasures, which should be taken in order to reduce such generation, and to avoid the escape of any remaining energy into the external environment.
- **Susceptibility** or immunity issue, in contrast, refers to the correct operation of electrical equipment (victim) in the presence of unplanned electromagnetic disturbances.

It was already recognized in the 1930s that unintentional man-made electromagnetic noise can interfere with radio reception. Regulatory work with the purpose of ensuring interference-free reception started as early as 1933 in Europe, and in the following decades the engineering discipline of EMC has been developed, together with a formidable array of emission and immunity standards, which are presently in effect, and have become mandatory. EMC standards are internationally harmonized, however the extent of adoption of EMC standards into national regulations may vary significantly between countries.

EMC is essential for most electrical and electronic products to allow them unimpeded access to the market. For instance, in industry, electronic control systems should work well in an environment full of other electrical and electronic devices like motor drives, high-frequency ovens, and welding equipment, which emit strong EMI. In a car, electronic on-board systems must function while a mobile telephone is used or when it comes close to other vehicles (with interfering ignition systems). An electronically controlled wheelchair is presumed to function normally even when the person sitting in the chair uses a mobile telephone or a portable PC. We demand that life-supporting electro-medical apparatuses in a hospital function safely even close to high-frequency-radiating surgical equipment.

So to speak, although power-electronic devices, including converters, are of great benefit for human beings and are widely applied in our daily life, unfortunately, at the same time the widespread use of power-electronic products causes serious EMC problems. Therefore, international communities have set standard regulations, i.e., EMC standards, for electrical and electronic products to comply.

EMC standards for converters involve three basic concepts:

**Types of EMC Standards:**

- **Generic Standards** prescribe concrete requirements for emission and immunity for equipment used in specific environments, and are applicable to all equipment used in those environments when no specific product standards exist. Generic standards were issued by the European Committee for Electrotechnical Standardization (CENELEC) to facilitate compliance with the EMC Directive. The first series includes residential, commercial, and light industry environments.
- **Basic Standards** describe fundamental rules for meeting the requirements. They are concerned with characteristics of electromagnetic (EM) phenomena, EM environments, test procedures for emissions and immunity measurements, they set emission limits, give recommendations for immunity, and also provide application guidelines.
- **Performance Criteria** refer to four classes in immunity tests. Class A: no loss of function or performance due to the testing; class B: temporary loss of function or performance, self-recoverable; class C: loss of function or performance which needs intervention to restore; class D: permanent loss of function or performance due to damage, representing a failure.

## 4. Direct Current (DC-DC) Converters

Why do we take DC-DC converter as objects for fighting EMI?

Forming a class of power converters, DC-DC converters are circuits which convert sources of direct current (DC) from one voltage level to another by changing the duty cycles of the main switches in the circuits.

Nowadays, DC-DC converters are widely applied in almost all electrical and electronic devices like mobile and data communications, computers, office automation systems, industrial devices, military and spacial systems. For instance, laptop computers and cellular telephones are supplied or charged by direct current (DC). Therefore, AC-DC converters are necessary to convert supplied alternating current (AC) out of sockets to the DC inputs of these devices, and DC-DC converters play a very important role for portable electronic devices, which are primarily supplied with power from batteries. Such electronic devices often contain several subcircuits with their own voltage requirements different from those supplied by batteries or external supplies. Additionally, the voltage of a battery declines as its stored power drains away. DC-DC converters offer a means to maintain required output voltages from partially lowered battery voltages, thereby saving space as compared with using multiple batteries to accomplish the same task.

DC-DC converters can be categorized in different ways, for instance, in terms of different power levels, into low, middle and high power DC-DC converters; by transformation types into isolated or non-isolated ones; by switch types into hard-switching and soft-switching ones; or, more commonly, by circuit topology, which will be introduced in the sequel.

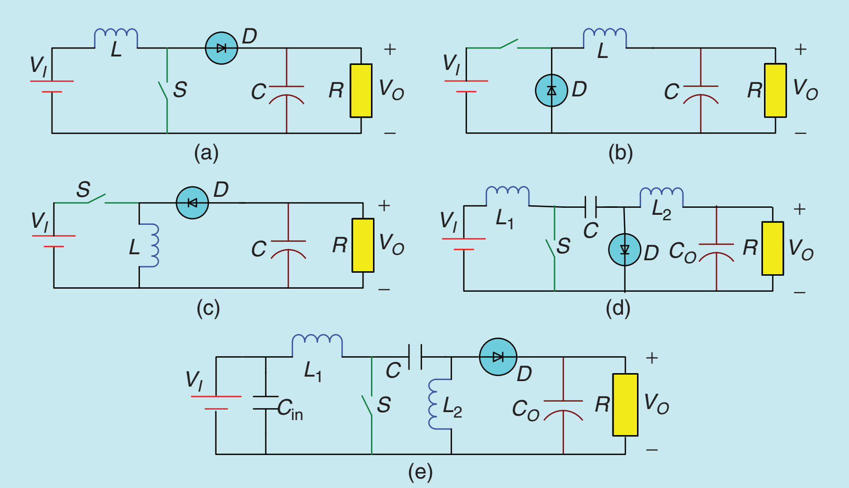



**Figure 4.** Basic topologies of DC-DC converters. (a) Boost converter. (b) Buck converter. (c) Buck-boost converter. (d) Cuk converter. (e) SEPIC converter.

### *4.1 Topologies*

The main topologies of DC-DC converters are shown in Fig. 4. Other topologies such as forward, push-pull, half-bridge, and full-bridge are isolated transformations of buck converters, and flyback is a transformation manner of the buck-boost converter. In addition, there exist isolated transformations of Cuk and single-ended primary inductor converters (SEPIC) [57].

### *4.2 Functions*

The most important function of DC-DC converters is switched-mode power supply (SMPS) for modern electronic products or devices to supply stable and smooth DC voltages at various levels.

Different to the conventional power supply, i.e., the linear power supply (see Fig. 5), a DC-DC converter controls its output voltage by adjusting the duty cycle of the power switch, other than by turning the adjustable resistor, which can lead to 20%–30% energy saving. A detailed comparison between linear power supply and SMPS is tabulated in Table 1.

It is seen from Fig. 6 that SMPS leaves out the heavy transformer and big output filter capacitors, which are needed in the linear power supply. Therefore, SMPS has the advantages in low cost, light weight, small size and high efficiency, and consequently, DC-DC converters have been more and more adopted to replace the conversional linear power supply.

Today, high-power DC-DC converters are widely used in various areas like subways, trains, electrical vehicles, and trolley-buses, as well as even in the controllers of stepless speed variation.

More recently, DC-DC converters are applied in new technologies, such as hybrid electric and fuel cell automobiles [23, 27, 46], renewable energy applications [38], mobile communication devices [14, 43], traveling wave tube amplifiers (TWTA), telecommunication satellites [4], or deep-space applications [16].

It is remarked that many power-electronic devices can "pollute" power lines, because they inject serious high-harmonics current into power lines, which causes the total power factor to degrade, and the voltage on the power lines to be spiky and abnormal. To eliminate electromagnetic pollution on power lines, the power factor correction (PFC) technique has been proposed and more and more applied for DC-DC converters [49].

### *4.3 New Generation of DC-DC Converters*

Due to the importance of DC-DC converters in power electronics, a new generation of DC-DC converters has been developed to fulfill increasingly higher practical requirements. The new generation exhibits the following new characteristics.

