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Output current analysis of multi and single phase noninverting buck-boost converters

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***Abstract* — in the paper, an interleaved noninverting buck-boost converter is presented and compared with a single phase one. The converter consists of six same buck-boost modules which are operating in parallel. The topology of multiphase buck-boost converter is suitable for many applications where high power with low interference is needed. Both single phase and multiphase converters are controlled with an ARM (Advanced RISC Machine) microcontroller in an experimental environment. This article describes the detailed operation of the single-phase and multiphase converter and provides simulation and experimental results of output current ripple. For achieving valid results the same electrical components with same value are used.**

***Keywords* — buck-boost converters, circuit analysis, DC-DC power converters, functional analysis, phase control.**

I. INTRODUCTION

In the present days the batteries are used in many applications. Among these applications are cell phones, laptops, electrical vehicles, renewable energy systems such as photovoltaic systems etc. [1-4]. Especially for a photovoltaic system are battery chargers very critical and their performance can improve efficiency of the complete charging system [5-7].The current ripple that is producing from power converters has negative demand on battery life. Therefore the high switching frequency is used for decreasing not only current ripple, but also volume and size of converters. However the high switching frequency has also negative characteristic. With the increasing switching frequency, the switching losses and electromagnetic interferences (EMI) are increasing too. Among the methods that reducing EMI is soft switching, advanced pulse-width modulation (PWM) and minimizing parasitic couplings.

Soft switching techniques are not providing significant efficiency and also complicate charging system itself. For avoiding these drawbacks, it is possible to use multiphase converters also known as phase sifted or interleaved converters [8-14]. Also, it can be used, some novel converters [15-16]. The converter presented in this paper uses multiple same converters where each phase (converter) is connected to each other in parallel. The each individual phase of the converter is switching with low frequency and the switching pulses are phase shifted to achieving interleaved effect. Due to parallel connect and phase sifted pulses the output frequency is n time higher than output frequency of single phase converter and also provides current with n time lower peak-to-peak ripple amplitude and smaller size of EMI filter [17-19].With the low switching frequency the switching losses are less significant than the switching losses witch high frequency. But the number of switches and passive components in multiphase converters are *n* times more than in the single phase one which requires larger sizes of the converter. For this kind of converter a special control system is required. In present days exist several control strategies which can be used for controlling multiphase buck boost converters in interleaved mode [20-21] and security aspects should also be considered [22].

This paper provides a comparison of multiphase buck-boost converter with single phase one in simulation and experimental environments. Multiphase buck-boost converter is possible to use in many applications due to its ability to operate as step-down and step-up converter with low current ripple, for example in [23] or [25]. The following chapter describes proposed topology for multiphase converter where the basic function and mathematic equation are presented. The third chapter provides simulation results where the waveforms of output current ripple of both converters are presented. The fourth chapter deals with experimental measurements which prove the theoretical assumptions and simulation results.

II. PROPOSED TOPOLOGY

The proposed topology of multiphase buck-boost converter is illustrated in Fig.1. It consists of six same buck-boost converter modules operating in parallel. Each phase consists from two diodes D_{X1} and D_{X2} (subscript 'x' mark particular phase. In this case the x ϵ (1÷6). Subscript 1 marks main switch/diode and 2 marks an auxiliary switch/diode), two switches S_{X1} and S_{X2} and inductors L_X. Diodes D_{X1} serve as rectifier diodes and diodes D_{X2} serves as freewheeling diodes. Switches S_{X1} ensures the short circuit and switches S_{X2} ensures connection and disconnection of supply voltage V_{IN} to the converter. The switches and diodes make complementary couples. Inductors L_X serve as an accumulator of magnetic energy.

