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Power Converters Electromagnetic Emissions with Methods to Measure, Compare and Reduce Noise Fields

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Abstract

Power electronic converters find widespread applications in the present times. However, they have been known to be rich sources of electromagnetic emissions. The converters are required to operate in compliance with their electromagnetic environment, for which they must adhere to emission limits imposed by the standards. The power converters are duly tested, and their emission levels are measured and checked for compliance. Therefore, understanding the emission mechanism is necessary to design a power converter that will satisfy the EMC requirements. In addition to the switches, parasitic elements, which are invariably present in every circuit, play a crucial role, especially in the higher frequency range, in degrading the EMC performance of converters. The present chapter takes up these aspects and discusses the reasons behind emissions and the roles played by switch characteristics and parasitic elements. Demonstrations through simulations and computations are presented all along with the discussions, and inferences are accordingly drawn. Finally, the standard specifications for emission measurements and analysis through measuring EMI receiver are briefly introduced. A few popular methods to reduce emissions are demonstrated. The final improvement in the EMI performance is shown with the help of EMI receiver output, in accordance with the CISPR standards.

Keywords: Power Converters, EMC, EMI, EMI receiver

1. Introduction

In electrical power systems, a number of potential sources capable of producing electromagnetic disturbances or noise are present. These include natural phenomena like lightning or electrical corona and electronic, especially power electronics circuits and devices. These sources either introduce or draw from the supply terminals, non-sinusoidal currents typically characterized by the rapid rise and fall times, or equivalently, high-frequency components (in MHz or GHz range) in their frequency-domain characteristics. Such currents can influence the operation of other circuits or devices present in the electrical systems in two possible ways:

1. By directly reaching the circuits through closed electrical paths

2. By producing electromagnetic fields of sufficient strength, which may couple with the other circuits directly through the air.

The former is known as conducted emission and has a frequency range of interest between 150 kHz to 30 MHz, whereas the latter is referred to as radiated emission, with the frequency range of interest being >30 MHz. With the proliferation of power electronic devices in everyday life, there is a potential increase for devices to interfere with each other. Applications of power electronics in the present times are abundant. This includes everyday household use in laptop and mobile battery chargers, Uninterrupted Power Supply (UPS), induction cooking, etc. Furthermore, in industrial applications such as control of motor drives or railway traction systems, power transmission systems such as Flexible Alternating Current Transmission System (FACTS) and High Voltage Direct Current (HVDC) transmission of electric power, utilization of power electronic systems can be found. In addition, with power electronics finding increased applications in renewable energy systems in recent times, the electromagnetic compatibility of power converter systems is a significant concern.

In view of the above, the present chapter will focus on understanding the origin of the electromagnetic noise from power converters, some methods to reduce emissions, and measurement procedures followed to quantify the noise.

2. Origin of electromagnetic noise from power converters

Power electronic converters employ semiconductor switching devices, which are operated in a manner required to produce the desired output. For example, consider the DC-DC Buck converter, the basic topology of the same has been shown in **Figure 1**. The buck converter is used to step down the input DC voltage to a lower level at the output. A controlled semiconductor switch, typically a MOSFET, is periodically turned ON and OFF to achieve the purpose.

During every switching action, the currents through certain elements or voltages at certain circuit nodes undergo rapid transition. For example, assuming every element, including the switches shown in **Figure 1**, to be ideal, the input current waveform I_{sw} for an ideal buck converter is a periodic pulse train, as shown in **Figure 2(a)**. The current undergoes rapid transitions to zero when the controlled switch is turned OFF and similarly rises rapidly (to the load current) when the switch is turned ON [1].

Figure 2(a) shows the current waveform for a switching frequency of 100 kHz, duty cycle D of 0.4 , a rise time of 25 ns, and fall time of 100 ns of the PWM pulse (control signal to switch). The FFT of the current is shown in **Figure 2(b)**. It can be observed that even though the switching frequency is only 100 kHz, the current

Figure 1.
Buck converter topology.

Figure 2.
 Input current to the ideal Buck converter. (a) Time domain waveform (b) frequency Spectrum of the currents.

waveform has significant spectral amplitude even in the MHz range (high-frequency components).