- **High Frequency** The volumes and weights of transformers, inductors, and capacitors are inversely proportional to the frequencies of power supplies. For example, when the frequency of a power supply increases from 50 or 60 Hz up to 20 kHz, the weight and volume of the electronic device can be decreased by about 90%–95%. Moreover, with high frequency, energy and production material can also be saved. Therefore, high-frequency operation can enhance the power density of DC-DC converters and bring about significant economic benefits.
- **Integration and Modularization** Although high-frequency operation of DC-DC converters can render many advantages, it results in increased switching loss and higher current or voltage stress, which could cause DC-DC converters to break down. In recent decades, however, with the rapid development of the printed circuit board (PCB) and other integration techniques, the problems

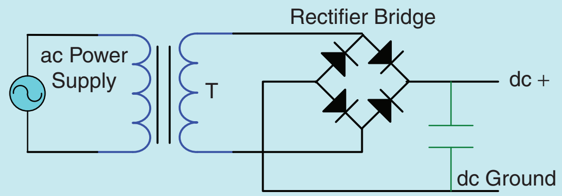



**Figure 5.** A simple linear power supply with transformer, bridge rectifier, and smoothing capacitor.

**Table 1.**
**Comparison of linear power supply and SMPS.**

| Linear Power Supply | Switched-Mode Power Supply |
|---|---|
| low cost | low or high cost |
| low EMI | large or small EMI depending on circuit design |
| simple structure, heavy weight and large volume | complex structure, light weight and small volume |
| low efficiency | high efficiency |
| fixed input voltage | universal input voltage |

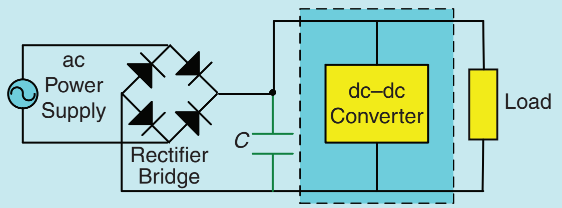



**Figure 6.** The structure of a SMPS.

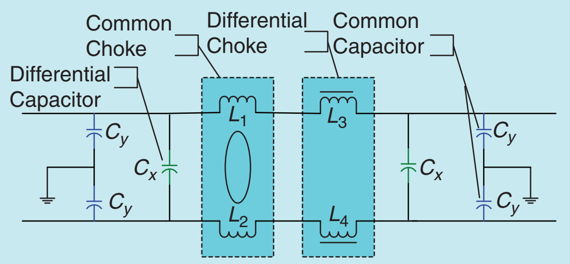



**Figure 7.** Passive EMI filter.

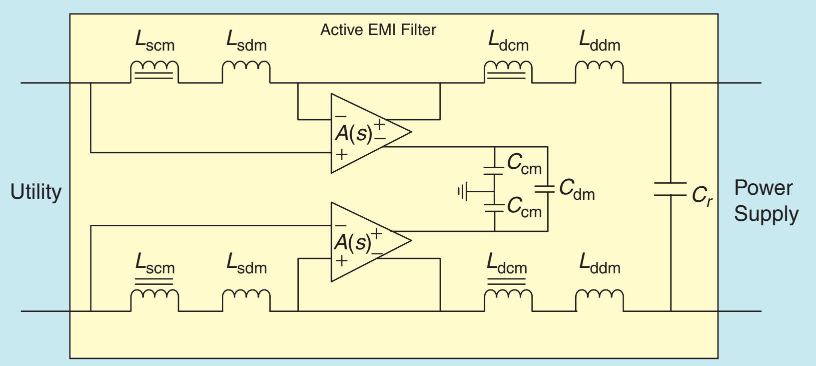



**Figure 8.** Three-wire active EMI filter.

caused by high-frequency operation can be solved. Nowadays, more and more DC-DC converters are produced as integrated modules.

The modularization of DC-DC converters makes them easy to use accomplishing stable operation also for higher power, for instance, the modularization provides the facility of realizing distributed power systems.

- **Distributed Power Systems** To improve the reliability of products or systems, distributed power systems have been proposed [42]. Distributed power systems are useful in areas such as telecommunication, renewable energy resources, space, aviation, ships and submarines, and electric and hybrid vehicles. The parallel DC-DC converter offers an important example of distributed power systems [42].
- **Greening** has two meanings: one is power saving, because electricity generation results in serious environmental pollution, hence, saving power can reduce environmental pollution; the other one is that power supply systems are not allowed to "pollute" the power lines, for which the International Electrotechnical Commission (IEC) constituted a series of EMC standards, such as IEC 555,IEC 917, or IEC 1000, to limit power line pollution.

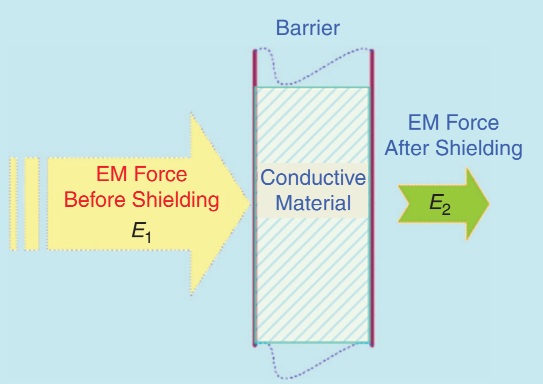



**Figure 9.** Electromagnetic shielding.

### *4.4 EMI in DC-DC Converters*

DC-DC converters are not only sources but also victims of EMI. They emit both conducted and radiated EMI. In conducted EMI, DM noise or current flow in and out of the power supplies via the power leads and their sources (or loads). It is totally independent of any grounding arrangement. Consequently, no DM noise or current flows through the ground connections. On the other hand, CM currents flow in the same directions either in or out of the power supplies via the power leads and return to their sources through the pathes of lowest impedance available, which are always the ground connections. Even if ground connections are not deliberate, CM currents flow through parasitical capacitors or parasitical inductors to ground, as shown in Fig. 2. Generally, only conducted EMI is concerned in practice when the switches operate in the low and middle frequency band.

Converters also generate radiated EMI emissions normally with frequency between 30 MHz and 1 GHz. Radiated EMI appears in the form of electromagnetic waves that "radiate" into the immediate atmosphere directly from a circuitry and its interface leads. The circuitry and its interface leads function like a transmitting antenna for this radiated EMI (Fig. 2). Normally, when the frequency of power switch operation exceeds 1GHz, radiated EMI should be taken into account.

## 5. EMI Suppression Techniques

Since the middle of the 1970s, many methodologies have been proposed to suppress EMI. Among them, EMI filtering is the earliest and most common one, which is used to reduce conducted EMI to satisfy the low-frequency

EMC standard. For meeting the high-frequency EMC standard, electromagnetic shielding is usually adopted, which is to reduce radiated EMI. The methods are like using a water filter for cleaning tap water and a curtain for shielding sunshine. Both methods can well suppress EMI, but have disadvantages with respect to high cost, large volume and weight, rendering products to lack portability. In order to meet the stricter international EMC standards and to overcome the disadvantages of the traditional approaches, some new EMI suppression techniques should be proposed and tested in the field, such as soft switching, random modulation, and the most promising solution, chaos control.

### *5.1 EMI Filters*

Basically, EMI filters are passive electronic devices that are used to suppress conducted interferences found on signal or power lines. An EMI filter works by presenting a significantly higher resistance to higher frequency content. In other words, the low-pass design of EMI filters (the combination of shunting capacitors and series inductors) results in restricting/impeding the flow of high frequency signals, effectively shorting it to ground. The final effect of EMI filters is to reduce and attenuate the unwanted signal strength, thereby affecting other components or devices only minimally [1].

Converters are sources of EMI due to pulsating input currents and rapidly changing voltages and currents [7]. Therefore, EMI filters for DC-DC converters should be designed to attenuate or suppress EMI emissions below acceptable levels.

Up to now, there are three kinds of EMI filters: passive, active, and hybrid ones.