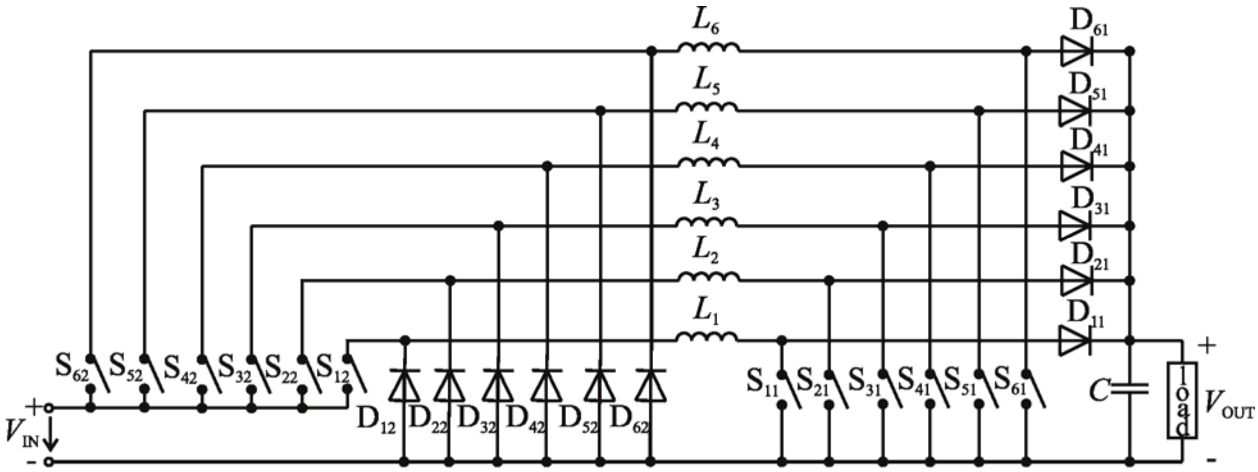


Fig. 1 Proposed six phase buck- boost converter.

The proposed converter has 6 operating cycles within each period T. The corresponding main courses are shown in Fig. 2.

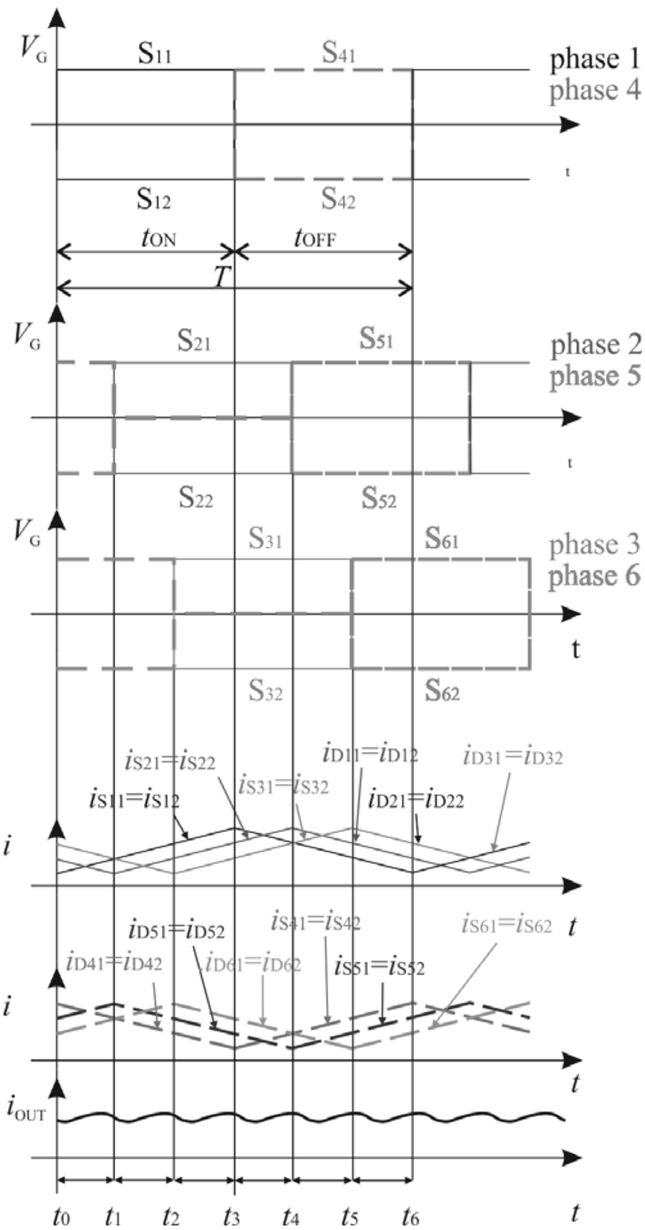


Fig. 2 Theoretical waveforms of six phase buck-boost converter.

