The Effect of the Output Capacitor on the Power Spectrum of the EMI Radiation of a SEPIC Converter

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Abstract: - This paper presents the effect of the output capacitor on the EMI spectrum of radiation. Two SEPIC converters were designed with LT1871 (Linear Technology) and LM2577 (National Semiconductor), for an input voltage of 4 to 16V, the output voltage of 5V, output current of 0.5A, and the switching frequency of 52kHz. The functionality of the converter was simulated in LTspice IV and OrCAD, and it was compared with the experimental results. It was observed the level of output ripple with different types of capacitors. An acceptable output ripple, who respects the standards FCC Class A and Class B, was obtained with solid and tantalum capacitors in parallel with small MLCC capacitors. The minimum of ripple and frequency spectrum was obtained by adding a LC Filter to the output of the converter. With this filter the converter respects the standard SAE J1113.

Key-Words: - SMPS, SEPIC converter, output capacitor voltage ripple, frequency spectrum

1 Introduction

Nowadays, the majority of electronic equipments have a switched-mode power supply (SMPS). Such equipments as: home appliances (CD/DVD Players, MP3 Players), power supplies for laptop and computers, photovoltaic battery chargers, illumination, medical, and automotive devices, have a DC-DC converter working in switching mode. The SMPS have some advantages like: great efficiency, small size, light weight, low heat generation. Though, they have also some disadvantages like: complexity, generation of high amplitude and frequency energy, ripple voltage at switching and harmonic frequencies, interference with audio/video equipments. They are widely used especially for their efficiency. For these noisy equipments, electromagnetic interference (EMI) filters were designed to comply with the international electromagnetic compatibility (ECM) standards.

The EMI of switched converters are very well discussed in literature. Most power supplies manufacturers use the International Electro Technical Commission (IEC) or Federal Communications Commission (FCC) rules for their products [1]. For automotive applications the level of EMI radiation standard is SAE J1113, and ISO 11452 [2]. Some methods to reduce the EMI spectrum of radiation are presented in [3], [4], and [5].

The purpose of this paper is to present the effect of the output capacitor of a SEPIC Converter on the power spectrum of radiation. The paper is organized as follows. Section 2 presents a short SEPIC converter design about how to choose the output capacitor. The influence of the output capacitor is given in Section 3. The simulations are presented in section 4, and the schematic diagram and the experimental results are given in Section 5. The paper concludes with some final remarks in Section 6.

2 SEPIC converter design

A SEPIC Converter Design Example is given in [6].

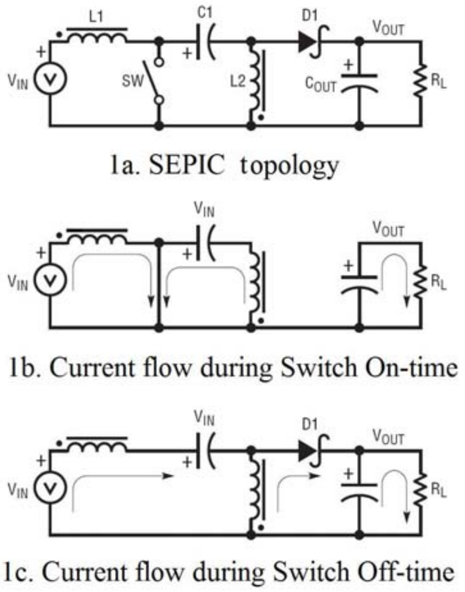


Fig. 1. SEPIC topology and current flow [6].

The SEPIC converter shown in Fig. 1 uses two inductors – L1 and L2 wound on the same core to reduce the input ripple and the size of the converter.

Step by step, the parameters of the converter are calculated in [6]. First, the duty cycle D (1),

$$D = \frac{V_o + V_D}{V_{in} + V_o + V_D} \tag{1}$$

where V_o is the output voltage, V_D is the forward voltage of the diode, and V_{in} is the input voltage of the converter.