Typically, the DC input V_{dc} to the converter is obtained by rectifying the 220 V or 110 V (50 or 60 Hz) AC supply. Therefore, the non-sinusoidal (pulse train) current drawn by the buck converter is reflected on the AC supply side, and the high-frequency components can flow through the electrical paths reaching various other neighboring devices and circuits connected to the supply. This can result in electromagnetic interference, and since the coupling of the electromagnetic noise takes place through closed electrical paths, this forms an example of *conducted emission* (CE), introduced earlier.

In practice, the entire circuitry contains numerous metallic or conducting paths and connections. Although, for example, the input DC supply (and even the load) is connected to the converter through a cable harness, the converter layout could be realized in a Printed Circuit Board (PCB) in which the PCB traces provide the connections. In addition, there are various metallic connectors and wires present in the entire circuit. When the high-frequency currents flow through these conducting elements, some of them (depending on the dimensions and frequency or wavelength) behave like radiating antennas. In such situations, the electromagnetic fields may couple directly through the air between two different circuits. This is the case of *Radiated Emission* (RE) which has earlier been introduced.

The above analysis considering the ideal buck converter topology clearly demonstrates that the switching transients that take place in a power electronic converter can lead to electromagnetic interference through conducted and radiated emissions. Although the buck converter topology has been used as an example for demonstration, it is clear that since the switching transients take place in all power electronic converters, electromagnetic noise is produced by all power electronic converters.

Although the ideal buck converter is a good example to consider for a first analysis, the situation is much more complicated in practical circuits, chiefly due to the presence of parasitic elements. Some of these aspects are discussed in the following section.

3. Effect of non-linearities and parasitic elements

The power semiconductor switches are inherently non-linear in their operational characteristics. These non-linearities lead to additional system dynamics during the

switching transients. This results in worsening of the EMI performance of practical converters compared to analysis carried out for ideal converters.

To demonstrate the above, the buck converter shown in **Figure 1** is simulated again. This time, however, the freewheeling diode is no longer assumed to be ideal. Instead, the well-known quasi-static model (diode models used in LTSpice), presented in **Figure 3**, is employed to obtain the terminal characteristics of the diode [2]. The equations of the model have also been presented below [2]. For more advanced diode models, the reader may refer to recent literature [3, 4].

The model provides the current i_d through the diode and the voltage across its terminals v_d . To compute i_d , the saturation current I_s , emission coefficient N and the threshold voltage V_T need to be known. The model also includes a series resistor R_s and a non-linear junction capacitor C_J . The junction capacitance is a function of the voltage v_d , and can be computed by knowing the zero-bias junction capacitance C_{J0} , junction grading coefficient M and the junction potential V_J . For the diode considered, MBR340, the values as obtained from the LTSpice library are; $I_s = 22.6 \mu A$, $N = 1.094$, $R_s = .042 \Omega$, $C_{J0} = 480 pF$, $M = 0.61$. V_T is taken to be $26 mV$ and $V_J = 1 V$, the default value.

The buck converter is simulated with the above diode model, keeping the switching frequency, duty cycle, and the load same as that of the ideal converter analysis. The simulated input current waveform obtained is shown in **Figure 4(a)**.

There is a sharp spike observed in the current waveform at the rising edge in the present case. This is not present in the ideal converter input current shown in **Figure 2(a)**. **Figure 4(b)** shows the rising edge of both the input current and current through the diode are plotted together. The sudden spike in the diode current is required to charge the junction capacitance when the controlled switch (MOSFET) is turned on and the diode is, turned off. This current is drawn directly from the DC supply V_{dc} and therefore reflects as a spike in the input current waveform. The effect of this spike on the emission performance can be clearly understood by comparing the frequency domain characteristics of the input currents in the ideal and practical buck converter cases. For example, the FFTs of the two currents (shown in **Figures 2(a)** and **4(a)**) are shown in **Figure 5**.

