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Resonant-mode Switched-Capacitor DC-DC Converter With Inductance on PCB. An Analysis and Comparison of Parameters

Abstract. *The paper presents comparison of operation parameters and components selection procedure for DC-DC switched capacitor converter in two cases of resonant inductors design. In both cases the inductors are connected in series with switched capacitors. Design with air cored inductor with PCB winding and inductor with planar ferrite core have been analyzed. Both cases differs in meaning of achievable inductance, resistance and demanded PCB area that have significantly influence on selection of other components and power losses of converter. The paper indicates the range of inductance of switched capacitors circuit that is beneficial in the meaning of optimization of size of components. In the paper, an analysis of resonant DC-DC switched capacitor converter with voltage gain of two, as well as simulation and experimental results have been presented.*

Streszczenie. *W artykule przedstawiono porównanie parametrów pracy i doboru elementów dla układu przekształtnika DC-DC o przełączanych kondensatorach dla dwóch przypadków realizacji indukcyjności rezonansowej w obwodzie przełączanego kondensatora. Analizowane będą przypadki, w których Indukcyjność uzyskano jako dławik powietrzny zrealizowany w obwodzie drukowanym (PCB) oraz jako dławik z rdzeniem ferrytowym planarnym. Oba przypadki różnią się pod względem możliwej do uzyskania indukcyjności, a także rezystancji i wymaganej powierzchni PCB, co znacząco wpływa na dobór pozostałych elementów w układzie oraz straty energii. W artykule wykazano, w jakim zakresie wartości indukcyjność obwodu przełączanych kondensatorów wpływa korzystnie, a w jakim niekorzystnie ze względu na optymalizację wielkości elementów układu. W artykule przedstawiono analizę układu, wyniki symulacyjne oraz wyniki badań eksperymentalnych przekształtnika rezonansowego DC-DC o przełączanych kondensatorach o podwójnym wzmocnieniu napięcia. (**Rezonansowy przekształtnik DC-DC z przełączalnymi kondensatorami i indukcyjnością wykonaną na PCB. Analiza i porównanie parametrów.**).*

Keywords: switched capacitor, DC-DC resonant converter, ZCS,
Słowa kluczowe: przełączalne kondensatory, rezonansowy przekształtnik DC-DC, ZCS

Introduction

Switched-capacitor DC-DC power converters can be attractive in some applications such as the high voltage gain systems or highly reliable converters. It can be an alternative solution to the switching mode DC-DC converters [1] – [3]. As power converters the switched-capacitor circuits are configured as resonant-mode converters to limit recharging currents of capacitors and to operate with zero current switching (ZCS) [4] – [6]. Resonant circuits are created by the switched capacitors and attached or parasitic circuit inductance. The inductance is necessary for achievement of oscillatory circuits with sufficient quality factor [7]. Then the converter can operate in Zero Current Switching mode and with low losses during recharging of switched capacitors. Another converters with switched capacitors such as topology as DC-AC and AC-AC were also presented in [8] – [11].

The switched capacitor converters function as charge pumps. Fig. 1 presents the MOSFET-based switched capacitor voltage multiplier, i.e. the multicell DC-DC converter that gains the input voltage:

$$U_{\text{out}} = (n+1)U_{\text{in}} \tag{1}$$

where: n – number of cells, U_{in} – supply voltage.

