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EMI Consideration of High Reliability DC-DC Converter: In Aerospace Based Electric Transport System Charger Application

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Abstract—High reliability and low electromagnetic interference (EMI) are two important factors for many industrial applications such as air based electric transport system charger (AETSC). Therefore, it is essential to introduce high reliability and low EMI power converters. This paper presents a new high reliability and low current ripple DC-DC converter. For the proposed converter, a spectrum analysis approach for suppressing the EMI using chaotic sinusoidal pulse width modulation is provided. In addition, the proposed converter has radio frequency (RF) EMI lower than 100 kHz. However, for higher than 100 kHz, EMI issue of the proposed converter has unsuitable situation.

1. NOMENCLATURE

A: amplitude of signal, f_c: carrier signal, $\upsilon_m(\tau)$: unitary amplitude of modulated signal, k_ω: a controlled factor, T_C: the main frequency of switch which is a constant, x_n: the nth output of chaotic mapping, β: a modulation factor.

2. INTRODUCTION

In AETSC applications, a power subsystem generates, distributes, regulates power, and stores it for periods of peak demand. The power subsystem may also need to convert and regulate voltage levels or supply multiple voltage levels. A power switch acts in on- or off-state. Hence, it is essential to increase the reliability of the converter. Moreover, it is necessary to protect it against short circuits and isolated faults. A satellite electric transport system, in some technologies, is fed through common DC bus. A subsystem includes communication, control and other sections. The importance of proper functioning of the subsystem depends on the electric transport system mission. EMI is a popular problem in electric transport systems. High-speed switching in power subsystems is the main source of EMI.

Switching in power conversion system generates conducted EMI noise through DC line between the power converter module and ground. In general, the flowing noise between two lines is called differential mode (DM) noise, and the flowing noise between each line and ground is called common mode (CM) noise. CM mode noise is mainly conducted through parasitic capacitance between component and ground plane. It is excited by the common mode voltage, which is source voltage of the top device or drain voltage of the bottom device in a phase. Also, the produced common mode voltage in motor terminals is the reason of leakage current. High value of dv/dt is also responsible for CM EMI as identified in [1–3]. On the other hand, High di/dt may result in differential mode (DM) EMI [4, 5]. Stray capacitors are excited by increasing the switching frequency. Stray capacitance consists of the capacitance between motor winding and motor body, power switch drain-source capacitor and other known and unknown capacitors.

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Technological progress in the building of semiconductor device makes the growth of power and switching frequency of the power electronics device possible. This leads to desirable growth of voltage rise and fall rate, decreasing switching losses but also increasing EMI emissions and acoustic noise [6–9]. Normally, EMI is suppressed by designing a filter to reduce the conducted interference in considerable frequency bands [7]. Size and weight of DC-DC converters are increased extremely by using filters. In order to remove filters and reduce EMI, various switching methods have been used. Firstly, soft switching method was proposed. Soft switching techniques [9, 10] have been proposed to reduce switching losses and switching stress on power electronics devices, which leads to the improvement of the energy efficiency and reliability of power converters. However, the effect of soft switching on EMI in boost converter is low [11]. Additional elements, such as diodes and capacitors, lead to increased cost of the converter. This problem is not desirable in some applications such as the power system of satellite. Therefore, the spread spectrum frequency modulation (SSFM) pulsating technique was proposed. This alternative option uses control signals in such a way that the output spectrum produces peak amplitudes lower than the conventional constant frequency trapezoidal signal and keeping the desired duty ratio [12]. Periodic and non-periodic SSFM spread the peak of energy in spectrum frequency. However, chaotic switching increases the output voltage ripple. Because of high ripple at output voltage and lower reduction of EMI, the SSFM approach is not useful for the boost DC-DC converter. In practice, the complex implementation of SSFM increases manufacturing cost. A method based on the combination chaotic and soft switching PWM was proposed to reduce EMI in boost converter in [13]. However, this approach needs two new diodes, and its implementation is complex. In this paper, the aim is a high reliability and low current ripple in a boost converter for high reliability EPS topology.

Active and passive filters are other methods for reducing EMI. In [14], the effect of switching frequency on differential and common mode noise filter has been fully discussed. A large proportion of the volume and weight in DC-DC converters are related to the passive filters. By increasing the power density of converters, the mentioned proportion increases. Usually, the active filters require an additional and independent DC source. This is a major disadvantage for these types of filters.

