New AC-AC Converter Topologies

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***Abstract*— This paper presents new AC-AC converter topologies operating as AC voltage regulators. Operation stages, static gain expressions, main waveforms and simulation results are shown. Laboratory experimental results for 1 kVA converters are also presented, which demonstrate the feasibility of the study carried out.**

***Index Terms*—AC-AC converter, voltage regulator, new topologies.**

I. Introduction

Direct AC-AC converters, with a reduced number of active power switches are lacking in the market. Therefore, in this work, some topologies of AC-AC converters are presented, that can provide energy to non-linear loads, isolate the load from the AC line voltage and act as an active filter using only two active switches and presenting high efficiency.

At the present time, the loads, residential, commercial or industrial, have become predominantly non-linear. The input stage of electronic equipments, in the majority of cases, is a rectifier with a capacitive filter, a typical example of a non-linear load. Non-linear power sources, in general, also use rectifying circuits with a capacitive filter as an input stage. Therefore, the converters must operate with loads of this nature.

One of the principal difficulties in building direct AC voltage regulators is the commutation process, since the switches must be bi-directional in voltage and current. To solve this problem [1] presented a Buck converter topology, which can operate overlapping the active switch's signals. In order to obtain an isolated structure capable of increasing the output voltage, the topology presented in [1] was changed, resulting in a modified Buck converter, as presented in [2], [3] and [4].

In this article, topologies are presented with the same principle of operation of [1]. Two of them are Buck converters isolated by means of low frequency transformers. Later, from [1], Boost and Buck-Boost converters are originated. For these, experimental results are presented.

II. Proposed Topologies and Principle of Operation

The structure presented in [1], as shown in Fig. 1, eliminates the necessity of dead time, solving the problem of high voltage over the components. However, this structure is not isolated and does not allow an increase in the output voltage. The structure presented in [2], [3] and [4], and shown in Fig. 2, allows increasing and decreasing of the output voltage, is isolated, but has the inconvenience of using two transformers.

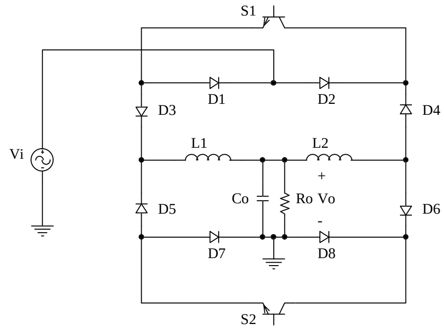

Fig. 1 – Topology presented in [1].

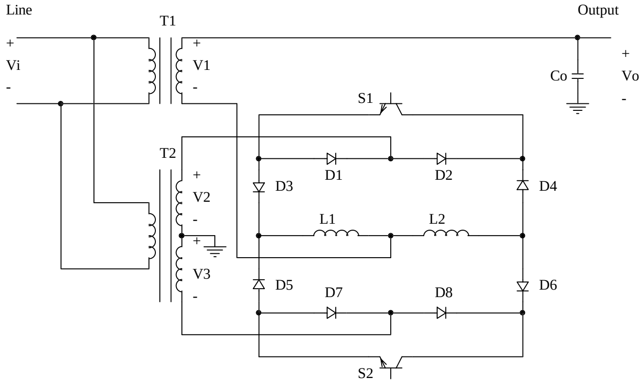

Fig. 2 – Topology presented in [2], [3] and [4].

In Fig. 3 and Fig. 4, two variations of the structure of Fig. 1 are presented. The first one uses a low frequency transformer (T_1) on the input side, while the second uses a transformer on the output side. It is noted that both structures are Buck converters and the output voltage can be adjusted by the transformer ratio of T_1.

The Boost converter obtained from [1] is shown in Fig. 5. The Buck-Boost converter is shown in Fig. 6. An advantage of the latter is the possibility of increasing and reducing the output voltage. However, the voltage across the switches is the sum of the output and input voltages.

In the presented converters, inductors L_1 and L_2 along with capacitor C_o constitute the output filter. The load is represented by R_o, to simplify the drawing. Actually, this load is non-linear and is constituted by a rectifier with a capacitive filter.

The operation stages of the converter shown in Fig. 3 will be described below. For the other converters, the number of operation stages are the same, not being presented here. In order to describe the operation stages, it is assumed that:

- The power switches are ideal;

· During a switching period, the input and output voltages are considered constant, due to the fact that the switching frequency (f_s = 20 kHz) is considerably higher than the line frequency (f_r = 60 Hz);

· The load is purely resistive.

