Multi-Level Contactless Zero-Voltage Switching Rectifier as a Pre-Regulator in a DC Laboratory Power Supply

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***Abstract*— The paper describes a new method of voltage pre-regulation in laboratory power supplies. It is a multi-level rectifier in which it is possible to switch output voltage in jumps. Contactless switching at zero voltage is ensured by triacs. The control circuits are also described in the paper and measurements on the realized sample are presented.**

***Index Terms*—multi-level rectifier, contactless zero-voltage switching, DC Laboratory Power Supply**

I. Introduction

Nowadays it is an effort to increase the efficiency of electrical equipment. This will reduce power consumption and reduce radiated heat from the machine. As a result, heat dissipation materials can be saved, reducing the size and weight of the entire system.

For laboratory sources with linear stabilization, measures to reduce losses are of great importance, as sources without pre-regulators must have a cooling system designed to dissipate the heat output greater than the rated output.

Here is described non-traditional method of voltage pre-regulation, which is characterized by high reliability and low interference.

II. Current Status

Laboratory power supplies of low output power (tens to hundreds of W) are produced exclusively with a linear stabilizer because these sources are subject to high demands for low output noise, low electromagnetic radiation into the environment and requirements for sufficient speed regulation of output voltage or current. And the ability to achieve a fast response in both constant voltage mode and constant current mode does not allow the use of high-quality passive output filters with high attenuation on the switching frequency of the pulse sources since such a filter would cause a slow response of the controller to rapid load resistance change. [3]

However, linear stabilizers in laboratory power supplies have high losses P_T on the control transistor at low output voltage and high current load.

$$P_\mathrm{T} = (V_\mathrm{C} - V - R_\mathrm{S} \cdot I) \cdot I \tag{1}$$

V_C indicates the voltage on the capacitive filter, V indicates the output voltage, R_S is the short-circuit resistance through which the output current I flows.

It is evident from the Eq. 1 that if V_C is a constant voltage of sufficient magnitude to power the output stage at the maximum output voltage, by reducing the output voltage V and keeping the current drawn I constant, the losses on transistor P_T will increase.

For some sources (especially those with low output power) this problem is not solved at all and the resulting losses are converted into heat. For sources with higher output power a pre-regulator is placed in front of the transistor to reduce losses on the output transistor. This pre-regulator is typically solved in the following ways:

- Phase thyristor control
- Switching pulse pre-regulator
- Switching-mode power supply
- Relay switching of windings

[4]–[6]

The first three have the common disadvantage of continuous interference due to the hard switching of the semiconductor elements. It is necessary to filter the filters of several order and considerably shield. The most commonly used option is

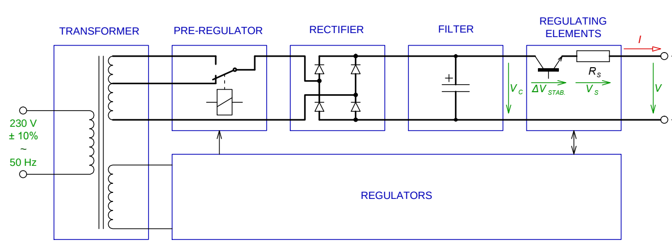
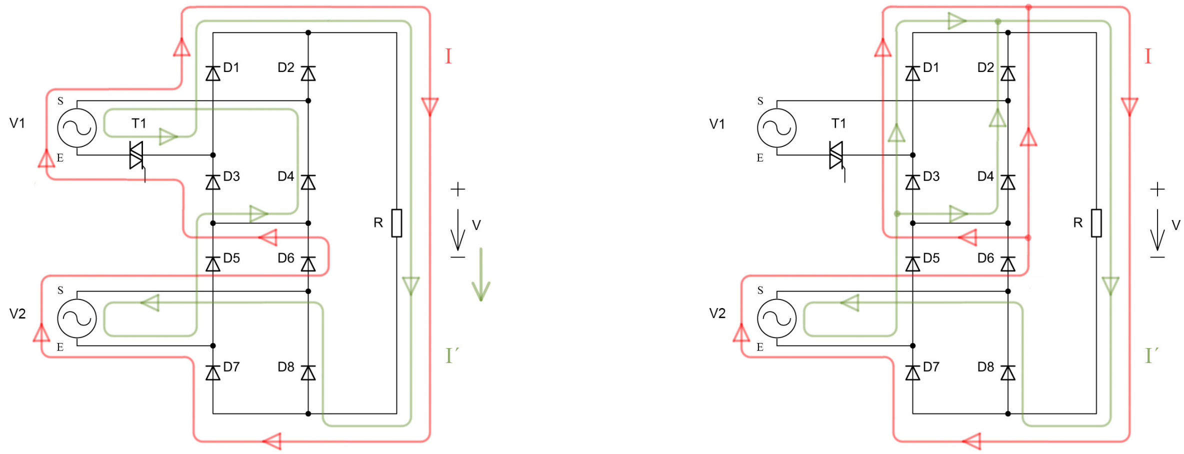