Despite the important progress steps in the technological area, semiconductors and their associated circuitry are the main reason of failure in industrial applications. According to [15], semiconductor and soldering faults are about 34% share of semiconductor device failures, whereas printed circuit boards' failure has 26% share. Power switch faults are typically caused by high thermal or voltage/current stress [16, 17]. Because any malfunction occurrence in the electric transport system may lead to human risks, the reliability issue is very problematic. In this paper, two power switches under a particular pattern are switched to increase the reliability of the studied converter and reduce the input current ripple. Low current ripple derived from battery can increase battery lifetime and increase the reliability of electric transport system charger.

3. EMI THEORY

The power converters are widely used in different applications such as general industrial equipments, transport machines, and power supply apparatuses. Inherently, power converters are the source of electrical noise and induce EMI. Therefore, it is important to carefully design power converters to meet the EMC requirements [18]. The main source of EMI emission in a power converter is the high-frequency switching at relatively high voltage and large current following a certain pulse-width modulation. A typical configuration of a power converter is shown in Fig. 1, where a line impedance stabilization network (LISN) is connected to test the conducted EMI [19]. The generated EMI noise from the power converter can be separated into two components which are called the DM and CM [20–22]. As indicated in Fig. 1, the DM noise flows through the operation paths, while the CM noise flows to the ground through the stray capacitance.

In [19], a boost converter is considered to describe the generation of DM and CM EMI noise currents. Fig. 2 shows a boost converter with the stray capacitances. C_1 and C_2 are parasitic capacitors between the DC link and the ground plane. The capacitance between the DC cable and the ground plane (or capacitance between the PCB path and the ground layer) and the stray capacitance between the solar plane and the ground plane can be modeled with C_1 and C_2, respectively. In Fig. 2, C_{CM} represents the parasitic capacitance between the ground and the power switch node. This node is a dynamic node

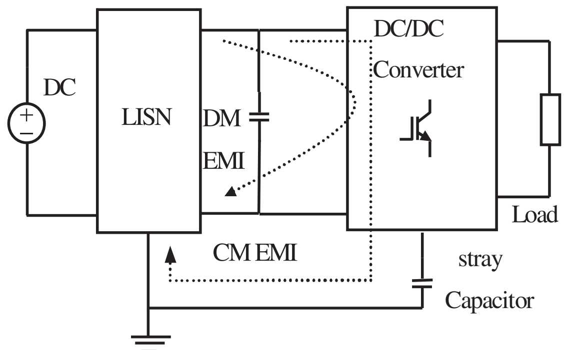

Figure 1. EMI mode illustration in typical power converter.

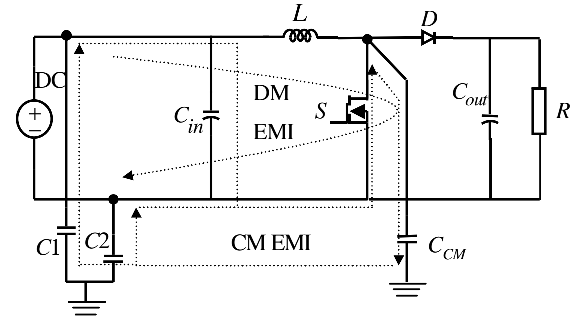

Figure 2. DM and CM paths and current in boost converter.

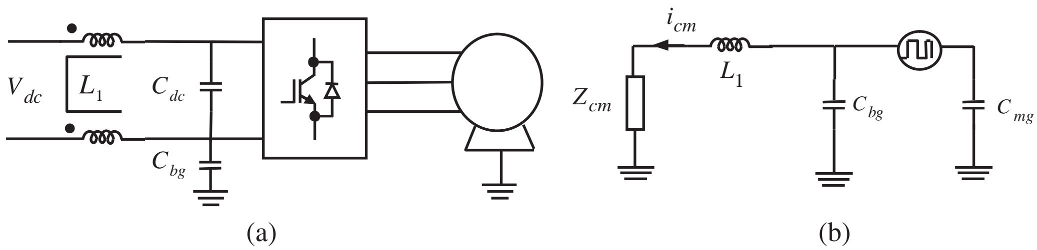

Figure 3. (a) Three-phase motor drive with CM input inductor and (b) its simplified CM equivalent circuit [20].

with large dv/dt when the switch operates at high frequency. Due to the high switching frequency, the potential changes rapidly in this node. Therefore, it is considered as a hot-node. When switching function occurs, C_{CM} is excited due to high dv/dt. High dv/dt consists of high-order harmonics. Therefore, the stray capacitors impedance will be low in the presence of high-order harmonics. Then, CM current flows to the ground. The flowing current through the loops consisting of inductor L, input capacitor C_{in}, and dc voltage source called DM EMI.