To simplify analysis, the following assumptions are made. All the components are ideal and the inductors L_X are so large that currents i_{LX} are considered to be constant during the time that currents flow through the circuit. The output capacitor is large enough so that the output voltage V_{OUT} is considered invariant during the switching cycle. Because the converter is controlled by phase shifted signals the principle of operation of each phase is the same. Therefore the principle of operation only one phase will be explained and described here. The theoretical waveforms and equivalent circuits of single phase are shown in Fig. 3.

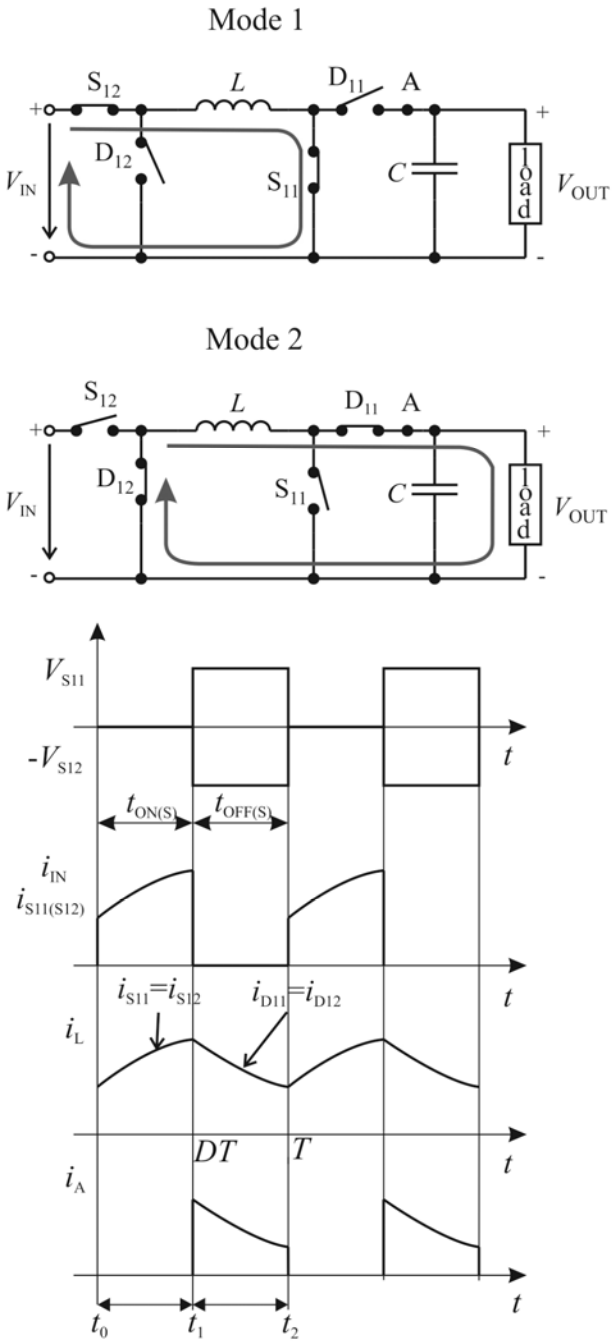


Fig. 3 Theoretical waveforms of single phase buck-boost converter.