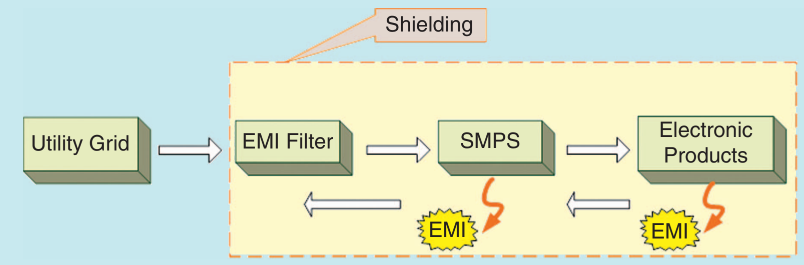



**Figure 10.** Shielding for SMPS.

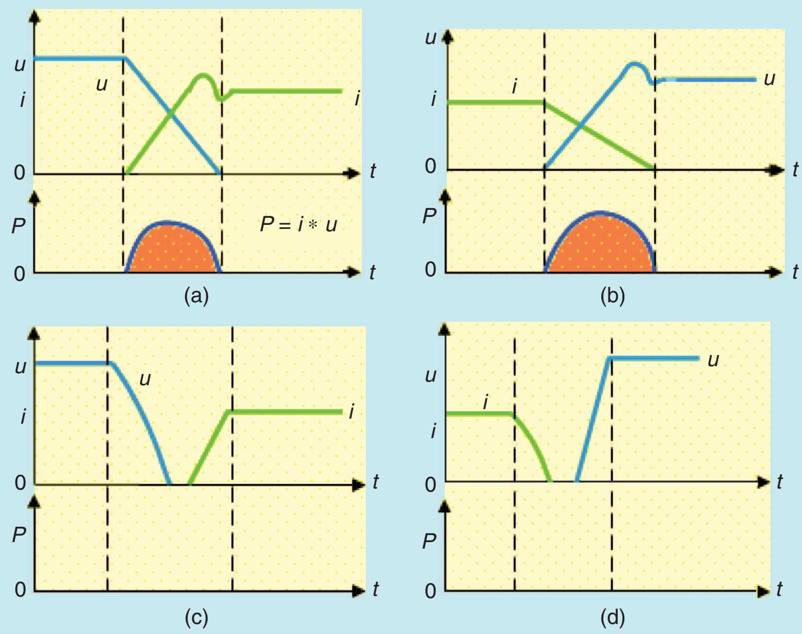



**Figure 11.** Turn-on and turn-off processes of a hard switching and a soft switching MOSFET. (a) Turn-on process of hard switching. (b) Turn-off process of hard switching. (c) Turn-on process of soft switching. (d) Turn-off process of soft switching.

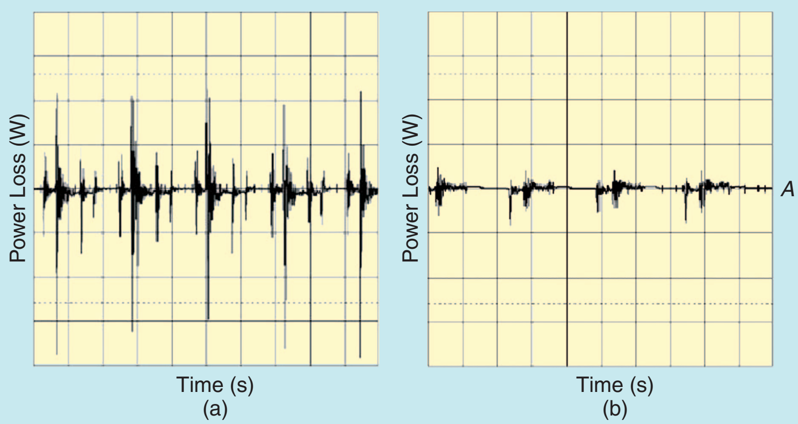



**Figure 12.** Power loss waveforms for a power MOSFET used in a DC-DC converter with hard- or soft-switching topologies. (a) Hard switching. (b) Soft switching.

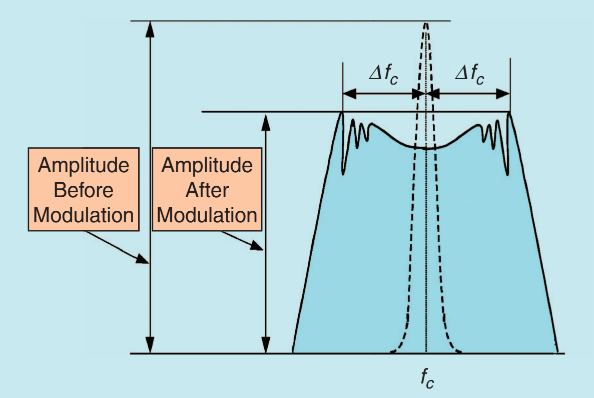



**Figure 13.** Spectrum of a frequency-modulated sine signal following a sine modulation profile in time (initial frequency $f_C$, peak deviation $\Delta f_C$).

- **Passive EMI Filter** means that a filter consists of inductors and capacitors, i.e., is an LC filter.

Since conducted EMI is made up of CM noise and DM noise, an EMI filter consists of two function blocks as shown in Fig. 7: $C_x$ and differential choke are used to filter the DM noise, while $C_y$ and common choke to filter the CM noise.

The common- and differential-mode EMI filters for power electronics were introduced in [50]. In designing passive EMI filters, the compensating bandwidth is comparatively narrow, thus only a certain part of noise can be suppressed. To alleviate this limitation, a tuned band EMI filter was proposed in [1], which can be applied in conjunction with conventional EMI filtering techniques. However, the limitations in size, weight, and temperature

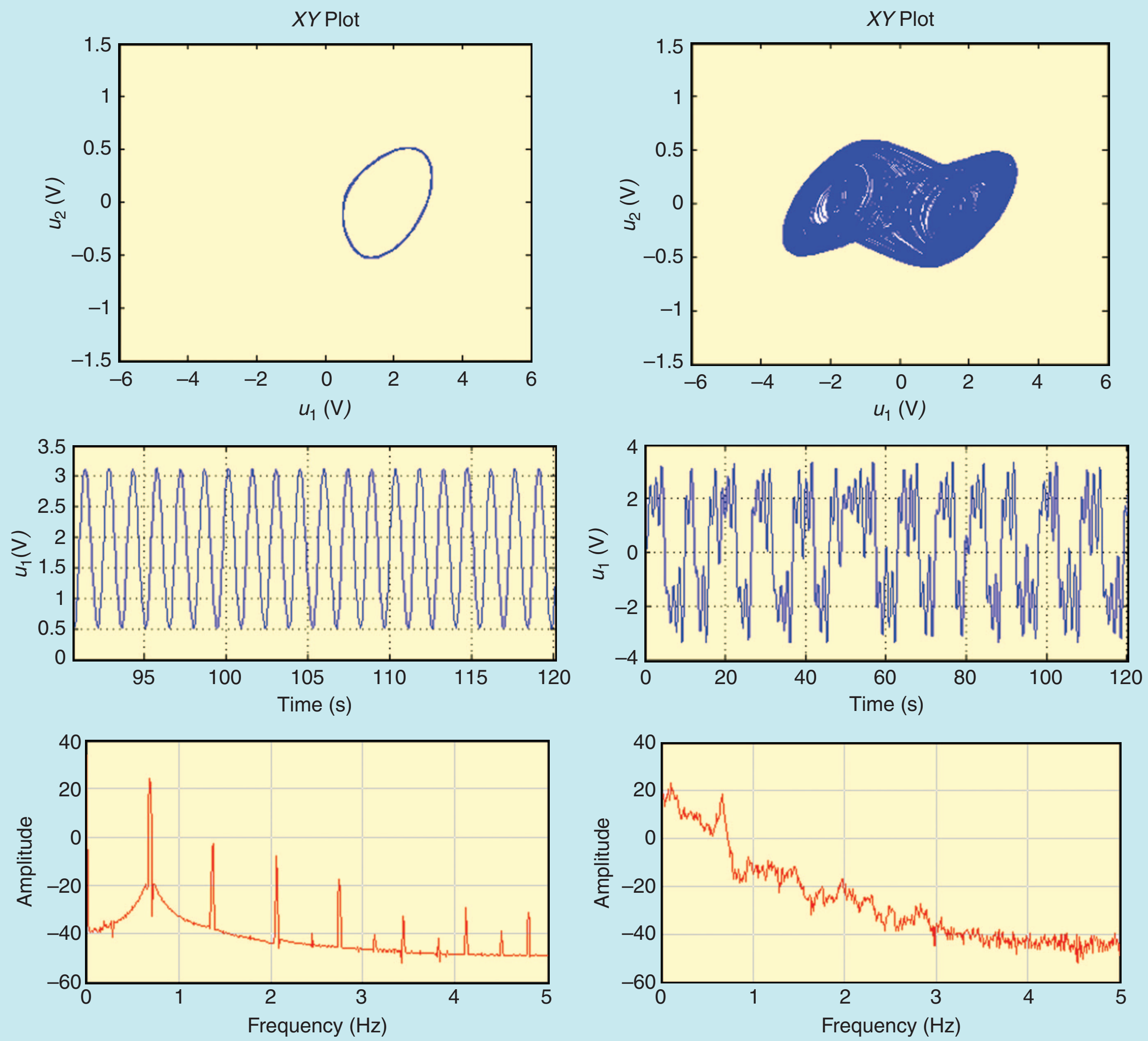



**Figure 14.** Phase portrait, time evolution, and spectra of periodic and chaotic signals.

range, as well as the reliability of magnetic cores present an obvious design constraint [9].