To develop the cancellation CM EMI methods, a simple CM equivalent circuit model is commonly used for electric systems such as a motor drive system [23]. Figs. 3(a) and (b) show a three-phase motor drive with CM input inductor and its simplified CM equivalent circuit, respectively. A common-mode choke L_1 is placed at the dc input terminals for CM EMI filtering. The most important ground current path in a motor drive system is through the parasitic capacitance between stator windings and grounded motor frame. If the used switch is ideal, the inverter CM behavior can be modeled by an ideal voltage source V_{cm} as follows:

$$V_{cm} = \frac{v_a + v_b + v_c}{3} \tag{1}$$

One of the main sources of EMI emission in power converters is a switching function using a certain pulse width modulation (PWM). When conventional PWM switching method is applied to the power switches, a trapezoidal wave (finite rise and fall times) with constant switching frequency and variable duty ratio is usually obtained. Consequently, the accumulation energy of the EMI spectrum is placed at the fundamental switching frequency and its harmonics. The proposed option uses controlled frequency in PWM function in such a manner that it produces a spectrum with peak amplitudes lower than the conventional constant frequency trapezoidal signal at the output, while the desired duty ratio is constant. If variable switching frequency (with finite and certain variance) is obtained by modulating the base frequency, the initial energy of each harmonic will be spread along a band of frequencies which is called spread spectrum frequency modulation (SSFM).

Figure 4 shows the spectra comparison of a pure sinusoidal signal with frequency f_c and the same signal modulated in frequency with a defined Δf_c at the nominal rate of f_m and following a sinusoidal

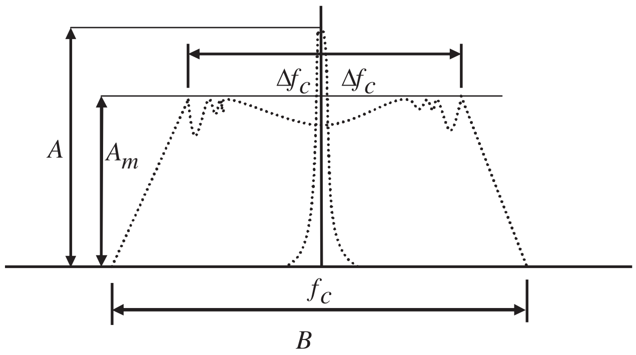

Figure 4. The spectrum of pure and modulated sinusoidal signal.

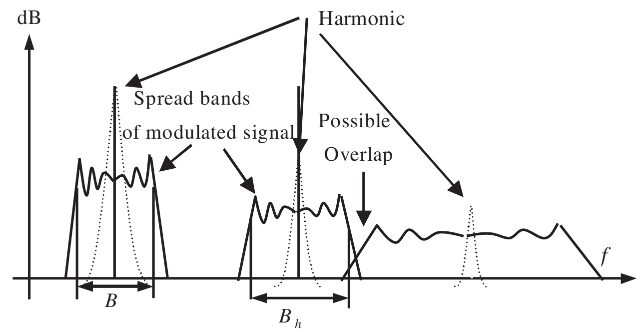

Figure 5. Overlapping phenomena in modulated signals.

profile. In Eq. (1), the general analytical expression of pure sinusoidal signal in time domain is written as follows:

$$F(t) = A \cdot \cos[2\pi f_c \cdot t + \theta(t)] \tag{2}$$

$\theta(t)$ is time-dependent phase angle that its relationship is:

$$\theta(t) = \int_0^t k_\omega \cdot \upsilon_m(\tau) \cdot d\tau \tag{3}$$

Due to the modulation, the energy of f fundamental component spreads into a neighbor band B. This band is given by Eq. (3):

$$B = 2 \cdot f_m \cdot (1 + m_f) = 2 \cdot (\Delta f_c + f_m) \tag{4}$$

The bandwidth associated with harmonic is defined as follows:

$$B_h = 2 \cdot f_m \cdot (1 + m_f \cdot h) \tag{5}$$

$$m_f = \frac{\Delta f_c}{f_m} \tag{6}$$

The bandwidth associated with hth harmonic increases with increasing the order of harmonic. Hence, the overlapping phenomenon may occur at higher harmonics as seen in Fig. 5.