From **Figure 5**, it is clear that for the practical converter, the spectral amplitude of the high-frequency components has increased by many times. The difference is even a few tens of dB in the higher frequency range. Therefore, it is clearly seen that the nonidealities of the power converter switches can play an extremely important role towards the magnitude of the electromagnetic emissions from the power converter circuit.

The situation in practical converters is further complicated by the parasitic elements which are inadvertently present in the circuits. To demonstrate this, a parasitic inductance of $1 nH$ is considered on the converter input side, as shown in **Figure 6**. Such inductances arise due to the connecting cables or wires, PCB traces, contacts, and connectors, etc., and are unavoidable in the practical circuits.

Figure 3.
Model of freewheeling diode.

Figure 4.
Simulated currents for the practical Buck converter. (a) Input current and (b) input current and the freewheeling diode current.

Figure 5.
Frequency domain characteristics of the input currents to ideal and practical buck converters.

Figure 6.
Buck converter with input side parasitic inductance.

Keeping everything else unchanged, the above circuit is simulated, and the input current is shown in **Figure 7(a)**. It is observed that the input current contains a damped, high-frequency oscillatory response at the rising (and falling) portions. Such oscillations are known as ringing and are due to the L-C resonance between the parasitic inductance and the diode junction capacitance. The frequency-domain

Figure 7.

Buck converter with input side parasitic inductance and diode effects considered. (a) Temporal variation of input current and (b) comparison of frequency domain characteristics.

characteristics are shown in **Figure 7(b)** along with the earlier two cases for comparison. The spectral amplitude of the current with parasitic inductance (plus diode) is the highest. In addition, resonant peaks are clearly observed in the high-frequency end of the spectrum. Therefore, the parasitic elements increase the high-frequency components of the input current and, correspondingly, the emissions from the power converter. These are, therefore, serious considerations in assessing the EMI performance of the converter.

In practice, it is often necessary to reduce the emission from power converters in order for the design to be EMC compliant. Damping out the ringing shown in **Figure 7(a)** is extremely important in this regard.

The discussion so far has been carried out towards understanding the origin of the electromagnetic noise (emissions) from power converters. In addition, the effects of parasitic elements and switching device features have also been examined. It is quite clear that electromagnetic noise from power converters is unavoidable due to their intrinsic switching operations. However, the design must also be EMC compliant. With this view, the discussion will next be directed towards methods to improve the EMI performance of power converters.

4. Methods to improve EMI performance of power converters

4.1 With RC snubber

In the previous section, it has been shown that the ringing in the current (and voltage) waveforms degrades the EMI performance of the circuit. Therefore, damping out the ringing will improve the performance. A simple method to achieve the same is the use of an RC snubber. Considering the case of a buck converter, the snubber is connected across the freewheeling diode (snubber is to be connected between switching node and ground), as shown in **Figure 8**. The values of the snubber elements R_s and C_s are computed as follows:

$C_s \approx 3$ times the diode junction capacitance. Since the junction capacitance is a varying quantity (with junction voltage), the maximum value corresponding to zero bias value, i.e., C_{j0} is considered for calculation. Therefore, $C_s \approx 3 \times 480 \text{ pF}$. This results in a value of 1.44 nF , and so a value of 2 nF is selected.

$R_s \approx 2\omega_0 L_p$ where, ω_0 is the angular frequency corresponding to the ringing oscillations to be damped and L_p is the parasitic inductance, 1 nH at present. The ringing oscillations in the current waveform shown in **Figure 7(a)** have a frequency of $\approx 500\text{ MHz}$. With these values, R_s is computed to be $6.28\ \Omega$, and therefore, the value of $10\ \Omega$ is selected.

With the snubber elements included in the buck converter circuit as shown in **Figure 8**, the input current is computed and is shown in **Figure 9(a)**. Also shown in the Figure is the current without snubber (shown earlier in **Figure 7(a)**) for comparison.

Clearly, the snubber results in damping out the ringing at the rising edge of the input current waveform. The same inference can also be drawn from the frequency domain characteristics shown in **Figure 9(b)**. The snubber has clearly damped out the resonant peak due to the high-frequency ringing. With snubber included in the circuit, the frequency spectrum plot clearly shows a reduction in the spectral amplitude of the high-frequency components, and hence an improvement in the emission performance.