- **Active EMI Filter** implies that a filter consists of small passive components and active operational amplifier circuits.

  The active EMI filter was first proposed in [52], and recent years have witnessed a considerable interest in the development and applications of active EMI filters [9, 17, 28, 29]. In [9], an active EMI filter was proposed for integrated power electronics modules (IPEM) to improve the low-frequency performance of passive filters. A topology was proposed in [17] (see Fig. 8) for applying active filters to the utility interface of a switched-mode power supply.

  It can be said that an active EMI filter is more effective in case it is desirable to minimize size and cost of the passive components.

- **Hybrid EMI Filter** refers to a hybrid of passive and active EMI filters.

  A hybrid EMI filter integrates active and passive EMI filters with the aim to an effective noise suppression over a very wide bandwidth [22]. In [9], a topology for hybrid EMI filters injecting a compensating current was built. The hybrid EMI filter represents a new trend in EMI filtering.

Critical considerations for EMI filter design have been introduced in [45], which include how to design the storage capacitors, and the EMI filter capacitors and inductors for common-mode and differential-mode chokes. These important guidelines for selecting EMI filter components provide an effective manual for designers.

It should be remarked that EMI filtering is effective to suppress conducted EMI, but it also has some shortcomings, for instance, the volume is too huge for some products, not only noise but also useful signals may be suppressed, and any EMI filter is only designed for a special narrow frequency band, not applicable to the whole broad frequency band.

### 5.2 Electromagnetic Shielding

Electromagnetic shielding is the process of limiting the penetration of electromagnetic fields into a space, by blocking them with a barrier made of conductive material, as shown in Fig. 9. The shielding effectiveness (SE) is calculated by $SE = 20\times\lg(E1/E2)dB$. Typically, it is applied to enclosures to separate electrical devices from the "outside world", and to cables to separate wires from the environment through which the cables run. Electromagnetic shielding used to block radio frequency electromagnetic radiation is also known as RF (Radio Frequency, about 3 kHz to 300 GHz) shielding.

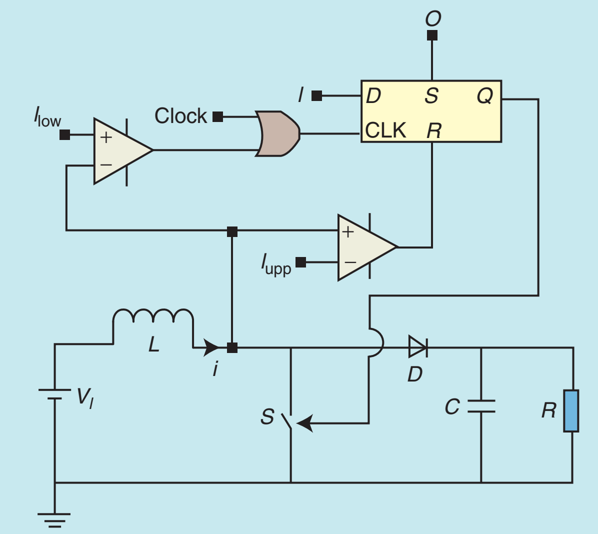



**Figure 15.** A chaotic current mode boost converter.

A popular approach of electromagnetic shielding for SMPS is to enwrap with a metal package (see Fig. 10). Thus, the design of SMPS packages is becoming more and more important. Therefore, the circuit components

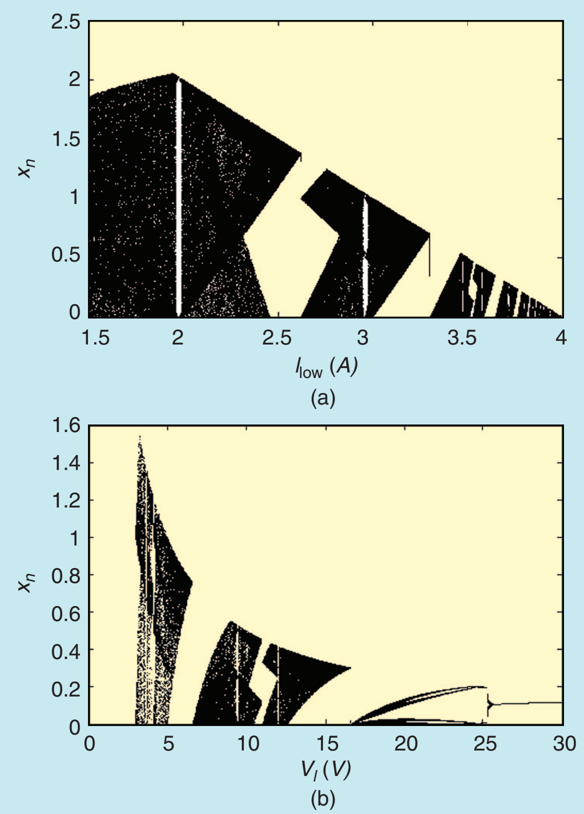



**Figure 16.** Bifurcation of $x_n$ versus $I_{low}$ and $V_I$. (a) Bifurcation of $x_n$ versus $I_{low}$. (b) Bifurcation $x_n$ versus $V_I$.

