Computer Applications in Electrical Engineering
Vol. 14 *2016*
DOI 10.21008/j.1508-4248.2016.0024

Analysis of circuit and operation for DC–DC converter based on silicon carbide

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In this paper operating analysis of DC–DC converter is presented. Silicon Carbide based DC–DC converter is investigated. SiC power switches (i.e. MOSFETs and diodes) were used. Synchronous buck topology is applied for converter structure. The DC–DC converter mathematical model is also presented. The parameters of LC circuit were calculated using shown equations. Working conditions determine the values of output LC circuit (inductance and capacitance). Real power semiconductors are equipped in output and input capacitances. This feature may influence the generated input signal. Parasitic capacitances and inductances of the paths causes oscillations and voltage overshoots of the input PWM signal. To avoid such phenomenon, it is necessary to use a snubber circuit. This issue is also presented. The analysis of working conditions is presented for different switching frequencies. The size of passive components (LC) is compared for different operating points. Experimental tests results were presented. Waveforms of voltage and current signals were also shown.

KEYWORDS: DC\DC converter, SiC MOSFETS, high switching frequency, DC–DC converter design, snubber circuit

1. Introduction

SiC based MOSFET power transistors and schottky diodes can reduce power losses and allow for switching frequency increase [1, 2]. Since SiC devices appeared on the market are increasingly replacing silicon devices in power converter devices. This phenomenon is caused of Silicon Carbide attractive characteristic such as high irradiation tolerance, good thermal conductivity, high electrical breakdown field. These features make them able to work at higher switching frequencies with lower loses compared with Silicon devices [3, 4].

The goal of this paper is to present the operating analysis of a DC–DC converter (buck configuration) for the assumed operating point. The mathematical model of the converter is presented. Based on proposed mathematical model the dependences for coil inductance and capacitor capacitance are introduced.

Power semiconductors (i.e. MOSFET, schottky diode) are equipped in output capacitance. The inductance of the paths in addition with the output capacitances creates a parasitic resonant circuit. This circuit influences the input PWM signal (voltage overshoots and oscillations). To obtain a proper, rectangular input signal it is necessary to use of an additional snubber circuit. Characteristics of the input are compared without snubber circuit and with it.

The parameters of passive elements were calculated for different switching frequencies (16 kHz, 50 kHz, 100 kHz). The sizes and mass of required coils and capacitors were compared. Experimental tests were carried out for all converter configurations.

2. Converter topology

Considered DC–DC converter topology (Fig. 1) consists a output LC circuit fed from SiC MOSFET transistor T1. It's a non–isolated buck configuration. There is also a SiC schottky diode D1, that conducts current during transistor T1 is in off state. This type of device is a pulse converter. Pulse Width Modulation (PWM) method is used for transistor switching. This technique is based on duty factor changes of a rectangular signal for a constant period. The period is determined by the switching frequency.

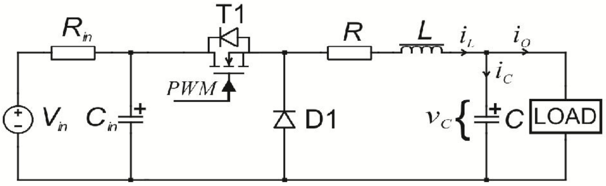

Fig. 1. Converter topology

This type of converters are able to reduce the output DC voltage level. It should be mentioned that DC link input voltage level should be higher than the output voltage. This condition is essential for the correct operation of the converter. The average output voltage is given by the following equation [5]:

$$v_{CAV} = \frac{t_{ON}}{T} V_{in} = D * V_{in} \qquad (1)$$

where: $v_{C\,AV}$ – average output voltage (capacitor), t_{ON} – MOSFET on–state time, T – PWM input signal period, V_{in} – input voltage, D – input signal duty factor (t_{ON}/T).

Power transistor state is changed during each period. There are two states: on state and off state. On state means that transistor T1 is open and is in conduction mode, current flows through the switch (Fig. 2.a). Off state means that transistor T1 is closed, current flows through the diode D1 (Fig. 2.b).