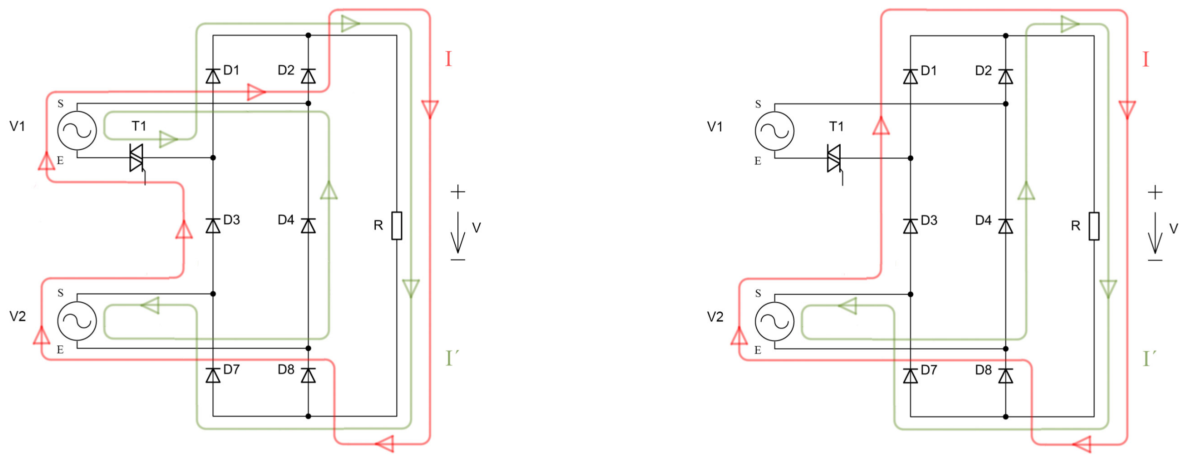
Fig. 1: Standard simplified scheme of DC laboratory power supply

switching the transformer taps by means of a relay, as shown in the Fig. 1. This is a very simple solution, but it also has many drawbacks.



(a) Switched on triac T1 (b) Switched off triac T1

Fig. 2: Contactless switching rectifier with indication of flow direction – topology 1



(a) Switched on triac T1 (b) Switched off triac T1

Fig. 3: Contactless switching rectifier with indication of flow direction – topology 2

The relay is an electromechanical element that can withstand significantly fewer switches than semiconductor switches. As the contact wear increases, the switch resistance in the closed state also increases and the switching reliability decreases. [1] Another disadvantage is the long response time and especially the non-constant on-time, making it difficult to synchronize the switching action with the input voltage. In addition, contact flickering occurs during switching. This causes sparking of the contacts and during switching it causes undesirable interference that penetrates the output of the source.

III. New Solution

A. Rectifier Principle

These weaknesses are solved by the proposed multi-level Contactless rectifier switched in zero. Basically, it is a sum rectifier whose output voltage is ideally proportional to the sum of the absolute values of the voltage of all input voltages. However, some windings of the transformer can be disconnected without interrupting the current by other transformer taps.

The design is based on the principle of series connection of rectifier bridges, which was used in power high-voltage controlled rectifiers. [2]

However, the controlled rectifier itself is not suitable for the laboratory source for the above reasons. However, it is advantageous to supply series-connected rectifiers with transformer taps, which are connected to the rectifier by contactless semiconductor switching elements at zero voltage.

As a result, there is no disturbance, either continuous or during transition processes. The principle of the basic non-optimized connection is outlined in the Fig. 2.

However, this circuit has the disadvantage of a voltage drop across the 4 diodes in series + voltage drop across the switching element. The first disadvantage can be eliminated by modifying the rectifier topology.