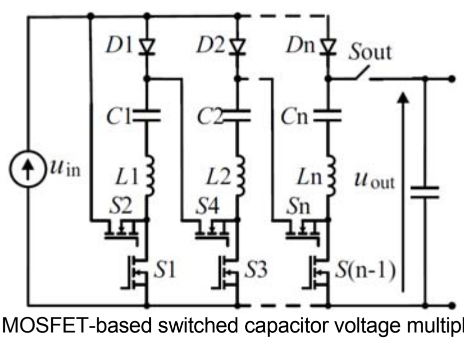


Fig. 1. The MOSFET-based switched capacitor voltage multiplier

The MOSFET-based SC voltage multiplier can operate with high switching frequency (even hundreds of kilohertz). The capacitors are recharged with high frequency, thus a substantial amount of energy can be transferred to the output with the utilization of small passive (accumulating) components. An application of parasitic inductances of components and connections can be enough to achieve the oscillations of current of SC. In order to improve the Q-factor and decrease the RMS value of current an additional inductance can be introduced by air PCB chokes design and additional choke usage. An interesting solution can be also to use the PCB type choke but supported by core (e.g. planar type). This paper focuses on comparison between the air inductor and ferrite cored inductor solutions of the SCVM. In particular there will be comparative approach where the choke is designed as coreless PCB type and the PCB core with planar choke. The advantages and disadvantages of both the solutions will be addressed. The investigation will be conducted with the use of the converter with the voltage ratio equal to two. This converter will be later referred as the SC voltage multiplier. The chokes are placed in the branch of the switched capacitor because in such case the inductive component is used both during charging and discharging of the SC.

MOSFET - based voltage multiplier

Fig. 2. presents a schematic of the single-cell of MOSFET-based voltage multiplier, and Fig. 3 an idea of operation.

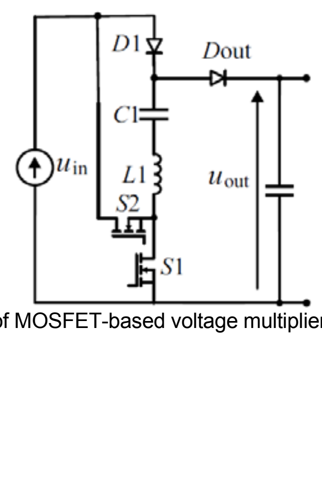


Fig. 2. Single-cell of MOSFET-based voltage multiplier

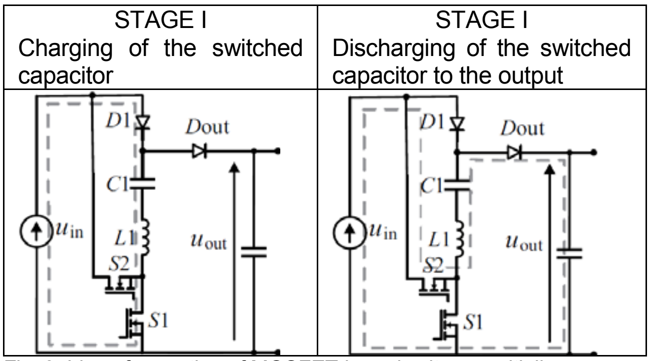


Fig. 3. Idea of operation of MOSFET-based voltage multiplier.

The switched capacitance is recharged in every switching cycle which makes it possible to transfer the charge to the output capacitor. Fig. 4 presents waveforms in the converter where the stage of charging as well discharging of the switched capacitor (STAGE I and STAGE II) is visible.