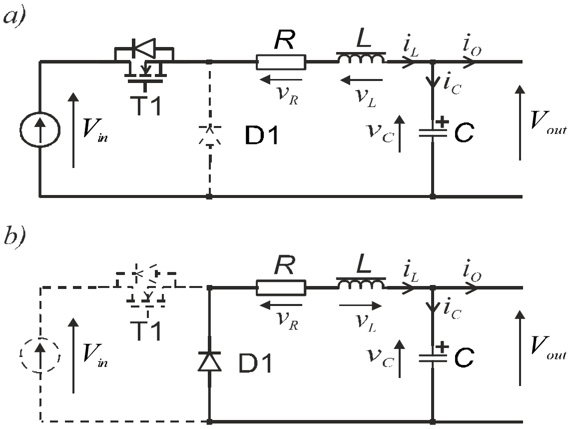

Fig. 2. Equivalent circuits in each state: (a) transistor T1 on, (b) transistor T1 off

Figure 2 contains two circuit diagrams (a) and (b). The first one represents the converter circuit in "ON state" – transistor T1 is conducting, the other represents the circuit in "OFF state" – diode D1 is conducting. Solid lines means that current flows through the circuit. Dashed lines means that in this circuit doesn't flow any current.

The behaviour of converter can be described using equation for equivalent circuit [5, 6]:

$$V_{in} = L\frac{di_L}{dt} + Ri_L + v_C \tag{2}$$

where: L – value of coil inductance, i_L – coil current, R – value of coil resistance.

In case of the off state equation (2) becomes a following form [5, 6]:

$$L\frac{di_L}{dt} = Ri_L + v_C \tag{3}$$

Current behavior describes the following relation [5, 6]:

$$i_L = i_C + i_O \tag{4}$$

where: i_C – capacitor current, i_O – load current.

Output capacitor voltage depends on the capacitor current and is given by the following equation:

$$V_{out} = v_C = v_{C0} + \frac{1}{C}\int_{t_1}^{t_2} i_C(\tau)d\tau \tag{5}$$

where: v_{C0} – initial voltage value of the output capacitor, V_{out} – output voltage. Equation (5) given in differential form is as follows [5, 6]:

$$C\frac{dv_C}{dt}=i_C \tag{6}$$

The mathematical model of the considered converter circuit is fully described by equations (2) – (6). It should be mentioned that perfect switches (transistor and diode) were taken into account in proposed model.

3. LC circuit

The output *LC* circuit is a very important part of the converter. It influences on the working conditions of the whole system. Therefore the design of output filter is a very essential issue. It is necessary to calculate the values of coil inductance and capacitor capacitance.

For coil inductance calculation, it is necessary to use equations (2) and (3). However some assumptions should be made i.e. coil resistance may be omitted because its value is negligible. Equation (2) refers to transistor T1 on–state (coil current increases) and equation (3) refers to transistor T1 off state, diode D1 conducts (coil current decreases). Accordingly, the equations take the following form:

$$L\frac{\Delta i_L}{t_{ON}}=V_{in}-v_C \tag{7}$$

$$L\frac{\Delta i_L}{t_{OFF}}=v_C \tag{8}$$

where: Δi_L – current ripple, t_{OFF} – MOSFET off–state time. Assuming that in equilibrium state current ripple is constant and assumes the maximum value for $t_{ON}=t_{OFF}=T/2$, based on equations (7) and (8) a following dependence can be obtained:

$$L=\frac{V_{in}}{4f\Delta i_L} \tag{9}$$

where: f – switching frequency ($1/T$). Equation (9) describes the relation between coil inductance and converter work conditions (i.e. input voltage, switching frequency and current ripple).

For capacitor capacitance calculation it is necessary to use equations (4) and (6). Both equations should be rewritten for transistor T1 on state and off state. Accordingly following equations are obtained:

$$C\frac{\Delta v_C}{t_{ON}}=i_L^{ON}-i_O \tag{10}$$

$$C\frac{\Delta v_C}{t_{OFF}}=i_L^{OFF}-i_O \tag{11}$$

where: i_L^{ON} – average coil current for on state, i_L^{OFF} – average coil current for off state. The average coil current for on state is calculated from the following relation:

$$i_L^{ON} = \frac{t_{ON}}{T} i_O \tag{12}$$

Assuming that in equilibrium state voltage ripple is constant and assumes the maximum value for $t_{ON} = t_{OFF} = T/2$. Taking into account equation (12) in equation (10), a following dependence can be obtained:

$$C = \frac{i_O}{4 f \Delta v_C} \tag{13}$$

Equation (13) describes the relation between capacitor capacitance and converter work conditions (i.e. output current, switching frequency and voltage ripple).