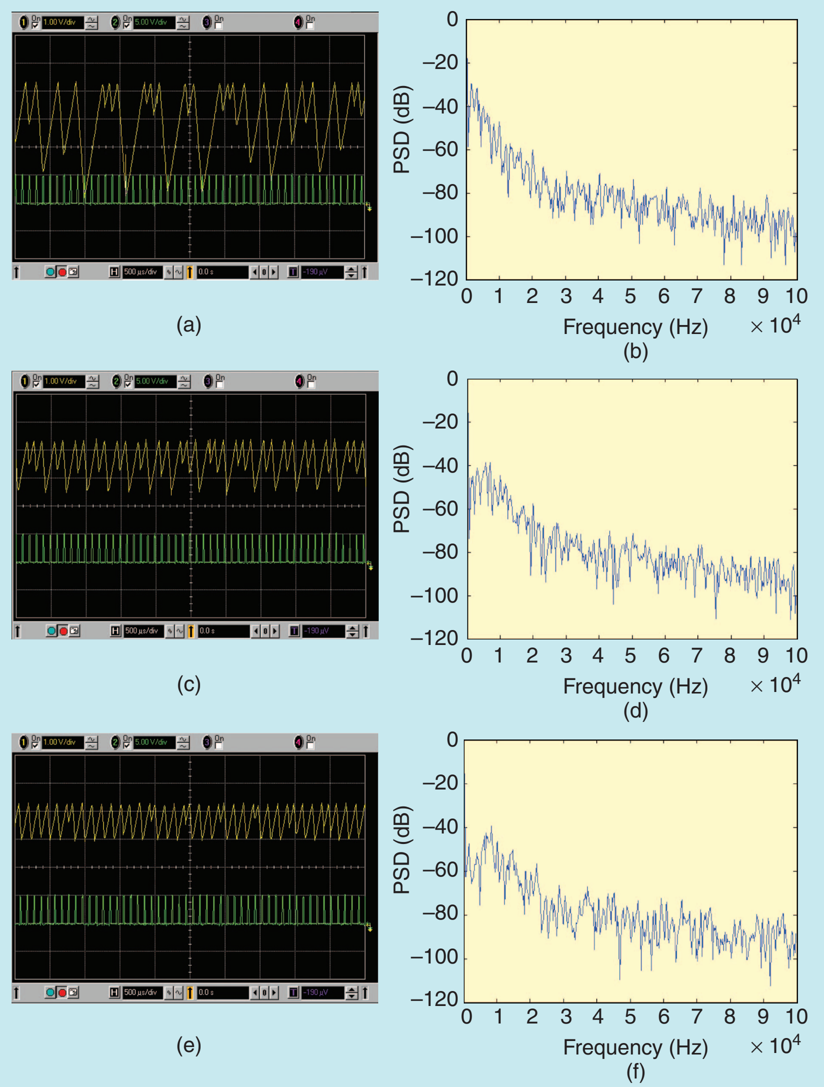



**Figure 17.** Current waveforms and corresponding spectra under three chaotic modes. (a) $i(t)$ with $I_{low} = 0A$. (b) Spectrum with $I_{low} = 0A$. (c) $i(t)$ with $I_{low} = 3A$. (d) Spectrum with $I_{low} = 3A$. (e) $i(t)$ with $I_{low} = 3.2A$. (f) Spectrum with $I_{low} = 3.2A$.

and mechanical materials required for the designed SMPS must be packaged into specified cases and meet specified performance requirements [53].

In [6], a realistic power converter shield for electric vehicle applications has been introduced, and a method to model the enclosure under test (EUT) in order to precisely predict the shielding effectiveness was developed. It is also well known that electrical isolations can be realized in SMPS by employing high-frequency transformers within the circuitries. However, the input power sources and the power supply outputs are coupled via magnetic fields [58]. Therefore, a Faraday shield, which is formed by a ground conductor between the two windings of the high-frequency transformer, was used to eliminate the noise coupling [41].

It is worth to notice that electromagnetic shielding is an effective but expensive solution for suppressing EMI, as it requires striplines, enclosures, cable shields, etc. There may exist many leak sources, such as intakes, display windows, sockets in real shields, which degrade the effectiveness of EMI shielding.

### *5.3 Soft Switching*

Large $dv/dt$ on the output, common in hard switching schemes, generates interference due to capacitive coupling, and inherently large $di/dt$ can often display EMI, leading to concern about the compliance of the respective conducted and radiated interference to EMC regulations. Further, large $dv/dt$ and $di/dt$ result in high switching loss, forming another source of EMI. Many methods have been proposed to solve this problem, such as snubbing systems, and especially soft switching.

Soft switching was first presented in 1990 [8], and has rapidly been developed in recent years [11, 10]. The main goal of soft switching is to reduce the switching loss, illustrated by the red areas in Figs. 11 (a) and (b), when converters operate at high frequencies by switching on and off at zero current or zero voltage as shown in Figs. 11 (c) and (d). Consequently, the high rates of change of voltage and current of switches are alleviated and, thus, EMI can be reduced. Sketches of soft switching and its effectiveness for EMI suppression are shown in Figs. 11 and 12 (www.xantrex.com), respectively.

Basically, the technique of soft switching can be classified as resonant switching, quasi-resonant switching, multi-resonant switching, zero-current switching (ZCS), zero-voltage switching (ZVS), zero-current transition (ZCT), and zero-voltage transition (ZVT) [47]. Soft switching combined with PWM control has widely been applied in many fields [47], and in [54], soft switching is suggested to be applied to aircraft power conversion systems.

Of course, soft switching has its limitations: it is only applicable for converters with power levels over 30 W (due to the auxiliary components adopted, soft switching even increases the power loss for low power converters [5]). Moreover, more components are needed, such as resonant inductors, resonant capacitors, auxiliary diodes, and even auxiliary switches, which not only increase the power loss but also make the design of switched-mode converters more complicated.

### *5.4 Random Modulation*

Random modulation is a new method to reduce EMI proposed in the recent two decades [15]. Random modulation means that the switch frequency is varied according to a given random signal. The total energy is, thus, spread over a wider frequency band, which is illustrated in Fig. 13.

In other words, the peaks appearing in the frequency band, when the converters operate in periodic mode, can be smoothed over the whole frequency band. The reduced peaks imply that EMI is thus suppressed. There are two main limitations to random modulation: one is that real random signals are difficult to generate in practice, and the other one is that random frequency makes the parameter design of converters difficult, since the parameter design is based on the frequency. For example, when a converter operates with frequency $f_1$, the equivalent inductance is $2\pi f_1 L$. Due to the difficulty of obtaining real random signals, pseudo-random signals can be used, leading to the term pseudo random modulation for the method.

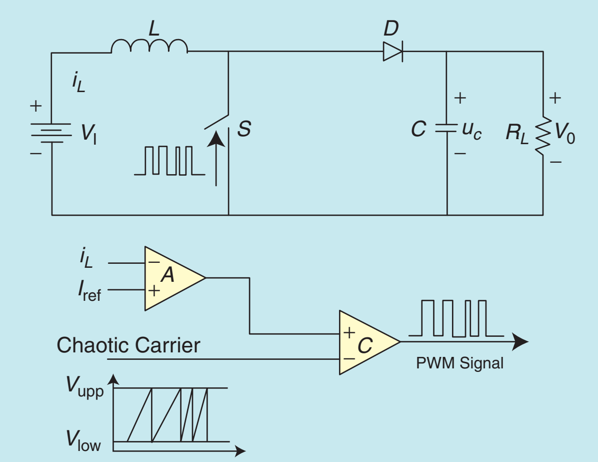



**Figure 18.** A chaotic PWM boost converter.

### *5.5 Chaos Control*

Scientific and mathematical chaos refers to deterministic behavior which is very sensitive to its initial conditions. Consequently, chaotic systems appear as random. Actually, however, they are deterministic systems governed by physical or mathematical laws

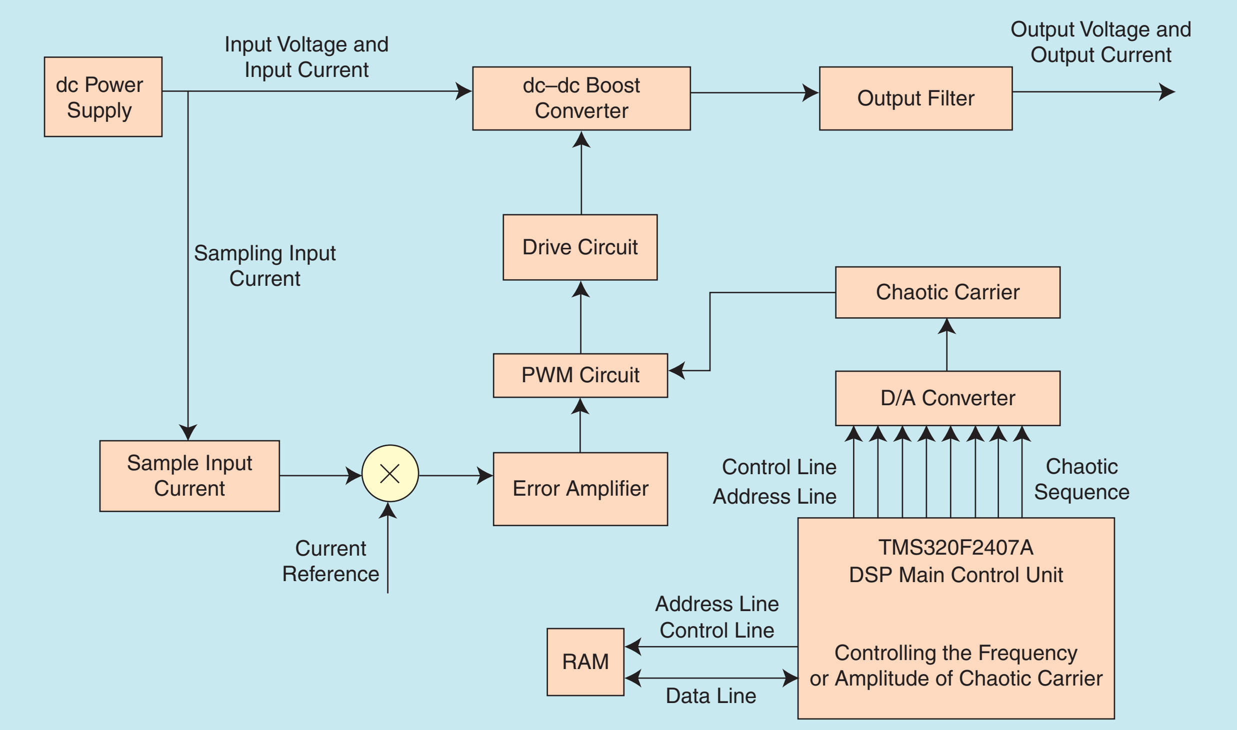
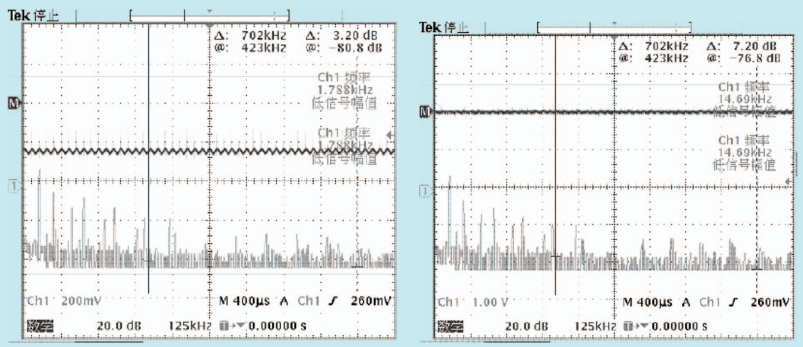