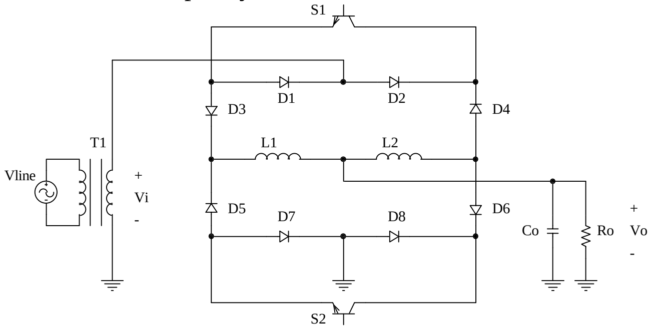

Fig. 3 – Buck converter with input transformer.

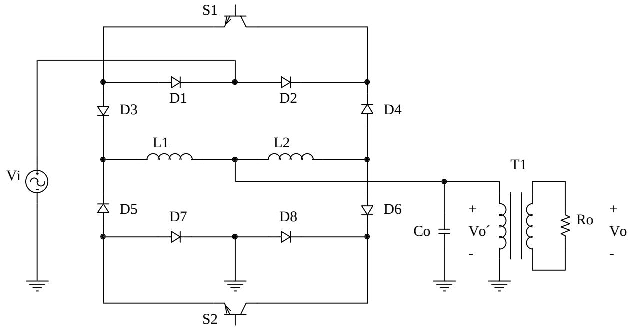

Fig. 4 – Buck converter with output transformer.

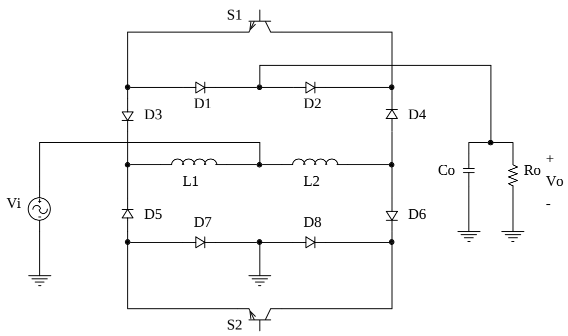

Fig. 5 – Boost converter.

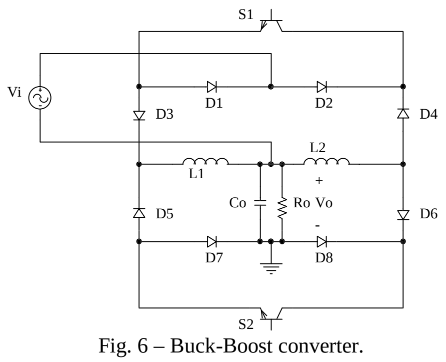

Fig. 6 – Buck-Boost converter.

The operation stages are as follows:

<u>1st stage (t_0, t_1), Fig. 8:</u> S_1 is in ON state. The load current flows through T_1, D_2, S_1, D_3, L_1 and $R_o//C_o$. The current of inductor L_2, i_{L2}, flows through L_2, D_4, S_1, D_3, and L_1. During this stage, energy is transferred from the line to the load. This stage finishes at time t_1, when S_2 is commanded to turn-on.

<u>2nd stage (t_1, t_2), Fig. 9:</u> This stage starts when S_2 is turned-on. Switches S_1 and S_2 are ON. The current of inductor L_1, i_{L1}, flows through T_1, D_2, S_1, D_3, L_1 and $R_o//C_o$. The current through inductor L_2, i_{L2}, flows through L_2, D_6, S_2, D_7, and $R_o//C_o$. The load receives energy from the line. This stage finishes when S_1 is ordered to turn-off, at t_2.

<u>3rd stage (t_2, t_3), Fig. 10:</u> At t_2, when S_1 is switched-off, the third stage begins. Switch S_2 is in ON state. The load current flows through L_1, $R_o//C_o$, D_8, S_2, and D_5. Current i_{L2} flows through L_2, D_6, S_2, D_7 and $R_o//C_o$. The load does not receive energy from the line. This stage finishes at t_3 when switch S_1 is commanded to turn-on.