4. Snubber circuit

Real power semiconductor devices are equipped with a non–zero output capacitance. Considered power MOSFETs are equipped in three types of parasitic capacitances: input, output and reverse transfer capacitance. Considered schottky diode is equipped in output reverse recovery capacitance. All of them are voltage dependent, it means that for different input voltage ratings the value of capacitances is changing. Output capacitances of the power semiconductors are parasitic capacitances, which form a parasitic *LC* circuit with the parasitic inductance of the paths (Fig. 3). In real circuits, it is impossible to eliminate these undesirable properties.

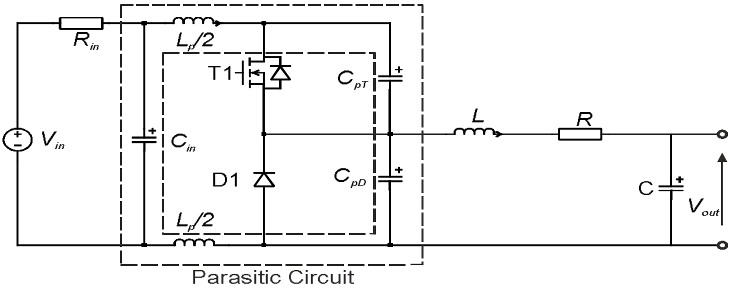

Fig. 3. Schematic of the converter with parasitic circuit

The parasitic *LC* circuit forms a resonant circuit which causes huge voltage overshoots during switching cycle (Fig. 4). The peak value of the impulse can be greater than 200% of the input voltage. The oscillations are not desirable – the input signal should be rectangular. In addition such a phenomenon can cause damage to power semiconductors (transistor or diode) i.e. an too large voltage spike may causes the breakdown of the switch. Breakdown of the switch can be the reason of a short circuit. It can cause a major failure of the device, which can be dangerous for the user.

To avoid overshoots and oscillations of the input voltage, it is necessary to use an additional snubber circuit for damping of oscillation and overshoot. There are a lot of snubber circuit topologies i.e. C, RC, RCD, double C, double RC and double RCD [7]. Using one of them, it is possible to eliminate voltage spikes and oscillations of the input signal (Fig. 5).

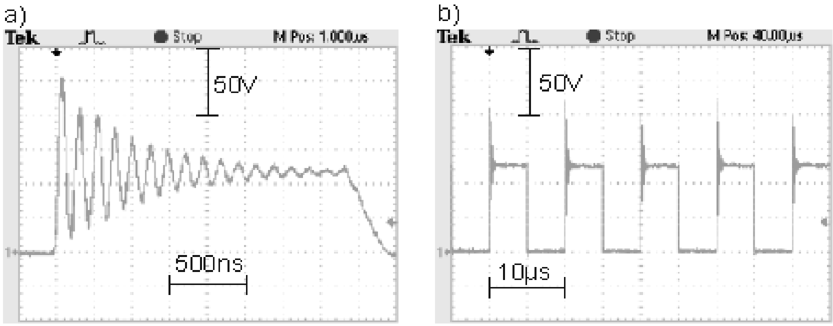

Fig. 4. Input PWM Signal without voltage snubber circuit a) single signal b) multiple signals

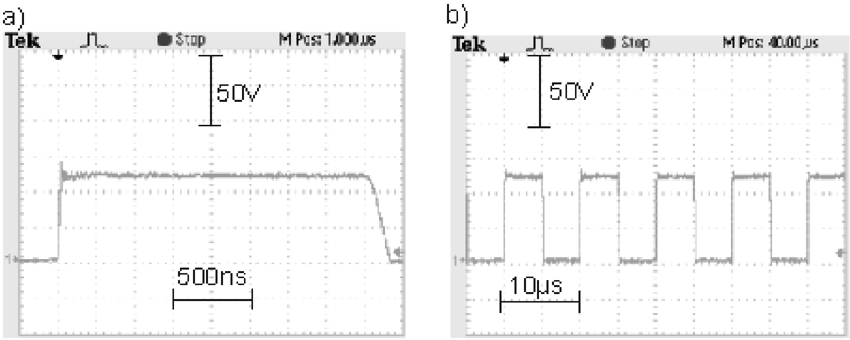

Fig. 5. Input PWM Signal with voltage snubber circuit a) single signal b) multiple signals

The use of snubbers helps to generate a proper rectangular input signals. This is a very important issue in pulse converters design. The input signal should be rectangular and without voltage spikes.