4. CHAOTIC CARRIER

The basic structure on chaotic soft switching is based on a chaotic mapping and sawtooth generation. It is difficult to obtain this carrier in a practical circuit. In [21], an applicable and practical real-time chaotic carrier design has been proposed as shown in Fig. 6. The nth sawtooth signal can be determined by the following mapping:

$$T'_{nc} = x_n \beta T_C + T_C, \quad x_n \in [-1, 1], \quad \beta \in [0, 1) \tag{7}$$

where T_C is the main frequency of the switch which is constant. x_n is the nth output of chaotic mapping and β a modulation factor. As an example, the chaotic sequence x_n can be generated by the logic mapping which is described by Eq. (8).

$$F(x_n) = 1 - \alpha x_n^2 \tag{8}$$

It is clear that the largest chaos occurs in $\alpha = 2$ which is used for the studied chaotic mapping. T_C and β are considered to be 10 µs and 0.2. It is obvious that the generation of a chaotic ramp is complex. Therefore, off-line chaotic sawtooth generator is used. The chaotic sawtooth waveform can be seen in Fig. 7.

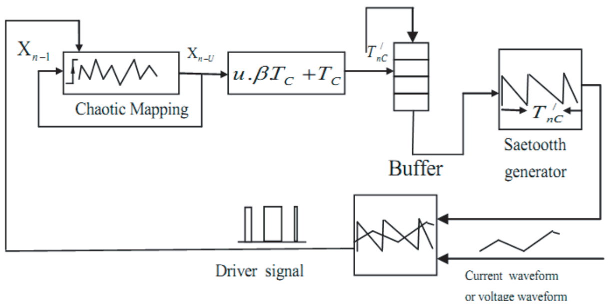

Figure 6. Generation of chaotic carrier shematic.

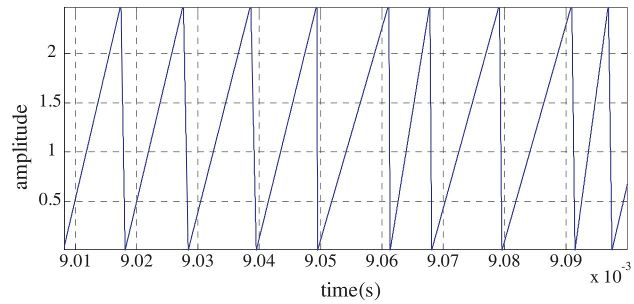

Figure 7. Generation of chaotic carrier in Simulink/Matlab.

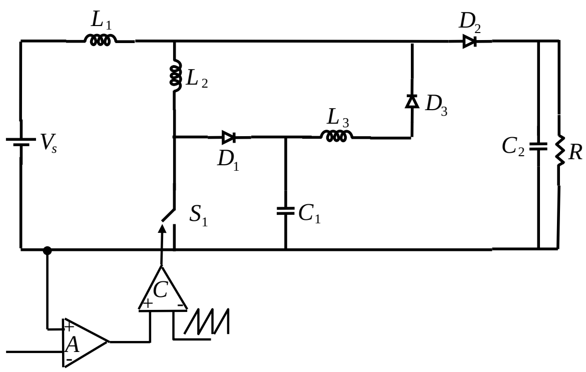

Figure 8. Soft switching boost converter.

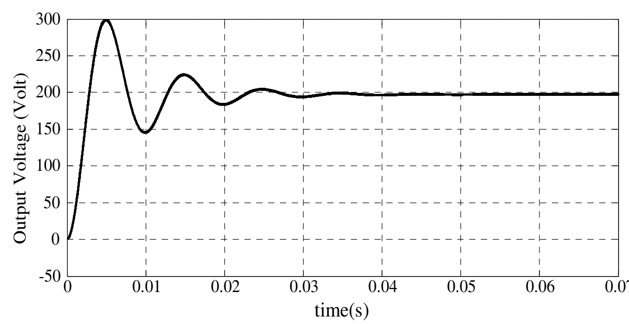

Figure 9. Output voltage of hard switching converters.