By interchanging the start and end of the winding, the middle junction wire can be omitted, resulting in a pair of diodes

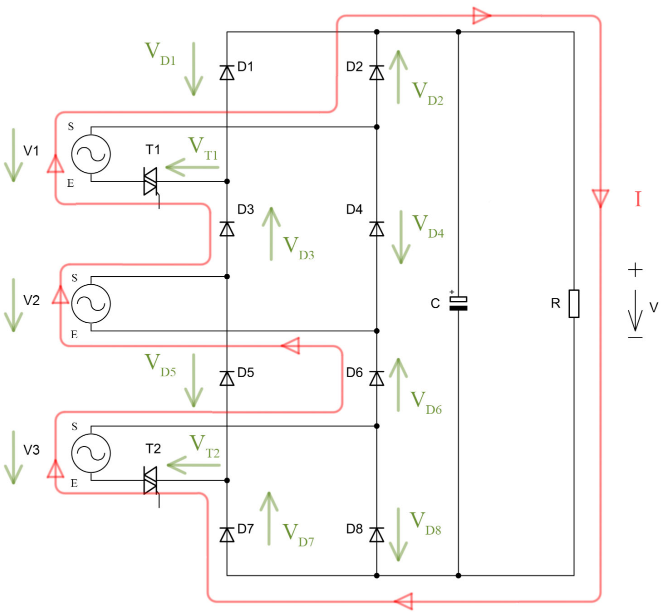


Fig. 4: Final topology of contactless switching rectifier

connected in series on each side of the rectifier bridge. One of these pairs can then be omitted, reducing the losses in the rectifier. The situation is clear from Fig. 3. In this case, 3 diodes in series are always active.

The rectifier can be extended to the other side in the same way. Thus, the transformer windings can be two. With suitable selection of secondary winding voltages, the winding can then be switched to produce 4 degrees of output voltage. Then 4 diodes in series are always active. Schottki diodes can be used to reduce losses on active diodes.

In the simplest case, triac can be used as an AC switch. It has a considerable voltage drop in the closed state. Thus, a pair of anti-series connected MOS-FET can be used to reduce the losses on the switching element. These, however, require a significantly higher control voltage than the triac for switching, so their use significantly complicates the switch driver.

The output voltage V is then given by the Eq. 2, where V_{Dx} indicates the forward voltage drop across the diodes and V_{Tx} is the voltage drop on the switched on semiconductor switches. (in this solution triac).

$$\begin{gathered} V = -V_{\mathrm{D2}} + \sqrt{2} \cdot V_1 - V_{\mathrm{T1}} - V_{\mathrm{D3}} + \\ \sqrt{2} \cdot V_2 - V_{\mathrm{D6}} + \sqrt{2} \cdot V_3 - V_{\mathrm{T2}} - V_{\mathrm{D7}} \end{gathered} \tag{2}$$

Assuming that all diodes and both switching elements are the same, the relationship can be simplified.

$$V = \sqrt{2} \cdot (V_1 + V_2 + V_3) - 2 \cdot V_{\mathrm{T}} - 4 \cdot V_{\mathrm{D}} \tag{3}$$

B. Rectifier Output Voltage Control

Control circuit requirements:

- It must ensure galvanic separation from switching elements, since switching elements are at a different potential (variable) than the ground of control circuits

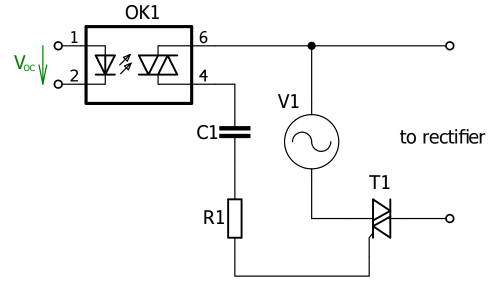


Fig. 5: Triac drive circuit

- Excitation voltage from circuit (without auxiliary sources)
- It must allow switching at or near zero voltage.

Galvanic separation is possible using optortiaks. However, using the standard optotriac-triac combination would cause the main triac to be switched on late, since the voltage drops at the semiconductor transitions are not negligible to the switched voltage. To ensure switching at exactly zero voltage, a capacitor is included in the excitation circuit, which stores energy from the previous period. Then the main triac can be switched on at a significantly lower winding voltage, thus avoiding steep switching. The triac excitation circuit is shown in the Fig. 5.