The maximum output voltage for a SEPIC converter is (2):

$$V_{o(\max)} = (V_{in} + V_D)\frac{D_{\max}}{1 - D_{\max}} - V_D\frac{1}{1 - D_{\max}} \tag{2}$$

The maximum currents in the inductors L1 and L2 are given by (3) and (4):

$$I_{L1(peak)} = (1 + \frac{\chi}{2})I_{o(\max)}\frac{V_o + V_D}{V_{in(\min)}} \tag{3}$$

$$I_{L2(peak)} = (1 + \frac{\chi}{2})I_{o(\max)}\frac{V_{in(\min)} + V_D}{V_{in(\min)}} \tag{4}$$

where χ is 0.2 to 0.4 (20% to 40% of the maximum average input current).

The inductor value is calculated in the equation (5).

$$L = \frac{V_{in(\min)}}{\Delta I_L f}D_{\max} \tag{5}$$

where ΔI_L is given by the equation (6).

$$\Delta I_L = \chi I_{o(\max)}\frac{D_{\max}}{1 - D_{\max}} \tag{6}$$

By making $L1=L2$ and winding them on the same core, the value of the inductance is $2L$ due to mutual inductance. Therefore, the equation (5) becomes (7).

$$L1 = L2 = \frac{V_{in(\min)}}{2\Delta I_L f}D_{\max} \tag{7}$$

The power MOSFET must satisfy the equation (8).

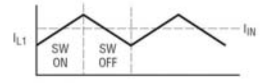
$$R_{DS(ON)} \le \frac{V_{sense(\max)}}{I_{o(\max)}}\frac{1}{(1 + \frac{\chi}{2})\rho_T}\frac{1}{\frac{V_o + V_D}{V_{in(\min)}} + 1} \tag{8}$$

where $V_{sense(max)}$ is typically 150mV at low duty cycle and it is reduced to 100mV at maximum duty cycle, and ρ_T is the temperature coefficient, typically 0.4%/°C.

To maximize the efficiency of the converter, a fast switching diode with low forward voltage and low reverse leakage current is chosen. The peak reverse voltage is $V_{in(max)}+V_o$. The average forward current is equal to the output current, and is given by the equation (9).

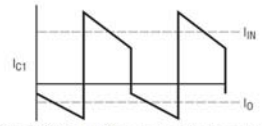
$$I_{D(peak)} = (1 + \frac{\chi}{2})I_{o(\max)}(\frac{V_o + V_D}{V_{in(\min)}} + 1) \tag{9}$$

Special attention must be given to the output capacitor selection. All the parameters of the capacitor have a contribution on the ripple voltage of the converter. These parameters are: bulk capacitance, ESR (Equivalent Series Resistance), and ESL (Equivalent Series Inductance). Their effects are illustrated in Fig. 2.

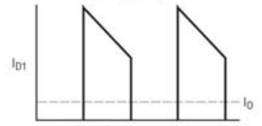


2a. Input inductor current

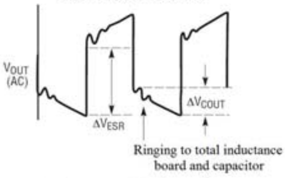
2b. Output inductor current



2c. DC coupling capacitor current



2d. Diode current



2e. Output ripple voltage

Fig. 2. SEPIC converter switching waveforms [6].

When choosing the component(s) one has to begin with the maximum acceptable ripple voltage (expressed as a percentage of the output voltage), and how this ripple should be divided between the ESR step and the charging/discharging ΔV. To simplify, 2% for the maximum output ripple was chosen, which was divided equally between the ESR and the charging/discharging ΔV. This percentage ripple can be changed, depending on the requirements of the application.

For a 1% contribution to the total ripple voltage, the ESR of the output capacitor can be determined using the equation (10):

$$ESR_{Cout} \le \frac{0.01V_o}{I_{D(peak)}} \tag{10}$$

where $I_{D(peak)}$ is given by the equation (9).

Considering that the bulk C component contribution is 1% to the total ripple, the value of the capacity is given by (11).

$$C_{out} \ge \frac{I_{o(\max)}}{0.01V_o f_{sw}} \tag{11}$$

where f_{sw} is the switching frequency of the converter. In most of the applications it is possible to choose a single capacitor that satisfies both the ESR and bulk C; but in others, the ripple voltage must be reduced significantly. This is done by connecting two ore more types of capacitors in parallel. The use of a ceramic capacitor with low ESR can minimize the ESR step, and an electrolytic or a tantalum capacitor can supply the required bulk C. This capacitor has a high RMS ripple current (12).

$$I_{RMS(Cout)} = I_{o(\max)} \sqrt{\frac{V_o}{V_{in(\min)}}} \tag{12}$$

It must be mentioned, that the ripple current rating is given by the manufacturer for only 2000 hours of life. For this reason, the designer has to choose a capacitor at a higher temperature than required.