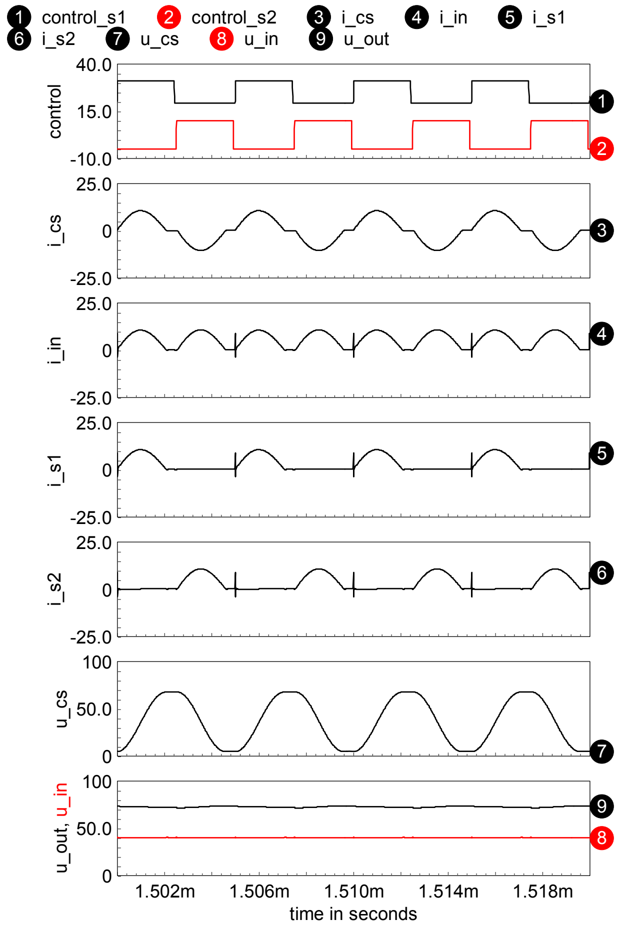


Fig. 4. Steady state waveforms in the SC voltage multiplier in the 200W output power. ICAP/4 simulation results. L_s=2uH, C_s=220nF, U_{in}=40V, P_{out}=200W. ICAP/4 simulation results

Selection of LC components

The energy from the input to the output is transferred via the switched capacitor. In order to transfer a rated power the requirement for the switched capacitor value C can be defined as follows:

(2) $$P \leq 2(n+1)U_{\text{in}}^2 f_S C$$

where: f_s – switching frequency.

For the particular rated power and switching frequency the switched capacitance can be optimized to the value where the full recharging of the capacitor occurs in a switching cycle:

(3) $$C \geq \frac{P}{2(n+1)U_{\text{in}}^2 f_S}$$

Minimization of volume of the switched capacitor is one of the aspects of optimization of the converter. It can bring a decrease of volume and cost of the capacitors but it increases a natural frequency of oscillation in the resonant circuits, which is presented in. Fig. 5.

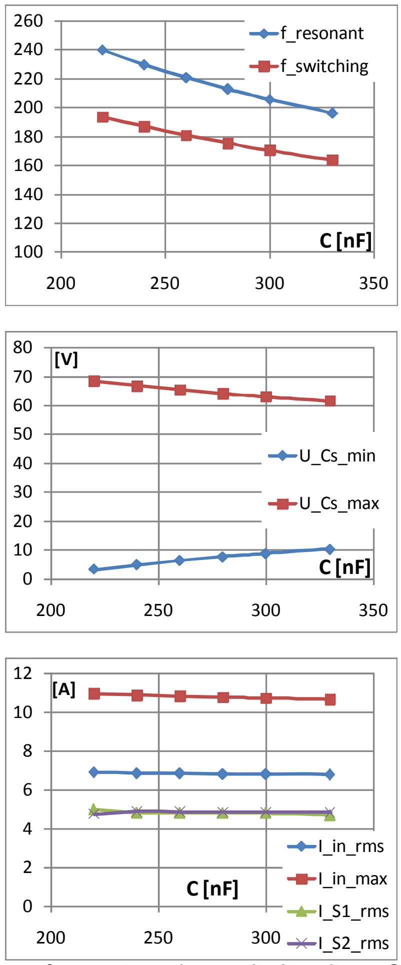


Fig. 5. Values of currents and capacitor's voltage Cs in the SC voltage multiplier when the converter operates in near resonance frequency in each point. *Pout=200W*. Values from ICAP/4 simulation results

Until the converter is controlled with the rated frequency (near the resonant frequency but decreased by the value of dead time) the RMS value of currents remains constant versus the capacitance change. However, when the converter operates with maximum feasible frequency (lower than the frequency of natural oscillations in the circuits in the converter) an increase in the difference between switching frequency and oscillation frequency causes an increase in maximum and RMS of currents in the converter. It can cause a substantial losses increase. Fig. 6 presents an impact of the capacitance of the switched capacitor on the RMS value of currents in the circuit when the converter operates with the inductance 2uH and constant switching frequency equals 164kHz (a rated switching frequency for the 330nF switched capacitor and 2uH inductance).