Due to the phase shift of the voltage to current in the excitation circuit, it is not possible to use an optotriac with integrated switching at zero, since the main triac would then be switched before zero crossing. Phase synchronization must therefore contain control circuits.

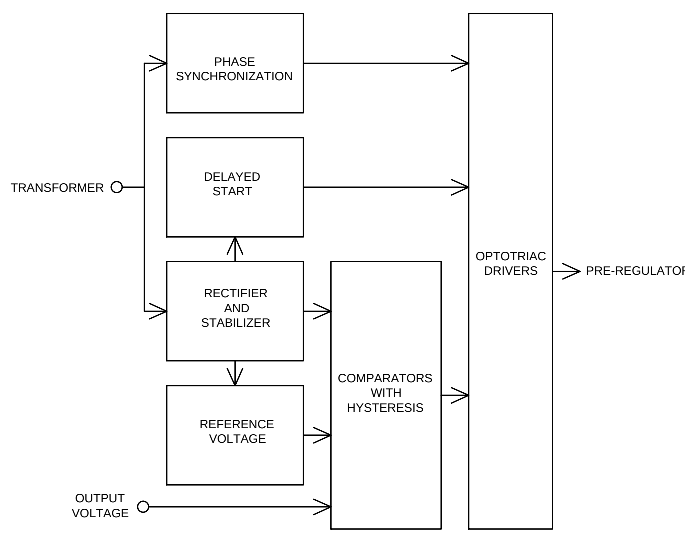


Fig. 6: Block diagram of rectifier control circuits

At the core of the rectifier control circuits are hysteresis comparators which select one of the four rectifier levels based on the source output voltage and the pre-regulator input voltage amplitude. Comparators must have an output level coded in binary code, so that if the voltage selection of individual transformer taps is properly selected, switching