<u>4th stage (t_3, t_4), Fig. 11:</u> When switch S_1 is commanded to turn-on at t_3, begins the fourth stage. As in the second stage, switches S_1 and S_2 are ON. The current of inductor L_1, i_{L1}, flows through T_1, D_2, S_1, D_3, L_1 and $R_o//C_o$. The current of inductor L_2, i_{L2}, flows through L_2, D_6, S_2, D_7, and $R_o//C_o$. The load receives energy from the line. This stage finishes when switch S_2 is commanded to turn-off, at t_4.

The main waveforms, for a switching period, considering the input voltage at its peak value, are shown in Fig. 7.

III. Analytical Study

The input voltage of the converters is sinusoidal, obtained from the secondary winding of transformer T_1 or directly from the mains. Expression (1) gives the line voltage and (2) the output voltage of transformer T_1, for the converter shown in Fig. 3. V_{i_p} is the voltage peak value of the mains.

$$V_i(t) = V_{line} = V_{i\_p} \cdot \sin(\omega t) \tag{1}$$

$$V_i(t) = n_1 \cdot V_{line\_p} \cdot \sin(\omega t) \quad \text{Where} \quad n_1 = V_i / V_{line} \tag{2}$$

To determine the static gain of the power stage, the intervals when both switches are ON will be neglected, that is, interval Δ_t presented in Fig. 7. These intervals are very small, when compared to a switching period, so their influence on the static gain can be neglected.

The ON intervals of switches S_1 and S_2 are given by expressions (3), (4) and (5).

$$\Delta t = t_2 - t_1 = t_4 - t_3 \tag{3}$$

$$\Delta t_1 = t_1 - t_0 \cong (t_1 - t_0) + 2 \cdot \Delta t \tag{4}$$

$$\Delta t_2 = t_3 - t_2 \cong T_s - \Delta t_1 \tag{5}$$

The output voltage of the converters is given by expressions (6) to (9) as a function of the input voltage, the transformer ratio of T_1 and duty cycle.

For the Buck converter, during the interval when both switches are ON, the energy flows from the source to inductors, appearing over L_2 an average voltage, given by (10). The voltage is proportional to Δ_t.

Consequently, the power transferred from the source to L_2 is given by (11).

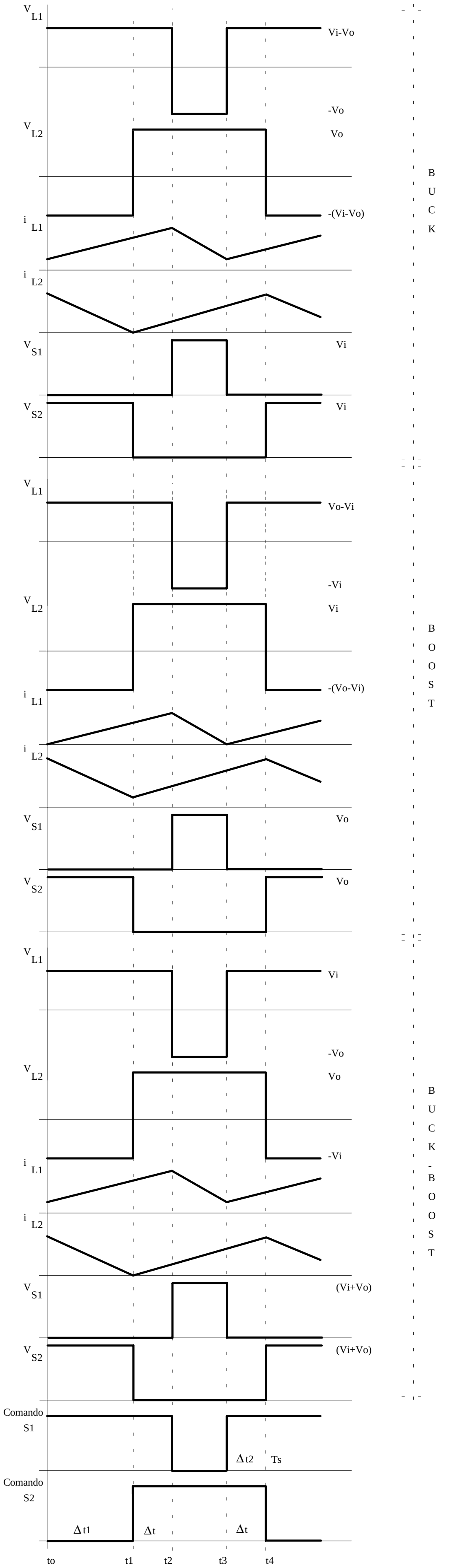

Fig. 7 – Main waveforms.