Mode 1 (t_0 – t_1): The complementary couples of switches S_{11} and S_{12} are turned on at the time t_0. The energy in the form of magnetic field begins to accumulate in inductor L. The both diodes D_{11} and D_{12} are reverse biased so the current is closed in loop $+V_{IN}$ $-S_{12}$ $-L$ $-$ S_{11} $-$ $-V_{IN}$. The equivalent equations are:

The inductor voltage $v_L(t)$:

$$v_{\mathrm{L}}\left(t\right)=V_{\mathrm{IN}}=L\frac{di_{L}\left(t\right)}{dt} \qquad (1)$$

The current flows through inductor L and co-operating switches S_{11} and S_{12} is:

$$\begin{aligned} i_L(t) &= i_{S11}(t) = i_{S12}(t) = \\ &= \frac{1}{L}\int_{t0}^{t1} v_L(t)\,dt + I_L(t_0) = \\ &= \frac{V_{IN}}{L}(t_1 - t_0) + I_L(t_0) \end{aligned} \tag{2}$$

The inductor current $i_L(t)$ linearly (in our simplified case, exponentially in general) increases from initial value I_L to the maximum value I_{Lmax} (reached at the time t_1).

Mode 2 ($t_1 - t_2$): The switches S_{11} and S_{12} are turned off at the time t_1. The inductor energy begins to deliver to the load through diode D_{11}. The polarity of inductor voltage $v_L(t)$ is reversed so the diode D_{12} is in on-state. The load current $i_{OUT}(t)$ is enclosed in the loop L – D_{11} – load – D_{12}. The equivalent equations are:

The inductor voltage $v_L(t)$:

$$v_L(t) = -V_Z = L\frac{di_L(t)}{dt} \tag{3}$$

It can be seen that the inductor voltage $v_L(t)$ changes the polarity during the time interval in *Mode 2*. This fact is declared by a minus sign in (3).

The currents flow through inductor L and couple of diodes D_{11} – D_{12}:

$$\begin{aligned} i_{D11(D12)}(t) &= i_L(t) = \\ &= \frac{1}{L}\int_{t1}^{t2} v_L(t)\,dt + I_L(t_1) = \\ &= -\frac{V_{OUT}}{L}(t_2 - t_1) + I_L(t_1) \end{aligned} \tag{4}$$

The above described process can be repeated six times (phase shifted) because six parallel phases are presented in proposed multiphase buck-boost converter.

If we assume that the average value of inductor voltage $V_{L(AV)}$ has to be zero for a period T then the average value of the output voltage $V_{OUT(AV)}$ of the proposed topology of buck-boost converter in continuous conduction (CCM) mode can be easily derived.

$$V_{L(AV)} = \frac{1}{T}\int_0^T v_L(t)\,dt = 0 \tag{5}$$

$$\left| i_L(t)_{Mode\,1} \right| = \left| i_L(t)_{Mode\,2} \right| \tag{6}$$

$$\left| \frac{V_{IN}}{L}(t_1 - t_0) \right| = \left| -\frac{V_{OUT}}{L}(t_2 - t_1) \right| \tag{7}$$

$$V_{IN} t_{ON} = V_{\mathrm{OUT}} t_{OFF} \tag{8}$$

If we consider that the duty cycle D is defined as:

$$D = \frac{t_{ON}}{T} = \frac{t_{ON}}{t_{ON} + t_{OFF}}[-] \tag{9}$$

The equation (8) can be easily transformed to form:

$$V_{IN} DT + V_{OUT}(T - DT) = 0 \tag{10}$$

The average value of the output voltage $V_{OUT(AV)}$ of proposed buck-boost converter in CCM can be easily derived from, (10).

$$V_{OUT(AV)} = \frac{D}{1-D} V_{IN} \tag{11}$$

Equation (11) shows that the proposed buck-boost converter really belongs to the family of buck-boost converters. It works in the buck mode for $D \in (0 - 0{,}5)$ and in boost mode for $D \in (0{,}5 - 1)$.

The current ripple in both cases can be calculated with the equation (12). Due to interleaved connection of six phase converter the frequency is six times greater frequency than in single phase converters. For this reason the current ripple I_r is six times smaller than the current ripple in the single phase converter.

$$I_r = \frac{D V_{out}}{C R^2 f} \tag{12}$$

III. SIMULATION RESULTS

In present days exist many simulation programs which can handle simulations of electrical circuits. It was made multiple comparisons of simulation programs included MATLAB [26-28].