Another component of the SEPIC converter is the coupling capacitor C1 of Fig. 1. The waveform of the current is almost rectangular – Fig. 2. The ripple voltage on this capacitor is (13).

$$\Delta V_{C1(pp)} = \frac{I_{o(\max)}}{C1 f_{sw}} \frac{V_o}{V_{in} + V_o + V_D} \tag{13}$$

The maximum voltage on C1 is (14):

$$V_{C1(\max)} = V_{in} + \frac{\Delta V_{C1(pp)}}{2} \tag{14}$$

This value is close to $V_{in(max)}$. A low ESR ceramic or a tantalum capacitor is adequate.

3 Output capacitor influence

As it was mentioned above, the output capacitor influences the ripple voltage and the EMI radiation of the converter. The right choice of the capacitor gives the best result of a design. A study of some types of capacitors used for output capacitor is given in [7]. The ESR of the capacitors depends on of the frequency, operation temperature and the DC voltage.

The conclusions of the benchmarks described in [7] for the capacity stability are:

- tantalum-MnO_2-technology capacitor is the best one
- niobium-oxide-MnO_2 devices are more sensitive to DC voltage
- tantalum-polymer is more sensitive to temperature changes
- MLCC (Multi Layers Ceramic Capacitors) are very dependent on both temperature and DC voltage
- Aluminum-electrolytic capacitors are stable with DC voltage, but very dependent on temperature.

Concerning the ESR stability the conclusions are:

- all capacitors are relatively stable with the DC voltage,
- temperature dependence provokes great differences:
  - tantalum-polymer and MLCC capacitors exhibit the most stable ESR
  - the ESR of the MLCCs is very low over the whole temperature range
  - for tantalum-MnO_2 and niobium oxide-MnO_2 devices, the ESR decreases as temperature increases
  - Aluminum-electrolytic capacitors have a growing ESR to very high values at low temperatures (below 0°C).

For the behavior of the capacitors in frequency, the conclusions are:

- the ripple voltage using the tantalum-MnO_2 device has a lower level of higher harmonic components than the tantalum-polymer-MnO_2,
- the MLCC capacitors have undesirable oscillations with frequencies around 50kHz, and high AC voltage due to the instability of the regulator,
- Aluminum-electrolytic types did not perform well, having a relatively high AC voltage.

Because the Aluminum-electrolytic capacitors are most used in such converters – although they are not the best option, a study of the effect of the ESR is done in [8]. A technique for evaluating the condition of these capacitors is presented in [9].

4 Simulations

The simulations for this paper were done with two circuits. The first circuit is a SEPIC converter using the circuit that was proposed by the manufacturer Linear Technology with the LTC1871 in [10]. The values of the components were changed to the next: R1=330kΩ (for a switching frequency of 52kHz), L1=L2=68µH (Coilcraft MSS7341-683MX), wound on the same core, C_{DC}=220µF (Nichicon ULP1H221MRH6), power MOSFET IRF7807 (International Rectifier), diode SS24 (Fairchild), Cout1=100µF (Panasonic EEFUD0J101R, I_{RMS}=3A, ESR=0.015Ω), Cout2=10µF (KEMET C0805C106K9PAC, I_{RMS}=11.832A, ESR=0.003Ω). The values of the rest of the components remained the same with those proposed in [10].

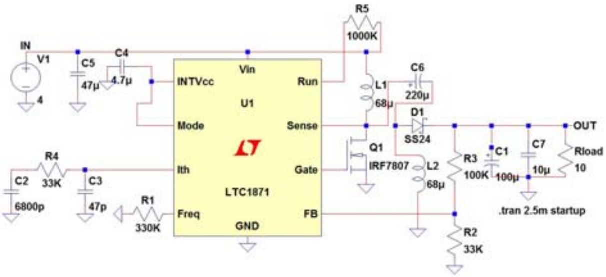


Fig. 3. SEPIC converter with LTC1871.