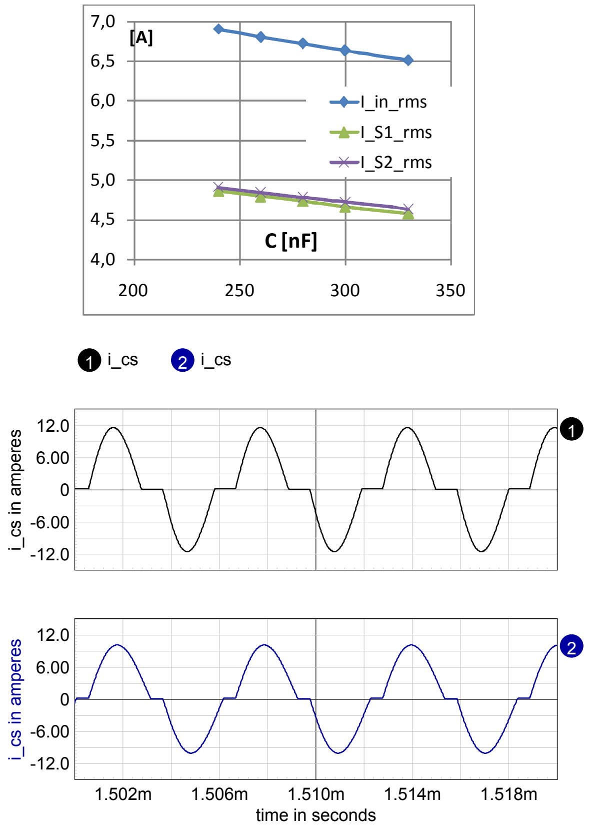


Fig. 6. RMS value of currents versus C in the SC voltage multiplier for constant inductance and switching frequency and waveforms in two particular cases. $L=2uH$ $R=500m\Omega$, f_S=164kHz. Values and waveforms from ICAP/4 simulation results

For minimized value of switched capacitance, according to the power demands, the achievable switching frequency can be lower than frequency of oscillations. In such a case an increase of inductance can be favorable because it causes the RMS value of currents decrease and limits resistive power losses. However if the converter operates with rated frequency (near the resonant frequency) an increase of the inductance is not desired because it decreases the resonant frequency and energy transfer rate. If the frequency of recharging of the switched capacitor decreases, and full recharging is achieved, the capacitance should be increased to maintain the rated power conversion. The value of switched capacitance should vary in proportion to the square root of inductance. Fig. 7 presents an impact of the inductance of resonant circuits in the SC voltage multiplier on the RMS value of currents that obviously affects the efficiency of the converter. The converter operates with the full recharging of the switched capacitor, the rated frequency and capacitor adjusted to the constant power rate (200W).

From the results presented in Fig. 7 it follows that when the optimum switched capacitance as well as switching frequency is reached an increase of the inductance in the switched capacitor circuit is not desired. Values of current do not decrease but bigger switched capacitance is needed. A decrease of the switching frequency can be favorable in some cases.

The inductance in the SC converter can be achieved as parasitic components, air choke or as an additional component.