5. Converter design

The parameters of LC output circuit is an essential issue in design process of the converter. To calculate the values of required inductance and capacitance equations (9) and (13) may be used. It can be seen that the given formulas are dependent from frequency. It means that increase of the switching frequency reduces the required value of the parameters of passive components. Silicon Carbide based power switches allow the use of higher switching frequencies. Switching losses are much smaller than in case of silicon based elements. This feature is big advantage because allows to increase of switching frequency without efficiency drop. Therefore using SiC based power switches, it is possible to achieve high efficiency at high switching frequency. This makes it possible to reduce the size of power electronics device.

In this chapter passive components parameters and sizes were compared for different switching frequencies (16 kHz, 50 kHz and 100 kHz). The input voltage of the converter was set by 200 V, maximum load current 5A, acceptable level of current and voltage ripple was set by 1 A and 1 V. The calculated parameters of passive elements are given in Table 1.

Table 1. Calculated values of passive components

Switching frequency [kHz]	L [mH]	C [μF]
16	3.125	78.125
50	1.000	25.000
100	0.500	12.500

In order to realize output LC filter circuit of the converter coils with amorphous cores (Fig. 6) and foil capacitors (Fig. 7) were chosen. It can be seen that the biggest passive components are required for the lowest switching frequency. In order to minimize core losses amorphous steel based cores were used. It can be seen that the increase of switching frequency allows to use smaller passive components. It means that for the same operating conditions of the converter, it is possible to use smaller and lighter passive components.

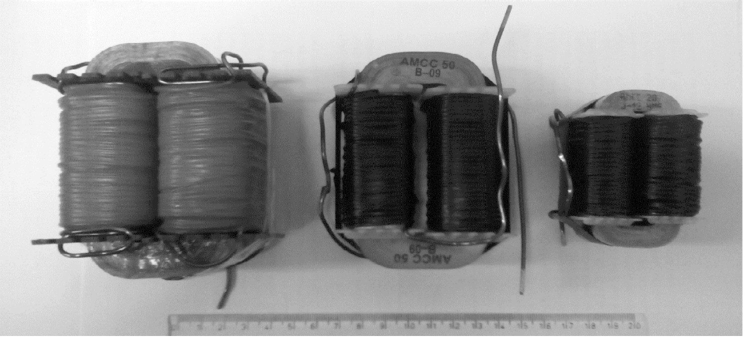

Fig. 6. Coil size comparison for different switching frequencies from the left: 16 kHz, 50 kHz and 100 kHz

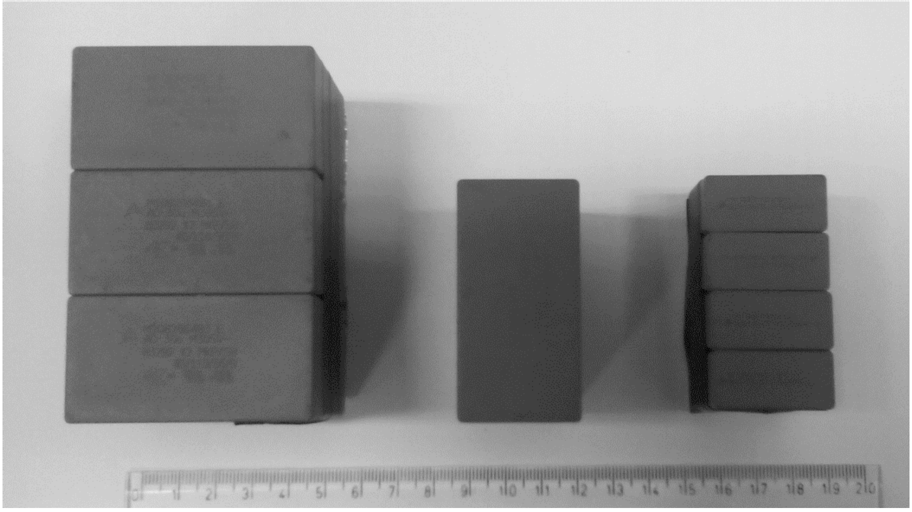

Fig. 7. Capacitors comparison for different switching frequencies from the left: 16 kHz, 50 kHz and 100 kHz