5. HARD, SOFT, AND CHAOTIC SOFT SWITCHING

The circuit of soft switching PWM Boost converter is shown in Fig. 8. Elements L_2, L_3, D_1, D_2 and C_1 have been used to satisfy soft switching. In this converter, the magnitudes of L_2 and L_3 are much less than the value of inductor L_1. Also, capacitance C_1 is smaller than capacitance C_2. Seven different modes based on the principle of soft switching are analyzed for the Boost converter. These modes have been described in [24]. The values of parameters in this converter are as $VS = 10\,\mathrm{V}$, $L_1 = 0.6\,\mathrm{mH}$, $C_2 = 10\,\mu\mathrm{F}$, $R = 200\,\Omega$, $I_{ref} = 1\,\mathrm{A}$, $T_C = 100\,\mathrm{kHz}$, $L_2 = L_3 = 10\,\mu\mathrm{H}$, and $C_1 = 10\,\mathrm{nF}$. It is notable that components L_3, L_2, C_1, D_1 and D_2 are not used in hard switching PWM control method. The reference current is considered to be 20 A ($I_{REFRENCE} = 20\,\mathrm{A}$). Moreover, the maximum amplitude of carrier signal is 2.5.

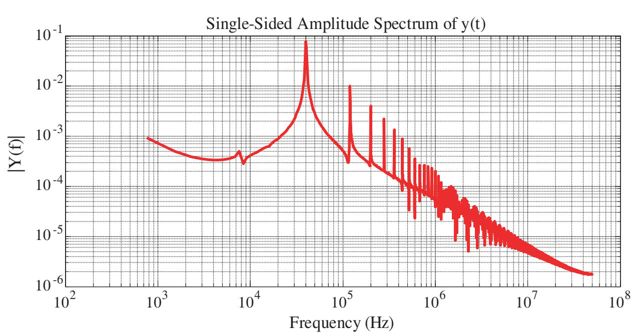

Figure 10. Input current of hard switching converters.

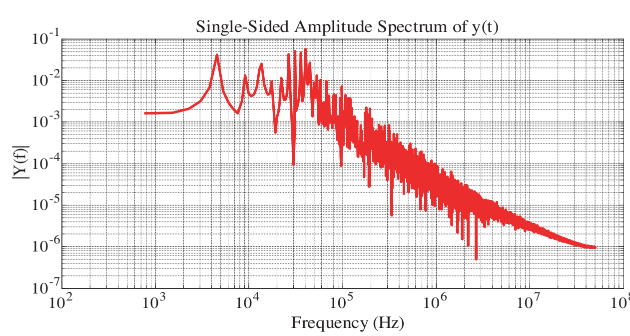

Figure 11. Input current of soft chaotic switching converters.

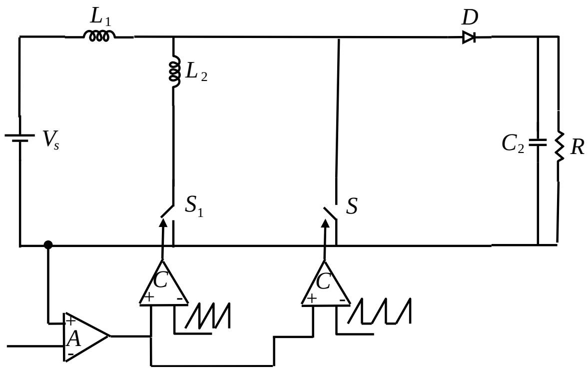

Figure 12. The proposed converter.

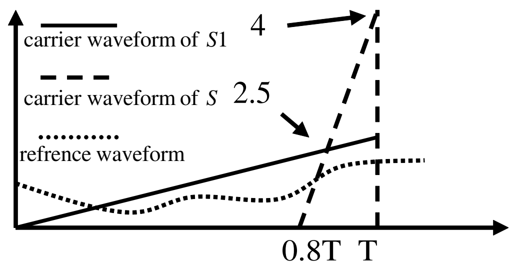

Figure 13. The strategy of switching for the proposed converter.