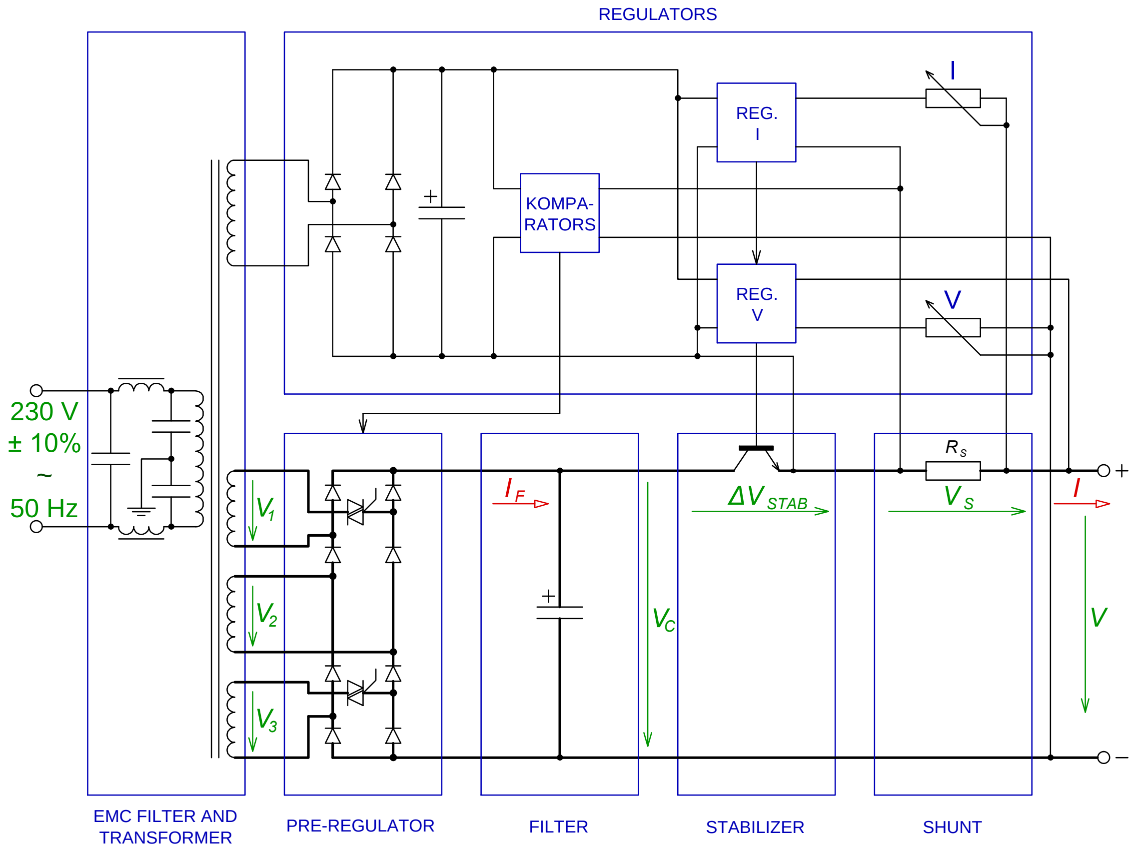


Fig. 7: Simplified scheme of DC laboratory power supply with new pre-regulator

of 2 triacs can ensure 4 output levels. It is therefore a two-bit A/D converter with defined hysteresis between transitions.

For the triac drive circuit to function properly, the control circuit output must have narrow pulses synchronized with the transformer sine waveform. The time course of the control pulses $V_{\mathrm{OC}}(t)$ and their time synchronization with the induced voltage on the transformer winding V_2 is shown in the Fig. 8.

IV. Use in a DC Laboratory Power Supply

A simplified circuit diagram of the DC laboratory power supply with the described pre-regulator and control circuits is shown in the Fig. 7. Both the control circuits and the power part are supplied from the common transformer. The described pre-regulator is connected to separate transformer windings. A linear regulator is powered from the pre-regulator through a filter. The connection of the linear regulator does not differ somewhat from the commonly used topology which is in the Fig. 1.

The switching diagram of the triacs and examples of voltage values in the power section for the individual rectifier levels are given in the Tab. I. Actual voltage values vary slightly depending on the output current of the power supply and the magnitude of the induced voltage on the transformer.

TABLE I: Example of output voltage

Level	T1	T2	V_{C}*	V
1			11.0 V	0 ÷ 8 V
2	•		18.5 V	7 ÷ 15.5 V
3		•	26.0 V	14.5 ÷ 22 V
4	•	•	33.5 V	21 ÷ 30 V

*Minimum voltage at full load.

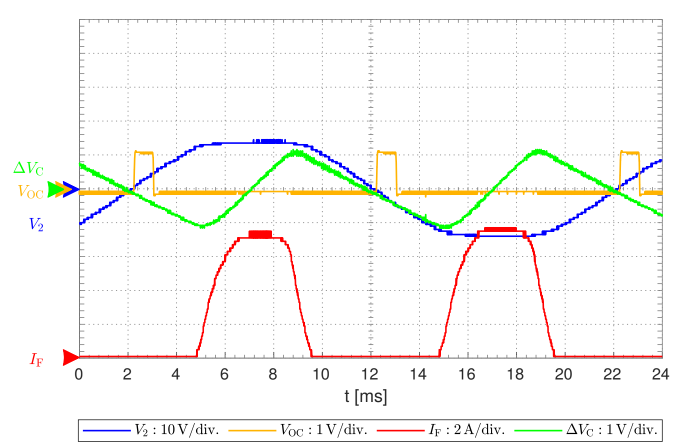


Fig. 8: Measured time courses in the pre-regulator – continuous mode

V. Results of Measuring

It can be seen from the measured time curve in the Fig. 8 that when the optotriac (V_{OC}) turns on, there is no current flowing through the rectifier. The current to the rectifier starts to flow after the rectifier diodes are opened naturally. The current pulse is smooth because the voltage slope on the capacitive filter is limited by the sine derivate at the diode opening. The ripple voltage on the capacitor filter V_{C} is sawtooth ripple.

The current spectrum I_{F} is shown in the Fig. 9. The main current component is 100 Hz and higher harmonics are only visible up to 2 kHz. Above this frequency the interfering components are already comparable to the noise of the probe (verified by switching off the instrument).