The parameters and sizes of used coils and capacitors were given in Table 2 and Table 3. The parameters of used elements are close to the calculated values. The increase of switching frequency influences the mass and size of passive components.

Table 2. Parameters of used coils

Switching frequency [kHz]	L [mH]	Width [mm]	Height [mm]	Length [mm]	Mass [g]
16	3.175	78.0	66.0	105.0	1478
50	1.073	70.0	49.0	106.0	816
100	0.611	49.0	44.0	74.0	467

Table 3. Parameters of used coils

Switching frequency [kHz]	C [μF]	Width [mm]	Height [mm]	Length [mm]	Mass [g]
16	89.0	57.0	43.0	87.0	231
50	27.3	30.0	43.0	57.0	79
100	13.2	32.0	24.0	60.0	57

6. Experimental tests

In this chapter experimental tests results were presented. SiC MOSFET transistor (C2M008120D) [8] and SiC schottky diode (C4D10120A) [9] are used to realize the input power stage of the converter. To reduce input PWM signal voltage overshoots and ringing, it was necessary to use of an additional snubber circuit. Single RCD snubber configuration was chosen [7]. The input PWM signal was generated using control and measuring card dSpace DS1104 with a connector panel. A power resistor connected to converter output were used as a load circuit. The resistance of the load circuit is about 22 Ω. The signals were measured using Tektronix TPS 2024B oscilloscope with Tektronix TPP0201 voltage probe and Tektronix A622 AC/DC current probe.

Converter behaviour in steady state for switching frequency at 16 kHz was shown on Fig. 8 and Fig. 9. The first one contains the waveforms of input signal and coil current. It can be seen that current ripple is close to the desired value. The current ripple is about 1.1 A. This overshoot can be caused by EMI. The input signal is rectangular with duty factor about 0.5. The value of output voltage (Fig. 9) is about 104 V. The output current (Fig. 9) is about 4.73 A.

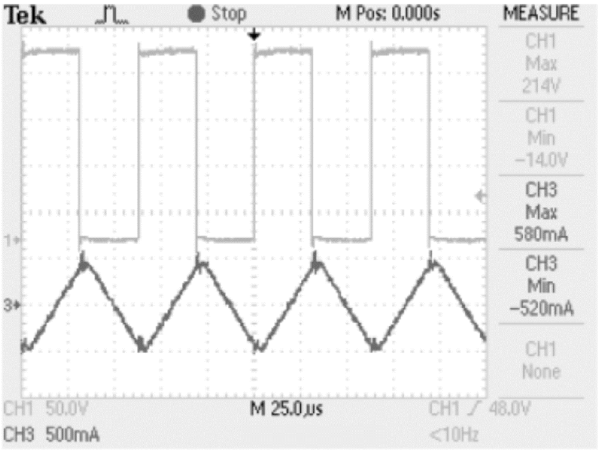

Fig. 8. Input PWM signal and current waveforms for 16 kHz

Converter behaviour in steady state for switching frequency at 50 kHz is shown on Fig. 10 and Fig. 11. The first one contains the waveforms of input signal and coil current. It can be seen that current ripple is close to the desired value. The current ripple is about 0.86 A. The input signal is rectangular with duty factor about 0.5. The value of output voltage (Fig. 11) is about 107 V. The value of output voltage is about 104 V. The output current (Fig. 11) is about 4.89 A.