The circuit was simulated in LTspice IV, in the following conditions: V_{in}=4-16V, V_o=5V, I_o=0.5A. The circuit diagram of the SEPIC converter with LT1871 is presented in Fig. 3. The switching frequency was reduced to 52kHz, because the experimental results were done for a SEPIC converter at that frequency.

The second circuit simulated in OrCAD was proposed in [11], using the UC2577 (Unitrode). The schematic diagram is illustrated in Fig. 4.

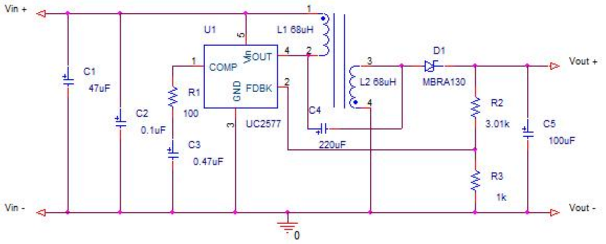


Fig. 4. SEPIC converter with UC2577.

The simulations were done in the same conditions. The results of the simulations will be compared with the experimental results in the next section.

5 Experimental results

The effects of the output capacitor were observed on a board with a SEPIC converter built with the controller UC2577 in Fig. 4 in the following conditions: V_{in}=4-16V, V_o=5V, I_o=0.5A.

The output voltage ripple was observed with an Oscilloscope LeCroy WaveJET334, 4 Channels, 300MHz. The frequency spectrum was observed with a Spectrum Analizer GW INSTEK GSP-830. The Start frequency was 10kHz, and the Stop frequency 1MHz while the reference level was -50dBm or 80dBμV.

The capacitors in tests are the most used in the electronic equipments made by different manufacturers, in different technologies, and by different materials.

5.1 Output voltage ripple with different capacitors

In the Table 1 it can be observed the effect of the value of the capacitors and the technology on the output ripple of the converter.

Table 1

No.	Type	Value [μF]	Manufacturer	Ripple [rms]	Percentage [%]
1	Al-el	100	SAMWHA	296	5.92
2	Al-SC	100	Nippon Chemi-Con	37	0.74
3	Al-el	2x100 parallel	SAMWHA	197	3.95
4	Al-el	220	S.H.I.	38	0.76
5	Al-el	220	Richey	172	3.44
6	Al-el	220	Jamicon	63	1.27
7	Ta	2x470 series	AVX	43	0.86
8	Ta	470	AVX	22	0.44

Accepting 2% as the maximum value of the ripple, not all the capacitors can be used in such converters (position no. 1, 3 and 5). The abbreviations used in the Table 1 are: Al-el – Aluminum-electrolytic, Al-SC – Conductive Polymer Aluminum Solid Capacitor (or "polymer capacitor"), Ta – Tantalum.

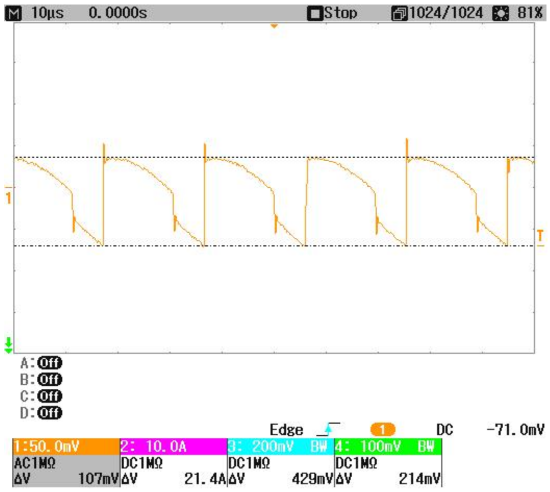


Fig. 5. Output voltage ripple with 100μF Al-SC.

Fig. 6. Output voltage ripple with 220μF (S.H.I.).