The simulation model of single phase converter was created in software environment called a Proteus, see Fig. 4. This software uses a well-known ProSpice simulation software.

To make the simulation more realistic, resistor R_{PAR} represents the resistance of a wire and resistance of input voltage source and inductor L_{PAR} represents parasitic inductances of the circuit were added to the simulation model of converter. The power MOSFET transistors with N-channel were used as switches.

The control structure of six phase converter was created with the help of script block where basic parameters of each pulse generators were defined in one place.

The six phases converter illustrated in Fig. 5 is also created in the mentioned simulation program.

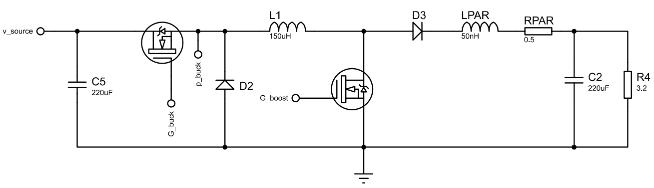


Fig. 4 Single phase buck- boost converter created in the simulation program.

The simulation parameters for six and single phase converters are:

Table I.
Parameters of converters in simulation environment

input voltage	$V_{IN} = 20$ V
load resistance	$R_Z = 3{,}2\ \Omega$
duty cycle	$D = 0{,}3$ (step-down mode)
switching frequency	$f_S = 20$ kHz
output capacitor	$C_f = 220\ \mu$F
inductors	$L_1 - L_6 = 100\ \mu$H
parasitic resistor	$R_{PAR} = 0{,}3\ \Omega$
parasitic inductor	$L_{PAR} = 50$ nH

In the following figures (Fig. 6 and Fig. 7) the simulation results of output current ripples for single and six phase buck-boost converters are illustrated. Due to a resistive load, the voltage ripple is not presented. From results can be seen that the current ripple for six phase converter is reduced. This happens as was mentioned before when the six phase converter is switching each leg with phase shifted signals. Therefore the output frequency is higher and voltage and current ripple is lower. This simulations results proved the correctness of equation (12).