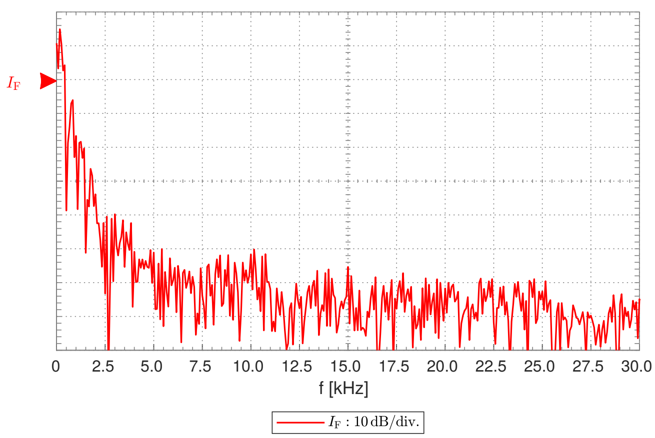


Fig. 9: Measured frequency spectrum in the pre-regulator – continuous mode

The activation process is shown in the Fig. 10. Before turning it on ($t \in 0 \div 50\,\mathrm{ms}$), the main filter was charged to $V_{\mathrm{C}} = 2\,\mathrm{V}$. After switching on, the filter always starts charging to the first level ($V_{\mathrm{C}} = 13\,\mathrm{V}$ no load). If the desired output voltage is set to a value greater than 8 V, the second level (22 V) will be set on after the value is reached first level.

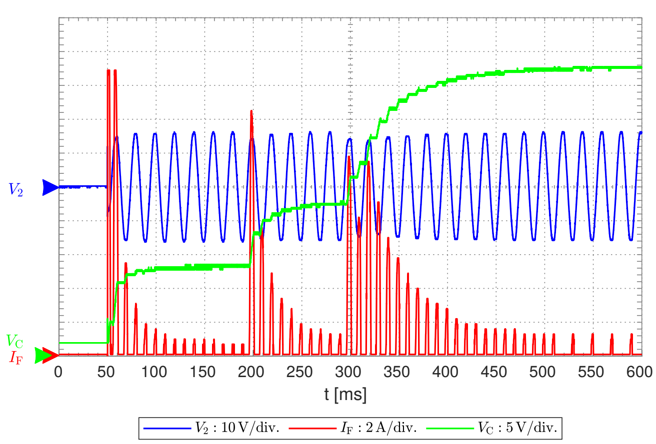


Fig. 10: Measured time courses in the pre-regulator – start mode

If the output voltage exceeds 15.5 V, it switches to the third level. Since the output is unloaded during power up, the output voltage reaches 22 V during the voltage increase on the filter after switching to the third stage. Thus, in the 8 graph, the third level is only for 20 ms (from 295 ms to 315 ms), after which it will switch to the fourth level.

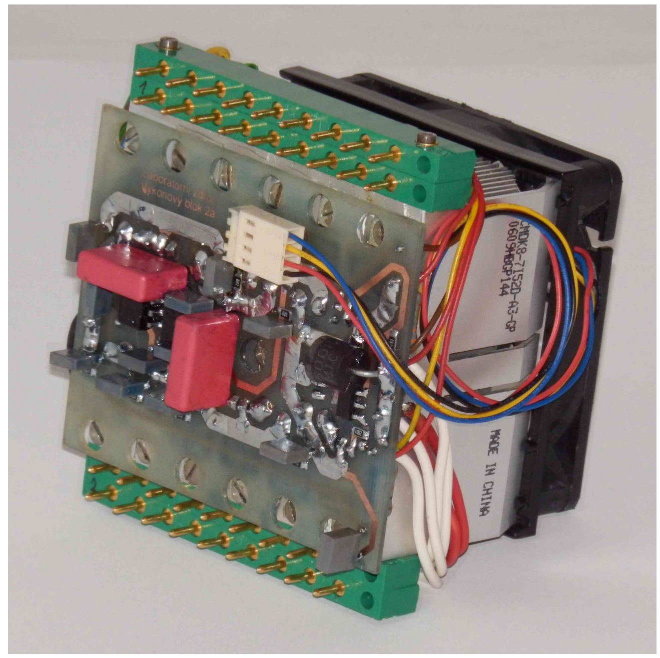


Fig. 11: Realized power block

Conclusion

The described type of pre-regulator has been thoroughly tested not only by a number of measurements, but also during operation by deployment in a newly built laboratory source. The whole pre-regulator with control transistors was realized as a standalone module, which is in the Fig. 11.

Due to the fact that the controller has 4 output voltage levels, losses on the output transistors are limited to an acceptable level. The switching elements do not introduce further interference into the circuit, and thus the output current has an output waveform comparable to a conventional diode rectifier. Uncontrolled interference does not occur even during transients. The solution does not cause any sound effects.

A minor disadvantage may be a higher voltage drop on the semiconductor elements in the pre-regulator. However, these losses only slightly increase power consumption when the output voltage is high.

Acknowledgment

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