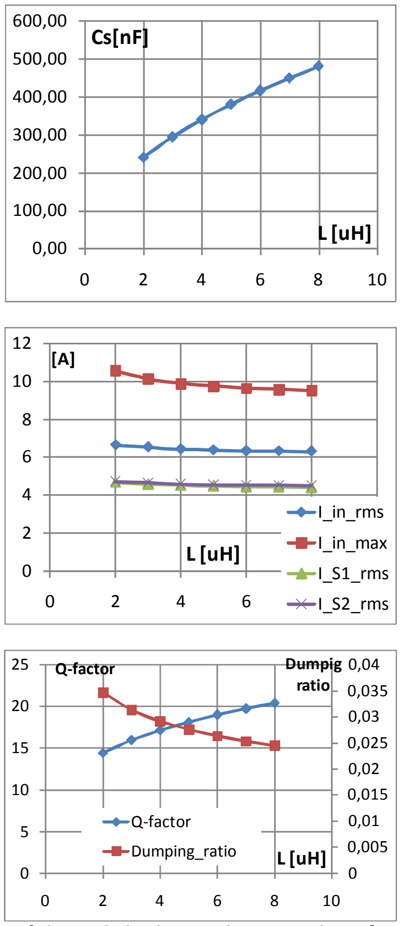


Fig. 7. Value of the switched capacitance, value of currents value as well as Q-factor and dumping-ratio vs. vs. L in the switched capacitor circuit. The converter operates with $f_s \approx f_0$ (decreased by dead-time). $R=200m\Omega$, $P_{out}=200W$. Values from ICAP/4 simulation results

The inductance of the switched capacitor circuit is necessary to achieve a rated operation conditions and in low power circuits can be achieved form parasitic parameters of circuit or designed on PCB for instance. When the parasitic parameters are used the converter is actually inductiveless and cost limited, but can have poor Q-factor, very high resonant frequency, high recharging currents and low efficiency. PCB air choke design can improve the Q-factor and efficiency but needs some space and also introduces substantial resistance to the recharging circuits. This issue is discussed in the next sections.

In high power converters the rated capacitance rises which causes a undesired change in the Q-factor as well as the dumping-ratio (Fig. 8). To maintain oscillatory circuits in the converter the inductance should be increased as the rated power of the converter rises.

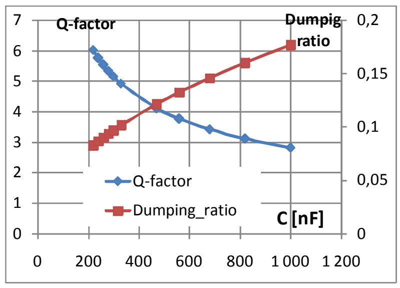


Fig. 8. Q-factor and dumping-ratio vs. Cs for $L=2uH$ and $R=200m\Omega$

Energy In The Inductance And Placement Of The Choke

In the inductive design the placement of the choke should be carefully analyzed. There are two general options for this problem:

- Utilization of a single, central choke in the input of the converter,
- Utilization of distributed smaller chokes in the cell of the converter.

A selection of the case depends on the construction or cost aspects. A comparison of these approaches is presented in [7].

It should be noted that using multiple distributed chokes is less efficient than central choke due to higher equivalent series resistance, and higher form factor of input current. However, in some cases using distributed inductors may be advantageous, for example because of the mechanical demands of the converter in low profile design. Also in the case of ferrite core less design the main inductance can be designed in the capacitor branch, as a stray component or an air PCB choke (Fig. 9).

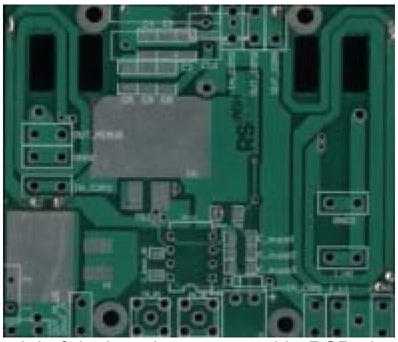


Fig. 9 The model of designed converter with PCB air choke.

This solution is favorable, because the inductance exists both in the charging and discharging circuit. However, in the hard switching mode or failure operation of transistors, the inductor can be deenergized in the analyzed converter by a corresponding diode (Fig. 2.). For the multicell converter the inductor current the deenergizing can occur in the avalanche mode. For very small inductances associate with the air choke the avalanche energy may not destroy any switch provided that they are properly selected.