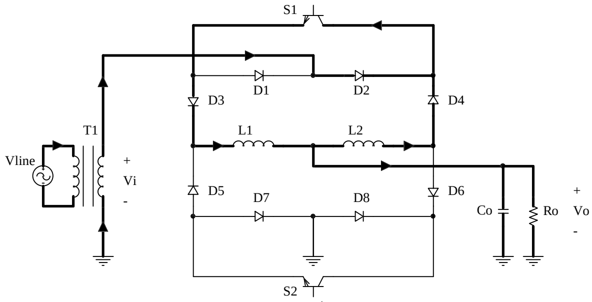

Fig. 8 – 1st stage.

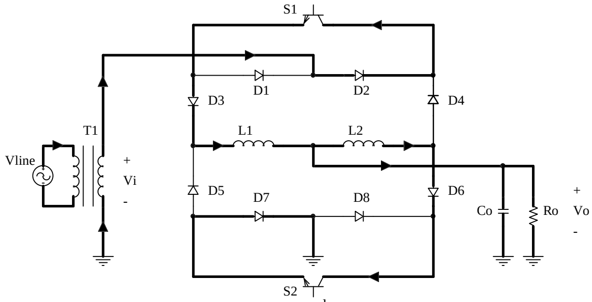

Fig. 9 – 2nd stage.

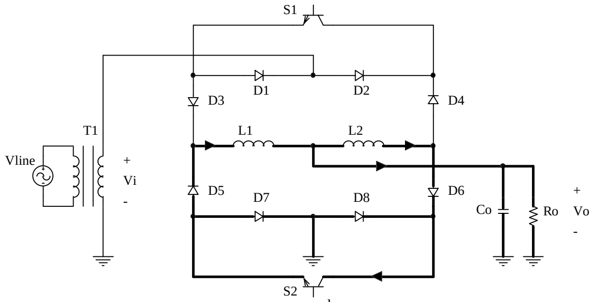

Fig. 10 – 3rd stage.

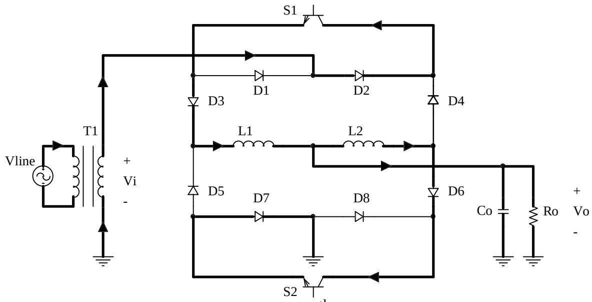

Fig. 11 – 4th stage.

$$V_o = V_{line} \cdot n_1 \cdot D \quad \text{Where} \quad n_1 = V_i / V_{line} \tag{6}$$

$$V_o = V_i \cdot n_1 \cdot D \quad \text{Where} \quad n_1 = V_o / V_o' \tag{7}$$

$$V_o = V_i \cdot \frac{1}{1-D} \tag{8}$$

$$V_o = V_i \cdot \frac{D}{1-D} \tag{9}$$

$$V_{Lavg} = 2 \cdot \Delta t \cdot f_s \cdot n_1 \cdot V_{line} \tag{10}$$

$$P_{Lavg} = \frac{2 \cdot f_s \cdot \Delta t^2 \cdot \left(n_1 \cdot V_{line}\right)^2}{L} \tag{11}$$

If this average power is not dissipated, it will cause an increasing of the current with a constant rate, provoking damage to the semiconductors. However, the inductor current, i_{L2}, is naturally limited by the semiconductors voltage drop and by the wire resistances.

IV. Simulation Results

In order to demonstrate the operation of the proposed topologies and validate the analytical study previously presented, the circuits shown in Fig. 3 to Fig. 6 were simulated, considering open loop operation.

The values of the parameters used were:

Variable\Fig.	3	4	5	6
V_i	220 V	220 V	110 V	220 V
V_o	220 V	220 V	220 V	220 V
n_1	2	2	-	-
P_o	1 kVA	1 kVA	1 kVA	1 kVA
L_1 e L_2	0.7 mH	0.7 mH	0.7 mH	0.7 mH
C_o	7 µF	7 µF	7 µF	7 µF
f_r	60 Hz	60 Hz	60 Hz	60 Hz
f_s	20 kHz	20 kHz	20 kHz	20 kHz
Δt	500 ns	500 ns	500 ns	500 ns

Fig. 12 shows the waveforms obtained from the converter presented in Fig. 3. It can be observed that the voltage over switches S_1 and S_2 have a good behavior, without voltage spikes.