It is also important to check the power loss in the snubber resistor and its impact on the efficiency of the circuit. The power loss is given by [5], $f_{sw} C_f V^2$ where, f_{sw} is the switching frequency (100 kHz), V is the peak voltage which appears across the diode terminals (approximately equal to the input voltage V_{dc}).

The power loss is calculated and found to be 28.8 mW . The output power is $\frac{(0.4 \times 12)^2}{5} = 4.6\text{ W}$. Therefore, the power loss in the snubber is $\frac{28.2 \times 10^{-3}}{4.6} \times 100 = 0.625\%$ of the power delivered at the output and can be neglected for all practical purposes.

Figure 8.
Buck converter with input side RC snubber.

Figure 9.
Input currents in buck converters with and without snubber. (a) Temporal variation of input current and (b) comparison of frequency domain characteristics.

Although the snubber improves the EMI performance of the converter, designing the snubber elements can prove to be difficult since it is difficult to estimate the parasitic inductance accurately and switch capacitance and the maximum voltage at the switching node (due to overshoot). In addition, the snubber damps out or attenuates the high-frequency oscillations, which take place at (or around) a certain frequency. If all high-frequency components (above a certain cutoff or threshold frequency) could be attenuated, further improvement in the EMI performance can be obtained. This can obviously be achieved by using a low pass filter. This is discussed in the following.

4.2 With damped LC filter

One popular method to reduce emissions from power converter and improve their EMI performance is using filters. Considering the example of the buck converter shown in **Figure 6**, a damped LC filter is added on the input side, as shown in **Figure 10**.

The filter elements are the inductance L_f , capacitance C_f and the damping resistor R_f . The value of the damping resistor is selected from the condition $R_f \ll R/D^2$ [6]. Selecting $R_f = 1 \Omega$ easily satisfies the criteria. The values of L_f and C_f are selected to be $100 \mu H$ and $100 pF$, respectively. With these values, the resonant frequency is $\approx 5 MHz$. This is sufficiently away from the switching frequency of $100 kHz$ and therefore does not slow down the converter's response. However, it provides sufficient attenuation to the high-frequency components and, therefore, is expected to improve EMI performance. To validate the same, the buck converter with the input side filter is simulated, and the input current I_{sw} is obtained. This is shown in **Figure 11 (a)**, and the input current without the filter is shown in **Figure 7(a)** for a practical converter. The frequency spectrum of the currents with and without filters is shown in **Figure 11(b)**.

In the time domain current waveform, the effect of the damped LC filter in reducing the oscillation is clearly noticeable. The amplitude of the overshoot is also observed to have reduced. The attenuation provided to the high-frequency components can be seen from the frequency response. The reduction in the amplitude at some of the high-frequency components is around 20–30 dB. This is a significant improvement in the performance of the converter operation from the EMI/EMC point of view. Also, it is worthwhile to note that the damped LC filter attenuates both the resonant peaks present in the frequency characteristics. This can be compared with the method employing snubber elements (**Figure 9(b)**), where only one peak has been attenuated.

However, it is important to mention here that the LC filter changes the converter dynamics, often leading to a significant degradation in the transient response. Moreover, for converters operated under closed-loop control, the addition of the filter may even make the control system unstable [7]. Therefore, the

Figure 10.
Buck converter with input side damped LC filter.

Figure 11.
Input currents in buck converters with and without input side filter. (a) Temporal variation of input current and (b) comparison of frequency domain characteristics.

design of the filter is not a straightforward task, and the converter performance, closed-loop response, and EMI specifications must all be considered in satisfying all the requirements.

So far, the mechanism behind emissions from power converters, along with some of the important factors responsible for degrading the EMI performance, has been discussed. In addition, some popular methods to improve the EMI performance have also been discussed. In the following sections, the measurement of the emissions and analysis of the same through standard receivers will be briefly discussed.