Experimental Setup Realization

In Fig. 9 a picture of SC voltage multiplier is shown. On the PCB board two windings connected series with switching capacitor were made. Each one contains 4 turns made of tracks. Test experiments was performed in two variants: with mounted ferrite core on the one winding or without. Ferrite core inductor was designed with utilization of gapped planar core size ELP18/4/10 made of material N87. The main parameters of the core are summarized in Fig. 10. The winding of inductor was made as PCB layout with thin copper (35 um) which results in relatively high resistance of designed choke. Parameters of designed ferrite cored and air cored inductors can be found in Tab. 1. Ferrite core inductor has been designed as saturation limited due to very small PCB area achievable for ferrite core. With as high an operation frequency as 150 kHz, and magnetizing induction close to saturation (Bmax = 350 mT) the power losses of the core are very significant. Choosing a bigger core would be advantageous because of limitation of core losses and improve of cooling capability. Additionally, in order to get universal winding which is appropriate for both, air cored and ferrite cored designs without modifications (PCB layout), the turns of the winding are very long (in relation to optimum) in case of ferrite design. Thus, in ferrite cored choke the DCR (Direct Current Resistance) is definitely bigger than achievable value in case of design optimized for usage of only ferrite core.

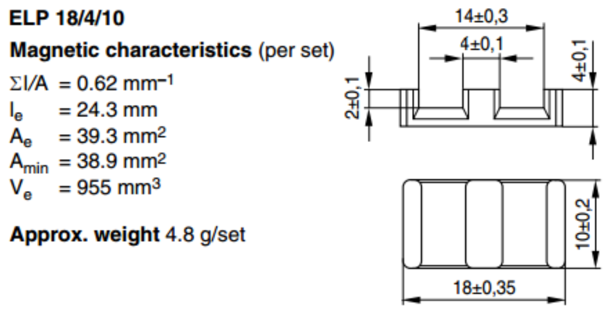


Fig. 10. Main parameters and measurements of planar ferrite core used in laboratory setup (based on EPCOS data sheet). Air gap was introduced by using plastic spacer on all columns

However ferrite cored choke, in spite of the mentioned problems, has more than twice the inductance, covers half of the area of the air cored coils and highly increases efficiency of the converter which will be refined in next section. This is because air cored design consist of two winding each with 4 turns and ferrite cored design utilizes only one winding since the second one is shorted. The design of ferrite core inductor could be optimized in the meaning of usage bigger core, shorter turns and thicker copper layers. Presented solution should be treated like initial design valuable for illustrating issue of comparison between switched capacitor converters with ferrite cored and air inductors.

Table .1 Parameters of designed chokes with air core and ferrite gapped planar core. Also the value of switched capacitance is stated.

Core	C_1 [nF]	L_1 [μH]	R [Ω]	A_{PCB} [cm^2]
Ferrite	320	4,5	0.10	9,5
Air	235	1,8	0.25	19