**Figure 19.** Block diagram of the chaotic PWM control experiment.




(a) (b)

**Figure 20.** Output waveforms and spectra of input current (a) and output voltage (b) of a boost converter controlled by traditional PWM.

devoted to study chaotic phenomena in various converters, such as boost, buck, boost-buck, or Cuk converters. DC-DC converters are nonlinear systems and, thus, can exhibit rich chaotic behavior [12].

Two kinds of chaos modulation have been proposed [3, 35]: one is to modulate circuitry parameters without any auxiliary circuits, while the other one is to append external chaotic circuits to the main control part of a DC-DC converter to drive the whole system chaotic. The second methodology involves the most popular PWM control. Thus, it is called chaotic PWM control, or chaos-based PWM control.

(predictable in principle, if one has exact information), whose behavior is impossible to predict in practice for relative long times. Since Li and Yorke's seminal paper of 1975 [39] and the equally influential work of Lorenz in 1963 [40], chaos has matured as a science (indeed, is still evolving) and has provided many deep insights into previously intractable and inherently nonlinear natural phenomena [25].

Like random modulation, the pseudo-randomness and continuous spectrum features of chaos can be used to suppress EMI. It is seen from Fig. 3 or from the left figure in Fig. 14 that the large peaks located at the multiples of the fundamental frequency imply EMI. Nevertheless, this is inherent in periodic systems. It is supposed that if the systems operate in chaotic modes, the peaks can be spread over the entire frequency band, as shown in Fig. 14, which is called chaos modulation [12].

Chaotic phenomena in DC-DC converters were first reported in [12], and since then, great efforts have been

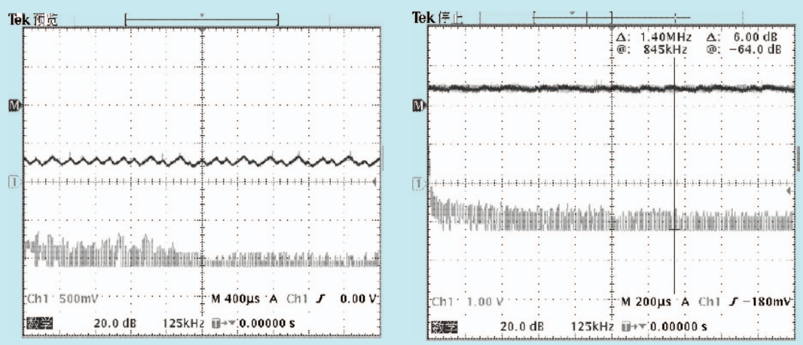
### 5.5.1 Chaos Control with Parameter Modulation

The first design of this kind of chaos control can be dated back to 1996 when Deane and Hamill [12] suggested to utilize chaos to improve the EMC of power supplies, and most chaos controls with parameter modulation were focused on current mode control [19, 20]. Using parameter modulation can greatly suppress EMI. Unfortunately, along with which, it results in larger ripples in the output waveforms, which degrade the quality of SMPS and are not allowed in practice [3]. Therefore, in [33, 34], a new chaotic peak current mode boost converter has been proposed for EMI reduction and ripple maintenance, as shown in Fig. 15.

Unlike the design in [13], the switch $S$ is now controlled by a clock with period $T_C$, a lower reference current signal and an upper one, denoted by $I_{low}$ and $I_{upp}$, respectively. Thus, the output ripple can be controlled easily by $I_{low}$ and $I_{upp}$. The chaotic phenomena of the proposed boost converter along with parameter modulation are shown in Fig. 16, where $x_n = t_n/T_C$ and $t_n$ is the $n$-th turn-on interval of the switch.

Simulation and experimental results show the effectiveness in suppressing EMI of the chaotic boost converter with different output ripples by adjusting $I_{low}$, as depicted in Fig. 17.

Thus, the proposed chaos control with parameter modulation can easily control the magnitude of ripple and, at the same time, reduce EMI [33]. In principle, this




(a) (b)

**Figure 21.** Output waveforms and spectra of input current (a) and output voltage (b) of a boost converter controlled by CPWM.

method can restrain the ripples to a desired level by increasing the lower reference current, which, however, may greatly increase the frequencies of output current or voltage, leaving many circuit components out of their working areas. On the other hand, the parameters, under which the system exhibits chaos, may not be acceptable for a circuit working in practice. These problems restrict this method's applicability.

### 5.5.2 Chaotic PWM Control

Chaotic PWM control introduces the concept of chaos control into traditional PWM control [35, 34]. Unlike parameter modulation, chaotic PWM control drives DC-DC converters to operate in chaotic mode by adding external chaotic signals, as illustrated in Fig. 18, which makes the design of DC-DC converters more flexible. Since the external chaotic signal, i.e., the chaotic carrier, can be programmed by a digital processor, the ripple magnitudes can be controlled by a program.

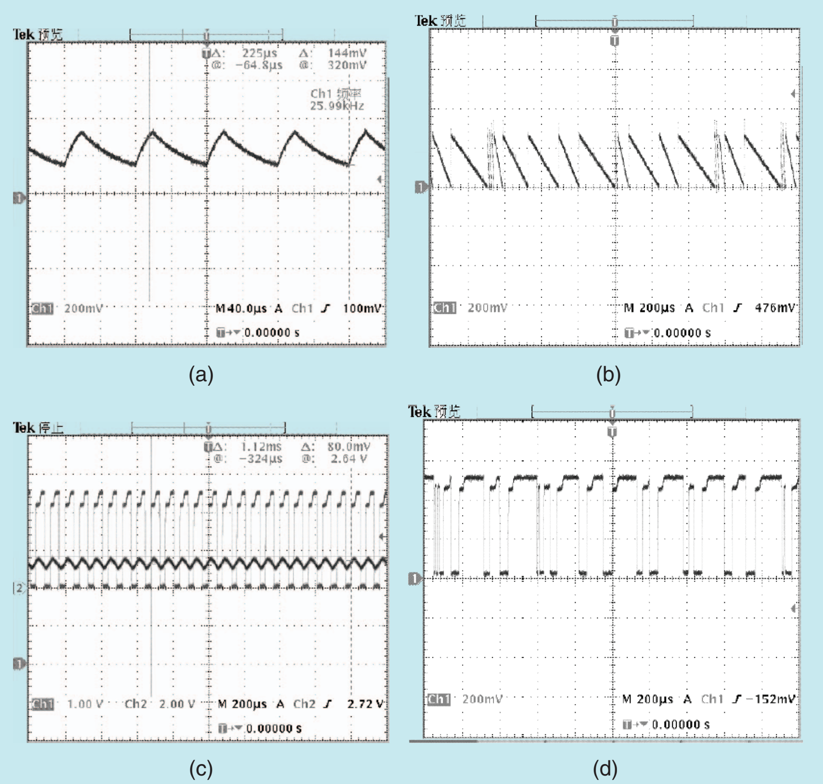


**Figure 22.** Comparison of two kinds of carrier waves and drive waves. (a) Periodic carrier wave. (b) Chaotic carrier wave. (c) Periodic drive wave. (d) Chaotic drive wave.