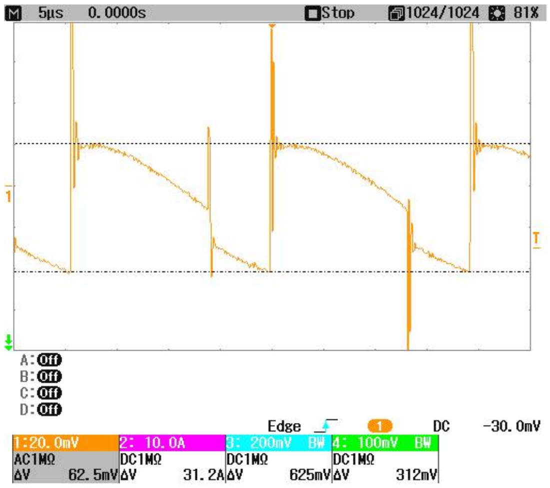


Fig.7. Output voltage ripple with 470μF series Ta.

The waveform of the ripple with the solid capacitor Al-SC 100µF is illustrated in Fig. 5, with an Al-el 220µF (S.H.I.) in Fig. 6, and with a Tantalum capacitor of 470µF in Fig. 7.
The frequency spectrum view with the capacitor of 100µF Al-SC is presented in Fig. 8, and with a 220µF (S.H.I.) in Fig. 9.

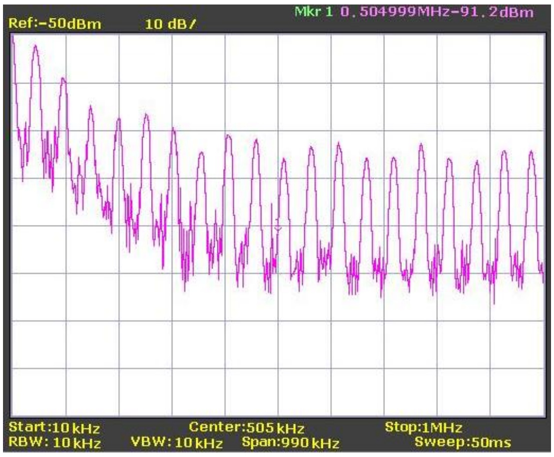


Fig. 8. Frequency spectrum with 100µF Al-SC.

The frequency spectrum of the ripple with a capacitor of 100µF Al-SC in parallel with a 10µF MLCC respects the standard FCC Class A and B [1], but not the standard SAE J1113 [2]. This can be seen in Fig. 10.
An important reduction of spectrum can be obtained by adding a LC Filter. This aspect can be seen in Fig. 11, where the EMI radiation respects the standard SAE J1113. This technique is used in automotive applications, where the EMI spectrum must be as minimum as possible.

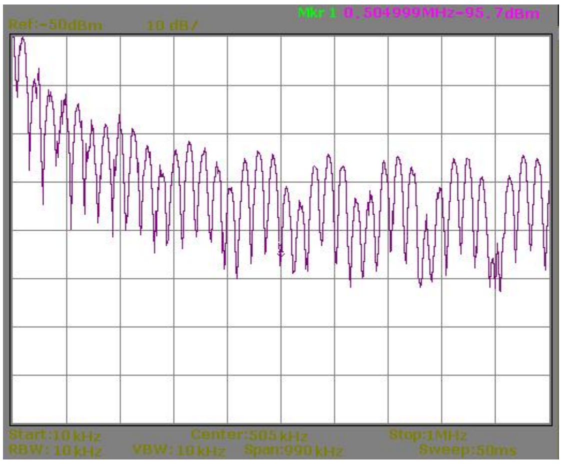


Fig. 9. Frequency spectrum with 220µF (S.H.I.).

5.2 Output voltage ripple with LC Filter

To reduce more the output voltage spectrum, a LC filter as in Fig. 12 was added (capacitor C5 of Fig. 4 was replaced by this circuit).

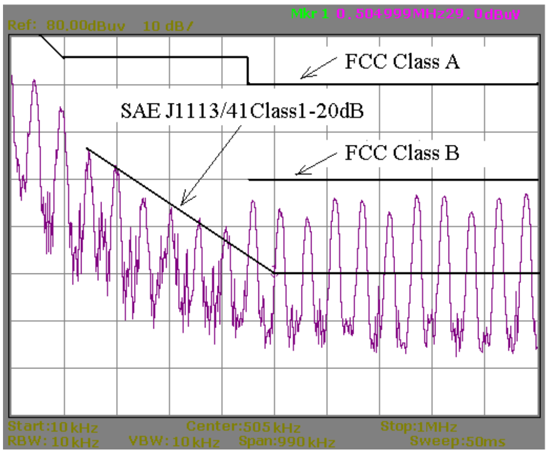


Fig.10. Frequency spectrum with 100µF SC + 10µF MLCC.