It is also verified that the output voltage is at the desired value, which was obtained by using a duty cycle of 0.5.

The same comments are valid for Fig. 13 to Fig. 15, in which the waveforms for the Buck, Boost and Buck-Boost converters are presented.

V. Experimental Results

A laboratory prototype was built in order to verify the operation principle of some of the presented topologies. The converters presented in Fig. 1, Fig. 5 and Fig. 6 were implemented, each with a unity transformation ratio input transformer. In this manner, the operation of the topology shown in Fig. 3 was also verified.

The parameters used for the prototype were:

Variable\Fig.	V_i	V_o	P_o	Δ_t
1	220 V	110 V	1 kVA	500 ns
5	110 V	220 V	1 kVA	500 ns
6	110 V	110 V	1 kVA	500 ns

Variable\Fig.	L_1, L_2	C_o	f_r	f_s
1	0.7 mH	7 µF	60 Hz	20 kHz
5	0.7 mH	7 µF	60 Hz	20 kHz
6	0.7 mH	7 µF	60 Hz	20 kHz

Variable\Fig.	n_1
1	1
5	1
6	1

The experimental results are presented in Fig. 16 to Fig. 19. The output and input voltages and the current of the inductor L_1 are shown in Fig. 16 for the circuit of Fig. 1, Fig. 18 for the circuit of Fig. 5 and Fig. 19 for the circuit of Fig. 6. Fig. 17 shows the waveforms of the current through S_1 and the voltage across S_1 and S_2. It can be verified that voltage across the switches does not present spikes.

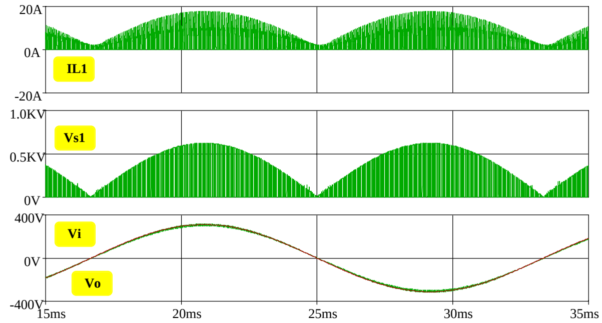

Fig. 12 – Simulation of the circuit of Fig. 3.

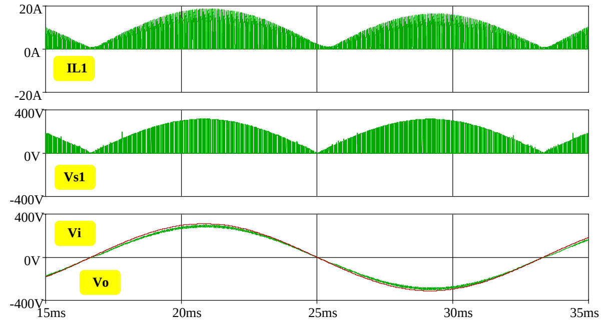

Fig. 13 - Simulation of the circuit of Fig. 4.

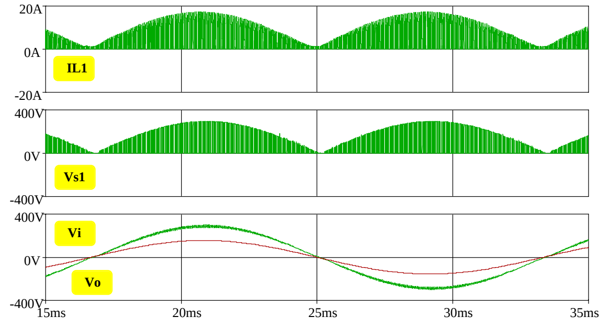

Fig. 14 - Simulation of the circuit of Fig. 5.

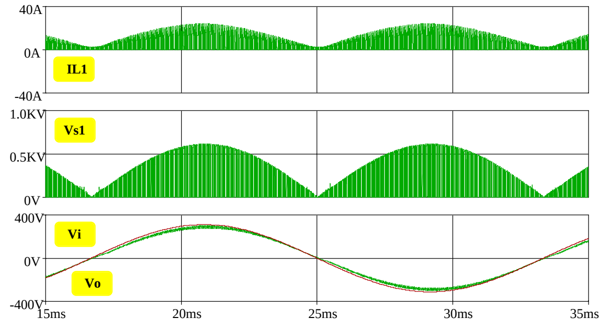

Fig. 15 - Simulation of the circuit of Fig. 6.