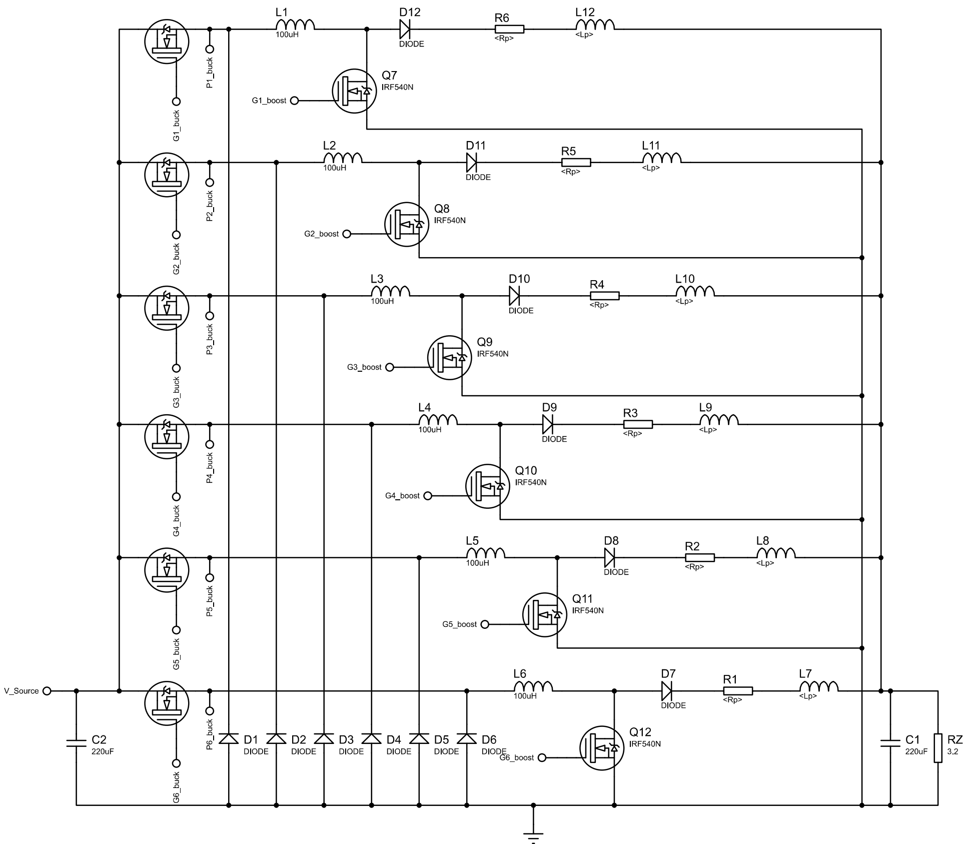


Fig. 5 Six phase buck- boost converter created in the simulation program.

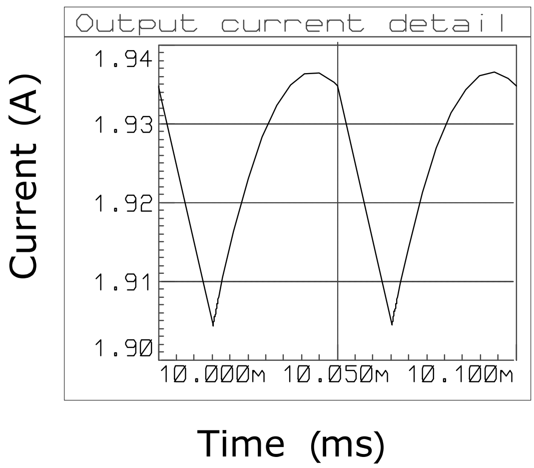


Fig. 6 Output current in simulation program for single phase converter

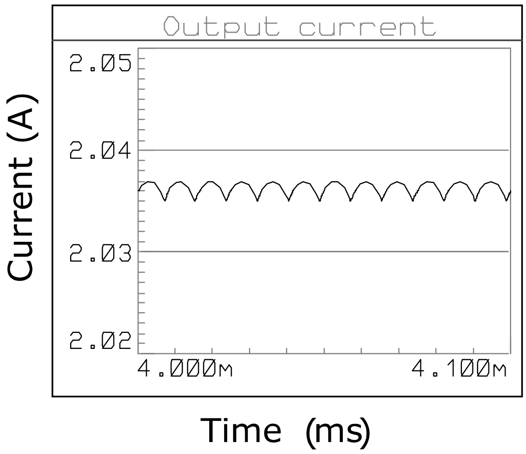
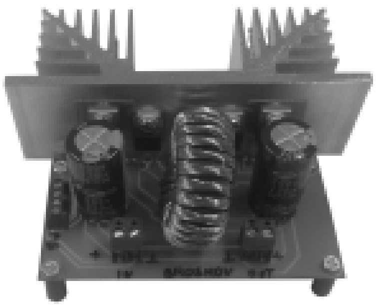


Fig. 7 Output current in simulation program for six phase converter

IV. EXPERIMENTAL RESULTS

To verify theoretical assumptions and simulation results a laboratory model of proposed six phases and single phase converters were built, as can be seen in Fig. 8. A printed circuit board for both converters were created with the help of UV (Ultra Violet) radiation. Both models are using same switching components, same filter values and same load value. Control pulses are produced with help of NUCLEO 64 microcontroller board which consist 32-bit ARM (Advanced RISC Machine) processor unit (STM32F446RE). The pulses from microcontroller are lead via galvanic isolation and MOSFETs drivers to MOSFETs gates.

a)



b)

Fig. 8. Illustration picture of a) six phase converter and b) single phase converter

As can be seen in Fig. 8 b) the inductor for the single phase converter is bigger than inductor in the six phase converter. The reason of that is because the single phase converter does not share a current like the six phase converter and of course can be used for higher currents.