In this application, the chaotic carrier plays a key role, since the distribution of harmonics is influenced by the carrier, and the chaotic behavior of DC-DC converters can be used to reduce EMI. Chaotic PWM can be designed with varying carrier frequencies or amplitudes, where the logistic map is adopted for modulation [35]. The effectiveness is verified by an experiment, as illustrated in Figs. 19, 20, 21, and 22.

It is seen from Fig. 23 that the ripples in output waveforms of DC-DC converters controlled by CPWM with varying amplitudes are relatively larger than those controlled by CPWM with varying carrier frequencies. However, their spectra are similar. It is also seen that as $\lambda$ (the parameter in the logistic map $x_{n+1} = 1 - \lambda x_n^2$, $\lambda \in [0, 2]$) increases, the ripples of the output waveforms increase, but the spectra remain unchanged. Thus, if the spectra have already satisfied the EMC standards, $\lambda$ should be as small as possible in practice.

To realize chaotic PWM control, a control circuit more complicated than that for traditional PWM control should be implemented. Fortunately, the control circuit can be integrated on a PCB or even in a small chip according to the development of electric components and integration technology.

Generally speaking, a chaotic carrier can be designed in digital or analog way. The advantages of a digital chaotic carrier (like the one introduced above) are that a digital chaotic signal is accurate, and its frequency and amplitude can easily be adjusted by programming a digital processor without changing its external interface circuit; while the disadvantages are also obvious, viz., the chaotic carrier's regulable range of the digitally generated frequency is dependent on the speed of a Digital Signal Processor (DSP), a single-chip or another digital processor, an external interface circuit is sometimes necessary, and the cost of the digital chaotic carrier is high. On the contrary, the cost of an analog chaotic carrier is much lower; and the regulable frequency can be much broader by changing resistance and capacitance of the analog chaotic carrier circuit, suitable to function in high-frequency DC-DC converters. Furthermore, numerous existing chaotic oscillators can be employed for designing analogue chaotic carriers. However, analogue chaotic carriers cannot be adjusted as accurately as digital ones due to the non-ideal performance characteristics of components, and their hardware implementation is a little more complex, since they are not realized by programming, but by components.

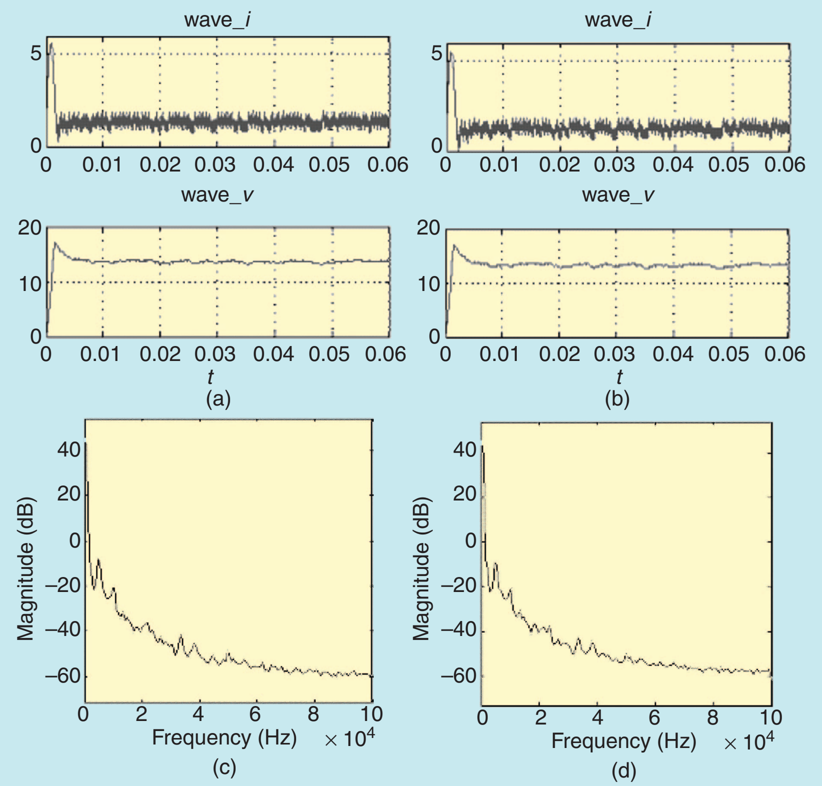



**Figure 23.** Output waveforms and current spectra of a boost converter controlled by CPWM for $\lambda = 0.4$ and $\lambda = 0.8$. (a) Output waveform for $\lambda = 0.4$. (b) Output waveform for $\lambda = 0.8$. (c) Current spectra for $\lambda = 0.4$. (d) Current spectra for $\lambda = 0.8$.

It is known that DC-DC converters always operate with high frequencies, and the frequencies of chaotic carriers must be as high as those of the DC-DC converters. Therefore, if a digital chaotic carrier were used, the speed of the corresponding digital processor would be required to be so high, resulting in a rather high cost. Even so, the existing processors can hardly satisfy the practical requirements. Instead, an analog chaotic carrier can be employed, leaving the question of how to design an analog chaotic carrier. This question is answered in [37] with a circuit design, as shown in Fig. 24. There, only one switch is adopted in the chaotic carrier by porting one of the numerous existing chaotic oscillator circuits, i.e., sawtooth map and Chua's chaotic oscillator, which renders the circuit design more flexible.

Experimental results on the EMI when using periodic and chaotic carrier are given in Figs. 25