Comparing the noise spectrum of various converters is appropriate for determining the best converter in terms of EMI. Firstly, the hard switching boost converter is simulated. To obtain the spectrum of electromagnetic noise with sampling time of simulation, Fourier analysis has been used. The output voltage of hard switching converter is shown in Fig. 9. In Fig. 10, the units of vertical and horizontal axes are dB and logarithmic frequency of Hz, respectively. According to Fig. 10, the EMI peaks appear in the switching frequency and its multiples. These peak values are high which cause to inject noisy current into common DC bus. Soft switching is applied in order to reduce the losses and EMI. However, the soft switching method in boost converter has no considerable effect on EMI reduction. Therefore, discussion on the results of soft switching method is avoided. For simulation, the combination of soft and chaotic switching methods is used. Simulation result is shown in Fig. 11. This figure shows frequency spectrum of input current. Due to the off-line control of chaotic switching method, the peaks are eliminated from the frequency spectrum of the input current (see Fig. 11). It causes the peaks of energy to be spread in the adjacent bands of the mentioned peaks.

6. THE PROPOSED CONVERTER

The circuit of the proposed converter is shown in Fig. 12. The presented converter has two switches S and S_1. Switch S_1 is in series with a small inductance that its value considered to be 100 nH.

The amplitude of DC voltage source is 100 volts, and the values of output capacitor (C) and inductor (L_1) are assumed to be 10 µF and 0.6 mH. The used carrier and reference waveforms are shown in Fig. 13. By knowing the power of output load, the average current of load is determined, so its value is considered as a reference current. The output voltage and input current of the proposed converter are shown in Fig. 14 and Fig. 15, respectively. As indicated in this figure, by implementing the mentioned switching method for the proposed converter, the input current ripple is low. Also, by comparing the setting time of output voltage of proposed converter with the setting time of hard switching method (see Fig. 9), it is clear that the setting time of the proposed converter is lower.

By comparing the spectrum in three conditions (shown in Fig. 16), i.e., hard, chaotic soft switching and the switching method of the proposed converter, these results can be seen:

- Low frequency components of the proposed switching method are smaller than two other methods which cause lower RF noise.
- Due to higher switching frequency in the proposed converter, the high frequency components have worse situation that causes interference with communication and control systems.

The main feature of the proposed converter is high reliability because there are two power switches. In this converter, every switch with corresponding pulsating order can supply the load. If any switch fails, the proposed converter can supply the load. Due to EMI spectrum reduction, the proposed converter has suitable noisy situation in comparison with the conventional boost converter. High frequency components of the input current are lower than hard switching. The low frequency components of input

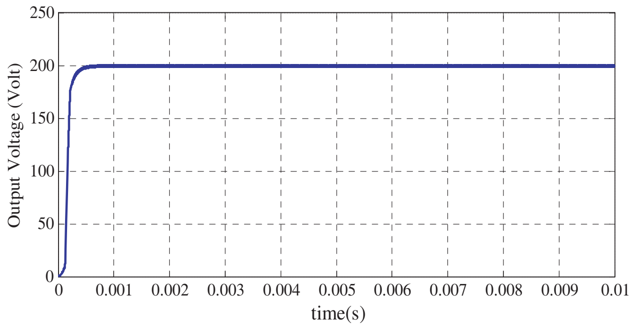

Figure 14. Output voltage of the proposed converter.

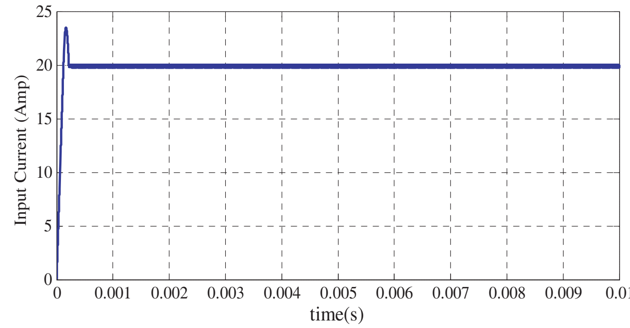

Figure 15. Input current of the proposed converter.