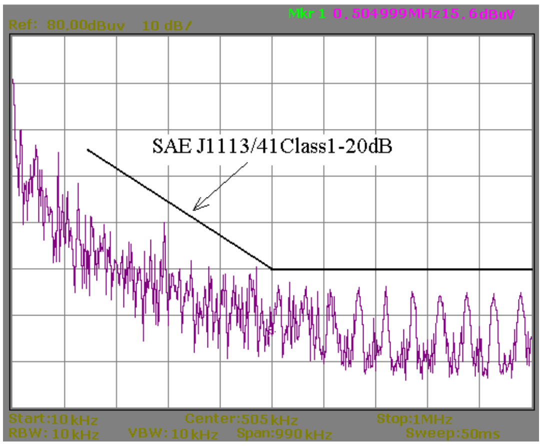


Fig. 11. Frequency spectrum with 100µF Al + 10µF MLCC, and a LC Filter.

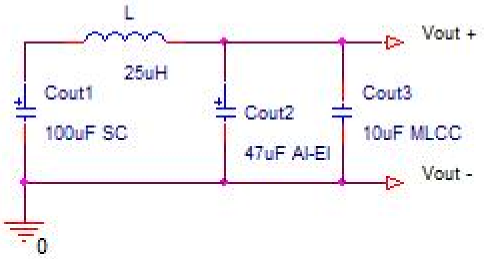


Fig. 12. Output LC Filter added to C_{out}.

With the circuit of the Fig. 12, the output voltage ripple is illustrated in Fig. 13.
The frequency spectrum of the output ripple with the LC Filter compared with that in Fig. 8 is represented in Fig. 14. In this figure a reduction of the EMI radiation with minimum 12dBm in whole the frequency domain can be observed.

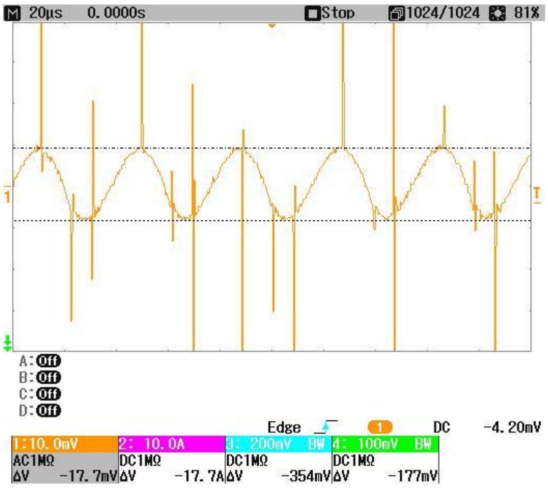


Fig. 13. Output voltage ripple with a LC Filter.

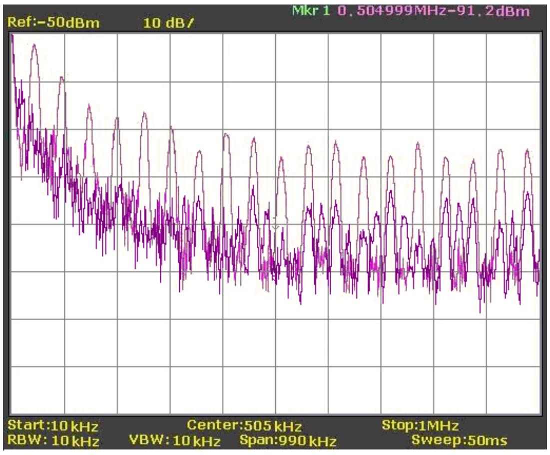


Fig. 14. Frequency spectrum without/with LC Filter.

6 Conclusions

This paper has presented some types of capacitors used as output capacitor of a SEPIC converter and how they affect the EMI spectrum. The converter was designed and simulated in LTspice IV for the LTC1871, and in OrCAD with an LM2577. A board was built with an LM2577 to verify the output ripple and the EMI spectrum of radiation. The converter with some output capacitor can respect the FCC standards, but not the SAE J1113. By adding a LC filter, the converter can satisfy the requirements of the SAE J1113 standard.

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