Fig. 9. Output voltage and load current waveforms for 16 kHz

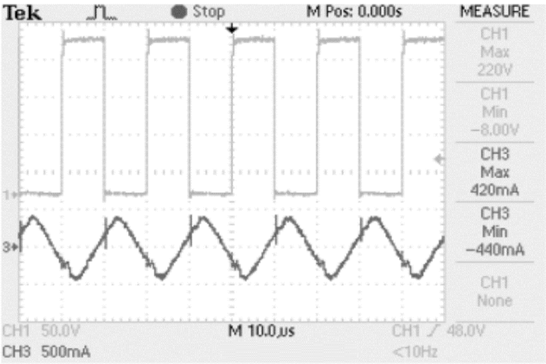

Fig. 10. Input PWM signal and current waveforms for 50 kHz

Fig. 11. Output voltage and load current waveforms for 50 kHz

Converter behaviour in steady state for switching frequency at 100 kHz is shown on Fig. 12 and Fig. 13. The first one contains the waveforms of input signal and coil current. It can be seen that current ripple is close to the desired value. The current ripple is about 1.0 A. At high switching frequency EMI noise can be seen on the current waveform. This is caused by switching of the transistors. This effect is undesirable. The input signal is rectangular with duty factor about 0.5. It can be seen that EMI noise occurs when the input signal changes value (signal edges). The value of output voltage (Fig. 13) is about 107 V. The output current (Fig. 10) is about 4.89 A. It can be seen that the value of output current is greater for higher switching frequencies (50 kHz and 100 kHz). This effect may by caused by lower magnetic losses in the coil core. It is related to size reduction of the coil.

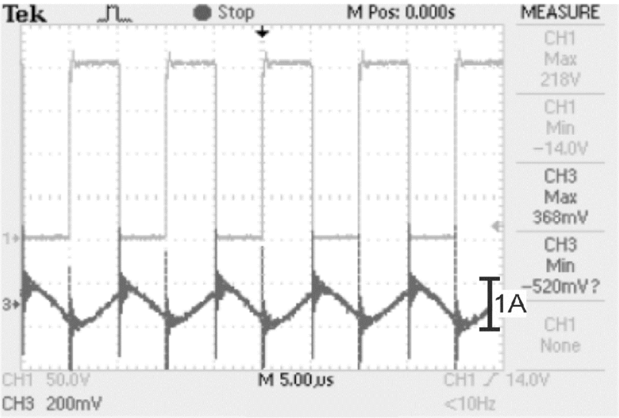

Fig. 12. Output voltage and load current waveforms for 100 kHz

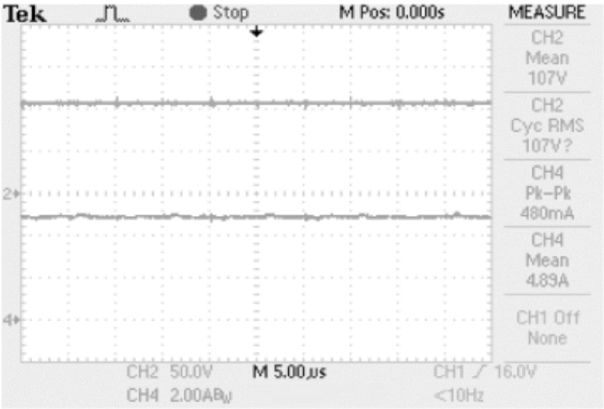

Fig. 13. Output voltage and load current waveforms for 100 kHz

7. Conclusion

The choice of passive components of LC filter is an essential issue in design process of a DC–DC converter. It influences the work conditions of the device and the quality of output voltage. Presented equations (9) and (13) can be used for calculation of required inductance and capacitance of LC circuit. Experimental tests provide their validity.

The power stage properties influence the input signal. Parasitic LC circuit causes the voltage overshoots and oscillations of the input signal. Therefore it is necessary to use of an additional snubber circuit. Applying a snubber circuit reduces the voltage overshoots and oscillations, thanks to which the shape of input signal is rectangular and without oscillations.

The increase of switching frequency allows to size and mass reduction of passive components. This feature make it possible to design more compact power electronics devices. Reduction of coil size decreases the magnetic losses in the core. Higher switching frequency increases the emitted electromagnetic noise. This effect is undesirable but it is the price of higher switching speed of the power semiconductor devices. The mass of coil can be reduced more than three times and the mass of capacitor can be reduced more than four times, at the same operating parameters of the converter.

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(Received: 1. 10. 2016, revised: 17. 11. 2016)