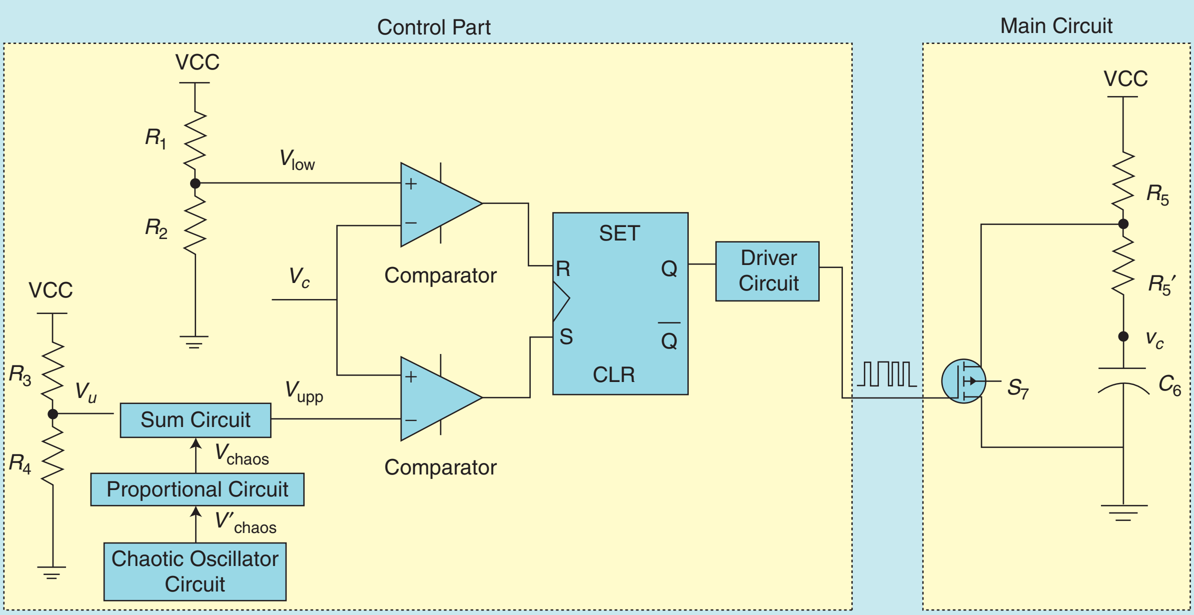



**Figure 24.** A chaotic sawtooth carrier generator.

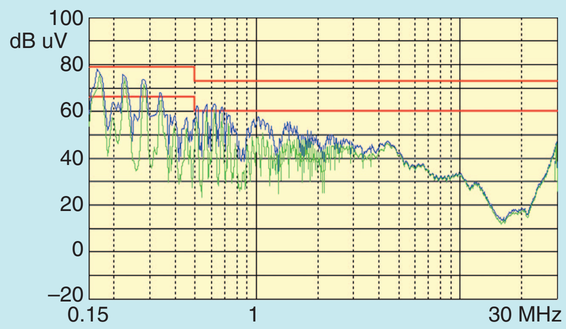



**Figure 25.** EMI of boost converter with periodic PWM control.

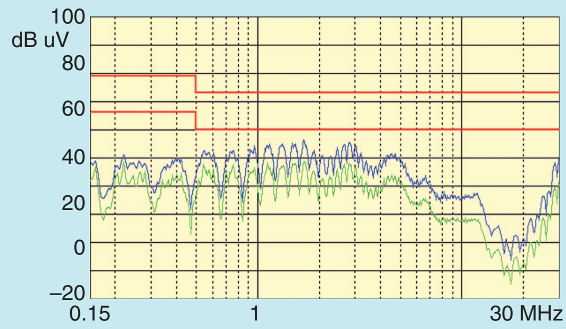



**Figure 26.** EMI of boost converter with chaotic PWM control.

and 26, respectively, which show that, in low frequency band, applying a chaotic carrier is much more effective in reducing EMI.

### 5.5.3 Chaotic Soft-switching PWM

It is known that the technique of soft switching can reduce EMI in DC-DC converters, by making the switch to turn on or off at zero current or zero voltage so as to alleviate the high change rates of voltage and current, thus reducing both switching loss and EMI; while chaos control reduces EMI by spreading the spectra of signals or time series over the whole frequency band. Obviously, soft switching and chaos control provide different ways to suppress EMI. In [32], these two methods are combined, named chaotic soft switching PWM control, to further improve EMC of DC-DC converters. Simulation results of a DC-DC converter's EMI under hard-switching PWM, soft-switching PWM, and chaotic soft-switching PWM controls are shown in Fig. 27, where PSD means power spectral density.

### 5.5.4 Some Theoretical Considerations

When chaos control is employed, the controlled system operates chaotically, probably leading to design and analysis methodologies totally different from conventional ones.

To facilitate the accurate design of the DC-DC converter parameters, a computation method for the invariant density of a chaotic mapping is proposed in [30] by using eigenvector method. Moreover, the power spectral density of the DC-DC converter's input current and the average frequency of switching are deduced.

A mean value estimation method has been proposed, which is useful to estimate the mean values of state variables for chaotic PWM boost converters to facilitate circuit parameter design and selection of circuit components. Although ripples are slightly increased, as caused by adopting chaotic carriers, DC-DC converters with reduced EMI are proven to be stable under chaotic PWM control in [36]. This work provides a theoretical verification of the effectiveness and practicability of the chaotic PWM DC-DC converters proposed.

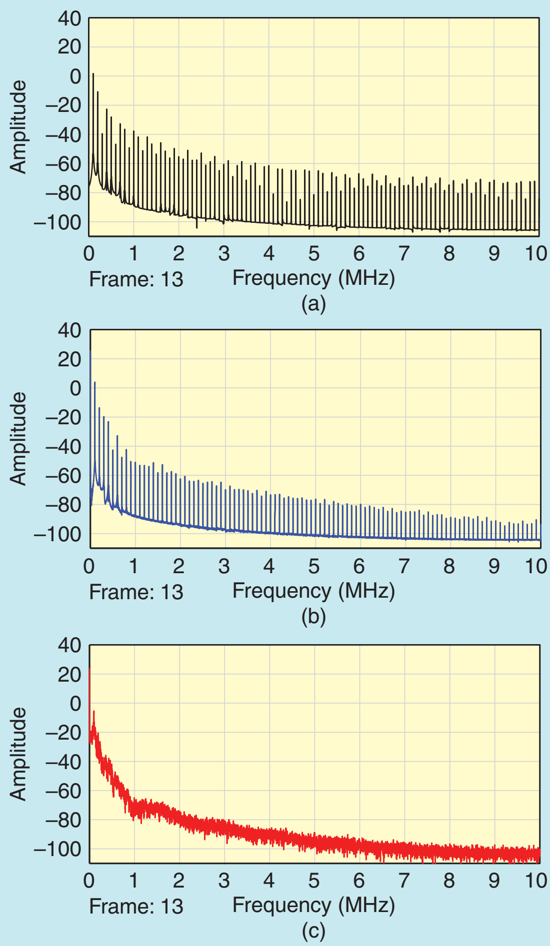



**Figure 27.** PSD of inductor currents based on different control methods. (a) PSD of inductor current with hard-switching PWM. (b) PSD of inductor current with soft-switching PWM. (c) PSD of inductor current with chaotic soft-switching PWM.

**The pros and cons of traditional EMI filters and electromagnetic shielding are discussed, and the very promising chaos control methods for EMI reduction are pointed out.**

It is known that EMI is estimated by its spectrum. Conventionally, the Fast Fourier Transform (FFT) is used to analyze spectra. However, it is not applicable to the inner-harmonics, the non-integral multiples of the fundamental frequency, which is a prominent feature of chaotic signals. As a remedy, the Prony method has been suggested to estimate the chaotic spectra of DC-DC converters in [31]. In addition, the frequencies, phases, amplitudes, and damping factors of the harmonics of currents or voltages of DC-DC converters can be obtained with the Prony method. Further, the Prony method can distinguish between the DC and the AC component of a signal. It is recommended to employ the Prony method instead of the popular FFT in applications such as spectral analysis of converters involving chaotic signals.

### *5.6 Other Techniques*

**Grounding** is a return path for current, aiming to close the current loop, but not to lead it into the earth, thus to divert EMI away from victims by providing an alternative, low-impedance path. If an interference current is successfully diverted into ground, it will simply come out elsewhere in order to return to its source [44]. Good grounding can improve EMI for DC-DC converters. How to use grounding to control EMI is introduced in [24].

**EMI Suppression Techniques for PCB** Along with the modularization and integration of DC-DC converters, more and more circuits are integrated on one or more printed circuit boards (PCB), which greatly increases the power density, and decreases the size, weight, and cost of products. Conducted and radiated EMI should also be considered carefully prior to designing PCBs. The EMI/EMC problems with PCBs are surveyed [18], including the basic EMI problems caused by integration, the methods to minimize EMI on PCBs, the corresponding EMC regulations.

## 6. Conclusions

The rapid development and wide deployment of electrical and electronic products have caused severe EMI problem to be faced by scientists and engineers. This paper surveys the EMI suppression techniques for DC-DC converters, since DC-DC converters have become increasingly important with the rapid development of electronic engineering. The pros and cons of traditional EMI filters and electromagnetic shielding are discussed, and the very promising chaos control methods for EMI reduction are pointed out, which exhibit prominent merits, yet, leave some questions to be further addressed. It aims to motivate more efforts in theoretical research and engineering practice towards promising novel technologies.

## 7. Acknowledgment

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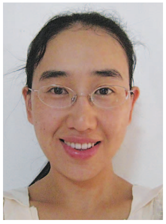

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