The parameters which were used in an experimental environment for six and single phase converters are shown in Table 2.

Table II.
Parameters of converters in experimental environment

input voltage	V_{IN} = 20 V
load resistance	R_Z = 3,2 Ω
duty cycle	D = 0,3 (step-down mode)
switching frequency	f_S = 20 kHz
output capacitor	C_f = 220 µF
inductors	L_1 - L_6 = 100 µH

The following oscillograms for single (Fig. 9) and six phase (Fig. 10) converters fully confirm the simulation results and theoretical assumptions. In both cases of converters are show DC output current $i_A(t)$ flowing to the load.

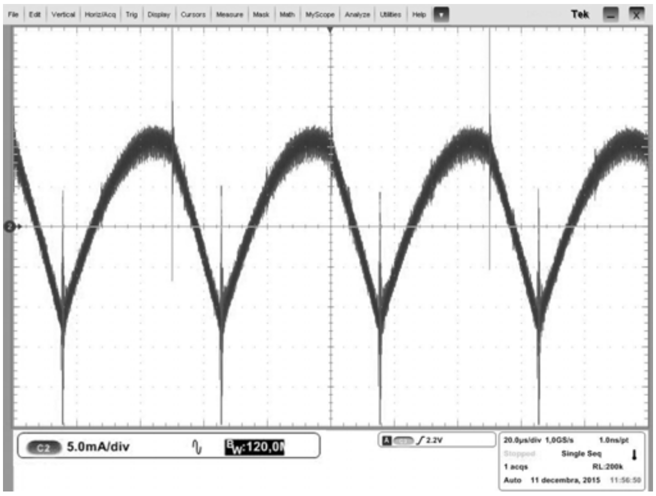


Fig. 9 Measured output current of single phase converter

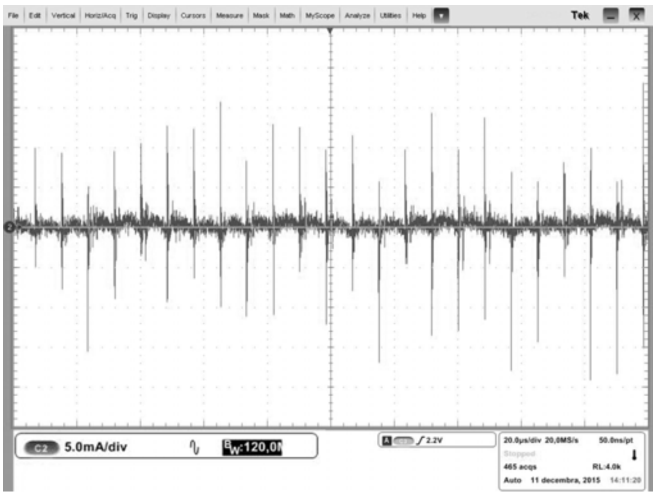


Fig. 10 Measured output current of six phase converter

As can be seen in Fig. 9 and Fig. 10 the six phase converter produce lower current ripple with higher frequency than a single phase converter where the values of filters are same for both converters. The experimental measurements were achieved with the help of DPO 7354 oscilloscope.

The advantage of this kind multiphase converter is possibility to easy changing number of legs with changing only control program. Also, it can be used in higher current condition with switching transistors in parallel at the same time and thanks for sharing current among legs it does not need the expensive switching components for higher current. Now can be use switching components with lower switching speed and smaller filters. This reduces not only the size of the filters, but also the size of whole devices because the switching transistor can be soldered nearby each other but the size of the filter cannot be reduced too much.

In simulation and experimental environment were used MOSFETs type of an IRF540N as switching components.

V. CONCLUSION

In the paper, modeling and implementation of six phase buck-boost converter has been presented and compared with a single phase one. The comparison is created by using the same value of electrical components for both converters. The experimental models of both converters were built and compared which prove theoretical assumptions and simulation results. From simulation and experimental results, it is possible to see that the multiphase converter is more suitable where lower current ripple with relatively cheap components is required. The simulation results are basically same as results in an experimental environment.

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