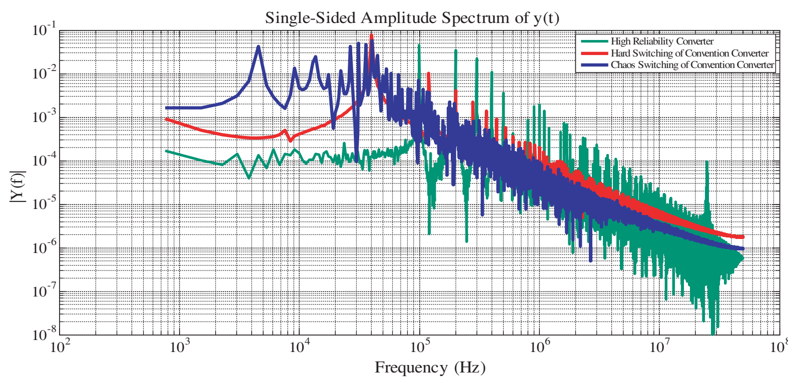

Figure 16. Comparison of input current spectrum of hard, chaotic switching and proposed converter.

Table 1. Maximum amplitude of EMI spectrumes for the studied converters.

The studeid converters	Frequency range		
	$f < 20\,\mathrm{kHz}$	$20\,\mathrm{kHz} < f < 100\,\mathrm{kHz}$	$f \geq 100\,\mathrm{kHz}$
Hard Switching Converter	≈ 0.001	≈ 0.09	≈ 0.001
Chaoatic Soft Switching Converter	≈ 0.04	≈ 0.07	≈ 0.0055
Proposed Converter	≈ 0.0001	≈ 0.0003	≈ 0.045

current are lower than hard switching and chaotic switching. The proposed switching pattern can be implemented as analog and digital forms.

The EMI levels of the studied converters, in three frequency ranges, are shown in Table 1. The maximum amplitude of EMI spectrums in the defined frequency ranges are inserted in this table. As indicated in this table, for $f < 20\,\mathrm{kHz}$ and $20\,\mathrm{kHz} < f < 100\,\mathrm{kHz}$, the hard switching and chaotic soft switching converters have higher RF EMI than the proposed converter. Therefore, the proposed converter is suitable for RF frequency ranges. However, for $f \geq 100\,\mathrm{kHz}$, the performance of presented converter is unsuitable.

7. CONCLUSION

In this paper, a new converter with improved switching method is presented. The proposed topology uses two power switches which increase the reliability of the proposed converter. It is compared with hard, soft, and chaotic soft switching methods. It is demonstrated that the EMI of the proposed converter is reduced which is an important advantage of the proposed topology and its switching method. For lower order of frequency components, the EMI noise has a better performance. However, the EMI noise in higher order of frequency components has unsuitable operation. The proposed converter can be used for aerospace based electric transport system charger applications.