5. Measurements of electromagnetic emissions

Measurements of emissions are performed to test for EMC compliance of any product. Therefore, the measurements must be carried out so that the results are easy to correlate across different measurement sites or EMC labs. To understand this, assume that the noise current injected by a certain product into the power supply needs to be measured for compliance. This could be conveniently carried out by using a current probe. However, the noise current injected into the supply depends on the equivalent impedance measured between the supply's terminals. This impedance varies over frequency and will be different at different places, time of the day, seasons, etc. As a result, the noise current will also vary, and therefore the measurement results cannot be correlated.

In order to eliminate the above uncertainties, a Line Impedance Stabilization Network (LISN) is employed for the measurement of Conducted Emissions (150 kHz- 30 MHz) [8]. The block diagram of the measurement setup is shown in **Figure 12**.

The LISN is connected between the supply lines and the product, usually referred to as Device under Test (DuT) or Equipment under Test (EuT). LISN has the following two purposes [8]:

1. To offer a constant impedance (of 50 Ω), looking from the terminals of the product, over the entire CE frequency range (150 kHz – 30 MHz).
2. To block the noise that may enter from the supply terminals and otherwise be wrongly attributed to the DuT.

Therefore, with **Figure 12**, only the noise current from the DuT flows through the LISN to the supply terminals. Since the impedance is fixed, a linearly related equivalent noise voltage drop is produced at the LISN, which is then fed to a measuring receiver (EMI receiver). The receiver’s measured noise is then analyzed, which will be briefly discussed in the following section.

In the case of radiated emissions, the emissions or noise is coupled directly through the air. Hence an antenna is used to capture the emissions, which are then fed to the measuring receiver for analysis. The block diagram is shown in **Figure 13**.

In the measurement of radiated emissions, typically, over the frequency range of 30–200 MHz, the biconical antenna is used, from 200 MHz – 1 GHz, a log-periodic antenna is employed, and beyond 1 GHz, horn type antennas are used. Discussion on antennas is beyond the scope of the present chapter. However, more detailed discussions are available in the literature [8].

The emission or noise measured by the antenna is sometimes passed through a pre-amplifier stage before feeding to the EMI receiver. The noise emitted by the devices or equipment must be within limits set by the standards. In the United States, the Federal Communications Commission (FCC) limits are required to be adhered to whereas, in most of the European countries, the limits specified by the International Special Committee on Radio Interference (CISPR) are followed. In order to test whether the device or equipment emits the noise, lies within the limit, the measured noise (by LISN or Antenna) is analyzed by a measuring receiver or EMI receiver. The standards also stipulate the analysis procedure to be followed by

Figure 12.
Block diagram of conducted emission measurement setup.

Figure 13.
Block diagram of radiated emission measurement setup.

such a receiver. The receiver, according to CISPR 16–1-1 standards, is briefly discussed in the following.

5.1 EMI receiver according to CISPR 16–1-1

As specified by the CISPR 16–1-1 standard, a measuring EMI receiver must be employed to obtain the noise produced by the DuT. The receiver is coupled to different devices (LISN for CE or different antennas for RE) depending upon the type of emission to be tested. The input impedance of the receiver must be 50 Ω or as close as possible. Otherwise, impedance mismatch might lead to standing waves which will introduce error in the results. The receiver can be operated in different modes, such as Peak, Quasi-Peak, Average, or RMS. The modes are selected based on the type of signal to be measured [9].

In the following, the peak detector mode is briefly discussed since it can be used for different types of input signals and indicates the worst-case scenario. In other words, if the emission of equipment is above the stipulated limit in the peak detector mode, it will fail all the other modes as well. Discussion and modeling of the receiver in quasi-peak, average and RMS modes can be found in literature [10, 11].

The receiver frequency range is divided into a number of different bands. Each band has its range as well as bandwidth for the Intermediate Filter (IF). **Table 1** specifies the important requirements for the receiver in peak detector mode.

CISPR Band	A	B	C	D	E
Frequency Range	9 kHz – 150 kHz	150 kHz – 30 MHz	30 MHz – 300 MHz	300 MHz – 1000 MHz	1 GHz – 18 GHz
Bandwidth B6 (6 dB)	200 Hz	9 kHz	120 kHz	120 kHz	1 MHz

Table 1.
Requirements of CISPR 16–1-1 EMI receiver in peak detector mode.