Experimental Verification Of Operation And Efficiency Measurements

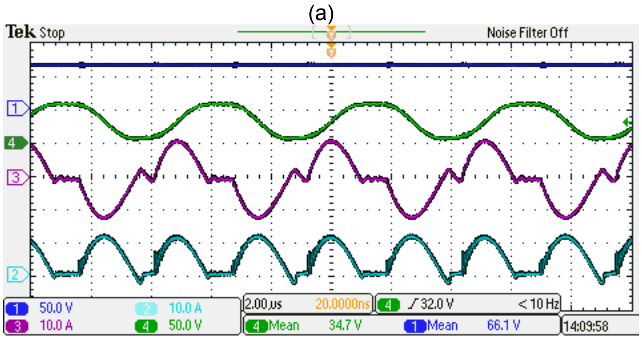
Results of measurements of the presented converter are stated in Tab 2. Both converters have been tested with the same input voltage $U_{in} = 40\ V$ and input power $P_{in} = 208W$. The main difference between operation of air and ferrite cored design is efficiency and effective output resistance. It could be noticed that there is very slight difference in value of form factor of current of switched capacitor but substantial difference in the efficiency of operation. Thus, in this comparison the power losses in air choke design are caused directly by increased series resistance of winding. Because in both cases form factors of current of switched capacitor are close to each other, increased dumping factor has almost no influence on the amount of power losses. Thus, experimental results are consistent with simulation results presented in previous sections. The effective output resistance of the converter is also higher in air core design, which limits real voltage gain factor. The converter with air core operated with 1,5 times higher frequency, in order to meet power requirements, which also has negative influence on efficiency of operation. Designing converters with air cored chokes brings much more problems because of magnetic flux which in air coils has definitely further range. Thus, magnetic flux from air cored coil penetrates near by pieces of metal like heat sinks, enclosure, connectors, causing eddy currents and additional power losses. It is also an important issue from the EMI point of view.

Table. 2. Measured parameters of tested converter with air cored and ferrite cored choke. ($k_f = I_{CRMS}/ I_{CARV}$). Both converters operated with P_{in} = 200W.

Core	I_{CRMS} [A]	I_{CAVR} [A]	k_f	f_s [kHz]	P_o [W]	U_o [V]	η [%]	ΔP [W]
Ferrite	6,5	5,2	1,25	107	184	71,1	92,7	15
Air	6,6	5,2	1,27	156	179	67,7	87,2	27

Fig. 11 presents waveforms of output voltage, capacitor voltage, capacitor and input current for steady state of the laboratory setup of converter. The SC voltage multiplier was operating in air cored (a) and ferrite cored (b) design. In both cases input power and dead time were the same. For the air cored mode with $L=2uH$ $C=257nF$ switching frequency is higher than in ferrite mode ($L=4{,}5uH$ $C=320nF$). Capacitor voltage decreases to zero. This indicates the maximum load. In case of air cored design, the maximum value of current is bigger than in ferrite mode. This is due to a lower inductance.

(a)



(b)

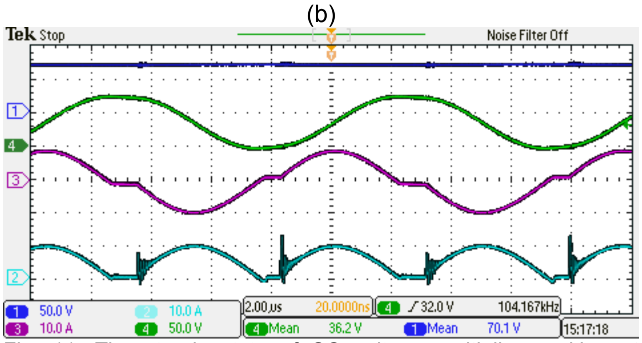


Fig. 11. The steady state of SC voltage multiplier working at $P_{in}=200W$ in two particular cases: (a) air cored design $C=257nF$, $L=2uH$ $f_S=156kHz$; (b) ferrite cored design $C=320nF$, $L=4{,}5uH$ $f_S=104kHz$. Waveforms from top: output voltage – 1, capacitor voltage – 4, capacitor current – 3, input current – 2. Experimental results

Conclusions

In this paper comparison between air cored design and ferrite cored design of choke in switched capacitor step up converter has been presented. The problem has been deeply analyzed with usage of ICAP/4 simulation program and laboratory verifications have been performed. For too low circuit inductances:

- The low power converter can operate with not optimized capacitors, or with too low frequency that causes a substantial power losses
- The higher power converter can operate with too low Q-factor and high dumping factor which increases power losses too.

Generally speaking, air cored design is less efficient, has to operate with higher frequency, needs more space but can be a trade-off between quality and price. In particular cases converter with air cored choke can be irreplaceable due to special demands, for example operation in extremely high temperatures at which ferrites are close to Curie point, or in case of extremely low profile design.

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