REFERENCES

1. Ran, L., S. Gokani, et al., "Conducted electromagnetic emissions in induction motor drive systems part I: Time domain analysis and identification of dominant modes," *IEEE Trans. Power Electron.*, Vol. 13, 757–767, Jul. 1998.
2. Costa F., et al., "Influence of the driver circuits in the generation and transmission of EMI in a power converter: Effects on its electromagnetic susceptibility," *Eur. Power Electron. J.*, Vol. 5, No. 1, 35–44, Mar. 1995.
3. Chen, C., X. Xu, and D. M. Divan, "Conductive electromagnetic interference noise evaluation for an actively clamped resonant dc link inverter for electric vehicle traction drive applications," *Conf. Rec. IEEE-IAS Annul. Meeting*, 1550–1557, 1997.
4. Tang, Y., J.-S. Lai, and C. Chen, "EMI experimental comparison of PWM inverters between hard- and soft-switching techniques," *Proc. IEEE Workshop Power Electronics in Transportation*, 71–78, Dearborn, MI, Oct. 1998.
5. Zhu, H., J.-S. Lai, A. R. Hefner, Jr., Y. Tang, and C. Chen, "Analysis of conducted EM emissions from PWM inverter based on empirical models and comparative experiments," *Power Electronics Specialists Conference*, Vol. 2, 861–867, 1999.
6. Rahimi, T., S. Yousefi Khangah, and B. Yousefi, "Reduction EMI due to di/dt and dv/dt DC and AC sides of BLDC motor drive," *5th Power Electronics, Drive Systems and Technologies Conference (PEDSTC)*, 428–433, Tehran, Iran, Feb. 5–6, 2014.
7. Lecointe, J.-P., B. Cassoret, and J.-F. Brudny, "Distinction of toothing and saturation effects on magnetic noise of induction motors," *Progress In Electromagnetics Research*, Vol. 112, 125–137, 2011.
8. Guo, Y., L. Wang, and C. Liao, "Systematic analysis of conducted electromagnetic interferences for the electric drive system in electric vehicles," *Progress In Electromagnetics Research*, Vol. 134, 359–378, 2013.
9. Liang, J., L. Jian, G. Xu, and Z. Shao, "Analysis of electromagnetic behavior in switched reluctance motor for the application of integrated air conditioner on-board charger system," *Progress In Electromagnetics Research*, Vol. 124, 347–364, 2012.
10. Chen, R., J. D. Van Wyk, S. Wang, and W. G. Odendaal, "Technologiesand characteristics of integrated EMI filters for switch mode power supplies," *Power Electronics Specialists Conference*, Vol. 6, 4873–4880, Jun. 20–25, 2004.
11. Hua, G. and F. C. Lee, "An overall view of soft-switching techniques for PWM converters," *Eur. Power Electron. J.*, Vol. 3, No. 1, 39–50, 1993.
12. Hui, S. Y. R., K. W. E. Cheng, and S. Prakash, "A fully softswitched extended-period quasi-resonant power-factor-correction circuit," *IEEE Trans. Power Electron.*, Vol. 12, 922–930, Sep. 1977.
13. González, D., J. Balcells, A. Santolaria, J.-C. Le Bunetel, J. Gago, D. Magnon, and S. Bréhaut, "Conducted EMI reduction in power converters by means of periodic switching frequency modulation," *IEEE Trans. Power Electron.*, Vol. 22, No. 6, 0885–8993, Nov. 2007.
14. Li, H., Z. Li, W. A. Halang, and W. K. S. Tang, "A chaotic soft switching PWM boost converter for EMI reduction," *IEEE International Sympsium*, 341–346, 2008.
15. Hamzad, D., M. Swan, and P. K. Jain, "Suppression of common-mode input electromagnetic interference noise in DC-DC converter using the active filtering method," *IEEE Journal of Power Electronics*, Vol. 4, No. 7, 776–784, 2012.
16. Shaoyong, Y., et al., "Condition monitoring for device reliability in power electronic converters: A review," *IEEE Trans. Power Electron.*, Vol. 25, No. 11, 2734–2752, Nov. 2010.

17. Smet, et al., "Ageing and failure modes of IGBT modules in high-temperature power cycling," *IEEE Trans. Ind. Electron.*, Vol. 58, No. 10, 4931–4941, Oct. 2011.
18. Li, E. P., X. C. Wei, A. C. Cangellaris, E. X. Liu, Y. J. Zhang, M. D'Amore, J. Kim, and T. Sudo, "Progress review of electromagnetic compatibility analysis technologies for packages, printed circuit boards, and novel interconnects," *IEEE Trans. Electromagn. Compat.*, Vol. 52, No. 2, 248–265, May 2010.
19. Shih, F., D. Y. Chen, Y. Wu, and Y. Chen, "A procedure for designing EMI filters for AC line applications," *IEEE Trans. Power Electron.*, Vol. 11, No. 1, 170–181, Jan. 1996.
20. Ogasawara, S., H. Ayano, and H. Akagi, "Measurement and reduction of EMI radiated by a PWM inverter-fed AC motor drive system," *IEEE Trans. on Industry Applications*, Vol. 33, No. 4, 1019–1026, Jul./Aug. 1997.
21. Paul, C. R., *Introduction to Electromagnetic Compatibility*, 2nd Edition, Wiley, New York, 2006.
22. Chen, H., T. Wang, L. Feng, and G. Chen, "Determining far-field emi from near-field coupling of a power converter," *IEEE Trans. Power Electron.*, Vol. 9, 5257–5264, 2014.
23. Lei, X. and J. Sun, "Conducted common-mode EMI reduction by impedance balancing," *IEEE Trans. Power Electron.*, Vol. 27, No. 3, 1084–1089, 2012.
24. Li, H., Z. Li, W. A. Halang, and W. K. S. Tang, "A chaotic soft switching PWM boost converter for EMI reduction," *IEEE International Symposium*, 341–346, 2008.