Figure 14.
EMI receiver output for the input current to the buck converter.

The input time-domain signal to the EMI receiver is typically transformed to the frequency domain through the FFT algorithm. Thereafter, the windowing operation is performed with the IF filter, determined by the band specified in **Table 1**. An extremely short time constant for charging and a very long time for discharging is employed for the peak detector mode. For the other modes, the time constants are specified in the standard. The output of the peak detector stage is obtained across the frequency range of the EMI receiver to produce the emission result for the DuT [6].

As an example, consider the input currents to the buck converter shown in **Figures 7(a)** and **11(a)**, i.e., without and with the damped input filter, respectively. The noise currents are analyzed with the CISPR 16–1-1 EMI receiver (numerically implemented). The results are presented in **Figure 14**, up to 1 GHz.

The improvement in the emission due to the buck converter with the damped LC filter is clearly observed in the EMI receiver output. The output of the EMI receiver can be compared with the limits set by the standards to test if the equipment is compliant with the EMC standards or not. Since the standardized procedure is followed, the results can be correlated across different sites.

6. Conclusion

In this chapter, the emission from power electronic converters has been discussed. Beginning with a discussion on the origin of the emission, which was attributed to the rapid switching transients taking place during the operation of the switches, the effect of the device characteristics as well as circuit parasitic elements were analyzed. At each step, through simulations and computations, the effects were demonstrated to degrade the converter's EMI performance compared to an ideal buck converter performance. Thereafter, a couple of methods employed to improve the EMI performance were discussed and demonstrated.

The importance of stipulating a standard procedure for measuring and analyzing the emissions was briefly discussed. The different coupling devices used in measuring emissions over different frequency ranges were introduced along with the measuring EMI receiver according to CISPR 16–1-1 standard. The results of the buck converter currents were analyzed with a numerically modeled EMI receiver as per the standard, and it was shown that the input filter dramatically improves the EMI performance of the power converter. Finally, since the switching transient is common to all power electronic converters, the discussions hold good for power converters in general.

Conflict of interest

“The author declares no conflict of interest.”

Thanks

The author would like to thank his mother, Mrs. Jyotsna Nath, for everything.

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References

- [1] Mohan N, Undeland TM, Robbins WP. Power electronics : converters, applications, and design: John Wiley & sons 2003.
- [2] Halkias CC, Millman J, Jit S. Electronic devices and circuits: McGraw Hill, 1967
- [3] Zaikin DL. Basic Diode SPICE model extension and a software characterization tool for reverse recovery simulation: IEEE International Conference on Industrial Technology, pp. 941-945, 2015
- [4] Wang J, Liang S, Deng L, Yin X, Shen ZJ. An improved SPICE model of SiC BJT incorporating surface recombination effect: IEEE Transactions on Power Electronics, pp. 6794-6802, 2018
- [5] Zach Z. RC snubber design in EZBUCK circuit: Alpha Omega Semiconductor, Inc. 2008.
- [6] Erickson RW, Maksimovic D. Fundamentals of power electronics: Springer Science & Business Media; 2007
- [7] Chu Y, Wang S, Wang Q, Goswami R. Modeling and stability analysis of active/hybrid common-mode EMI filters for DC/DC power converters: IEEE Energy Conversion Congress and Exposition, pp. 247-254, 2015
- [8] Paul CR. Introduction to electromagnetic compatibility: John Wiley & Sons; 2006.
- [9] Schwarzbeck D. The EMI receiver according to CISPR 16-1-1: Schwarzbeck Mess-Elektronik.
- [10] Li C, Zhang L, Dong T, Wang T, Chen H. An EMI receiver model with consideration of the intermediate frequency filter: International Symposium on Electromagnetic Compatibility, pp. 233-236, 2016
- [11] Li H, See KY. Conversion factors between common detectors in EMI measurement for impulse and Gaussian Noises: IEEE Transactions on Electromagnetic Compatibility, pp. 657-663, 2013