VI. Conclusions

In this paper, new configurations of Buck, Boost and Buck-Boost converter topologies were presented, for AC voltage regulator applications. The Buck converters were isolated with a transformer at input side or output side. Simulation and experimental results proved the correct operation of the proposed topologies.

It was verified that the overvoltage problem of the switches is solved by an overlapping command. This overlapping method causes an average voltage over the inductors, but can solved by placing small resistances in series with them.

The Buck-Boost converter has the best static gain range. However, the voltage over the switches is higher when compared to the Buck converter. The latter, even operating only as a step-down converter, is still the best solution for ac-voltage stabilizing applications even when operating with non-linear loads, due to the simplicity of its closed-loop control.

VII. Acknowledgements

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VIII. References

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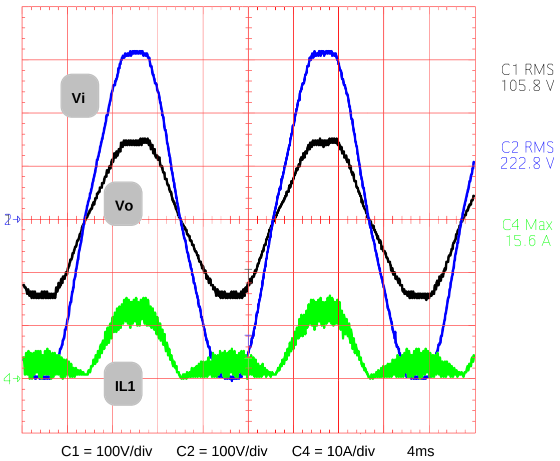

Fig. 16 – Results from Fig. 1.

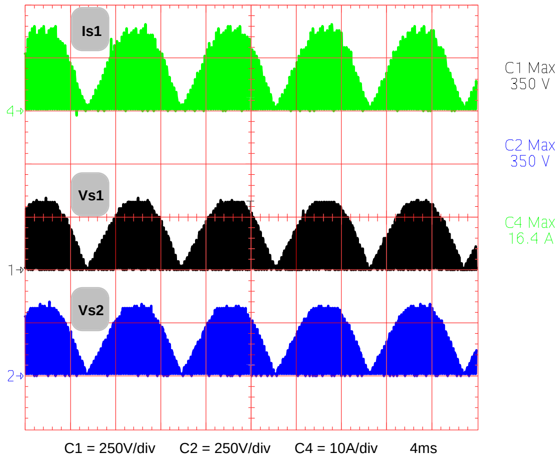

Fig. 17 – Results from Fig. 1.

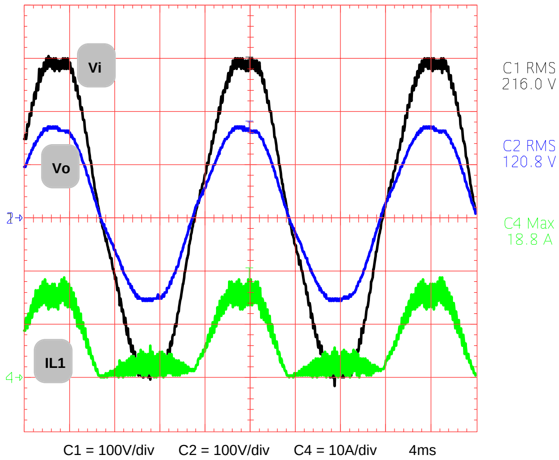

Fig. 18 – Results from Fig. 5.

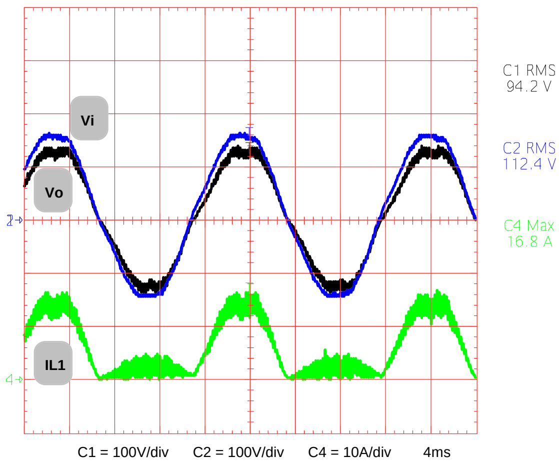

Fig. 19 – Results from Fig. 6.