

Optimization of efficiency of power electronic converter suited for electroplating

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ABSTRACT

This paper deals with optimization of full bridge converter with synchronous rectifier, used for electroplating. Main focus of the paper is on efficiency increase of power stage through reduction of conduction and switching losses on the secondary side of converter. First, losses and efficiency of the diode rectifier and synchronous rectifier are compared. Next the possible optimization steps are provided and experimentally verified through the experimental measurements. Several results show that efficiency increased when proper optimization steps were utilized.

1. INTRODUCTION

Switching power supplies for electroplating processes are characterized by low output voltage (tens of volts), which is comparable to the voltage drop of rectifying elements and large current output (thousands of amps). Permissible output current ripple is 2-5% of the average current. Ripple of the output voltage is 1%. Significant losses are caused by current flow through semiconductor structure for required parameters.

The goal of research is minimizing the switching power supply losses using of synchronous rectifier. It is necessary to use a transistor with low resistance in the conducting state of structure. It is also necessary to select an appropriate topology of the synchronous rectifier circuit with respect to the number of transistors. Very important part of topology is control of MOSFET transistors, which enables the transistor to conduct current from zero voltage UDS. Commutation failure is not acceptable. The paper describes the issue of power converter for electroplating processes, its control and also the principle of synchronous rectifier. It brings also experimental verification of the synchronous rectifier, efficiency comparison of power converter with synchronous rectifier and with diode rectifier, where

body diode of MOSFET transistor is used for rectification.[1]

2. REQUIREMENTS FOR POWER CONVERTER

All technological processes take place in an environment of galvanic baths of various sizes and designs. Their activities require (with some exceptions) power supplies of small DC voltage with high output currents. In the aspect of required performance we can divide resources for electrochemical applications to several categories. Power supplies with minimal performance (up to 1 kVA) are less important and used for technological processes like degreasing. Medium performance (up to 40 kVA) is typical for the metallization and small refinery links and big performance supplies (from 100 kVA) are used for large refining links and production of chlorine and aluminum.

Supplies specific characteristics depend on the character of electroplating techniques. It is a particular need for low output voltage, very high currents. The fact that the bath is a source of reverse voltage of variable level is important, too. For some technological processes, it is also necessary to allow change the polarity of the output voltage of power supply. Output current with minimal ripple allows achieve superior surface in most cases, ie. homogeneous layer of deposited metal. In the case of minimal current ripple of metalized material surface, liquid products are removed worse and we must remove it with additive surface washing. The optimal value of current ripple is topic of debates for years, but acceptable level of current ripple is set to 2-5% of current average value [1].

3. SYNCHRONOUS RECTIFIER

In synchronous rectifier, diodes are replaced with MOSFET transistors. Diodes must be engaged with

respect to the fact, that in presence of driving signal to the gate of transistor, this works in the third quadrant of the static output characteristics (Fig. 1).

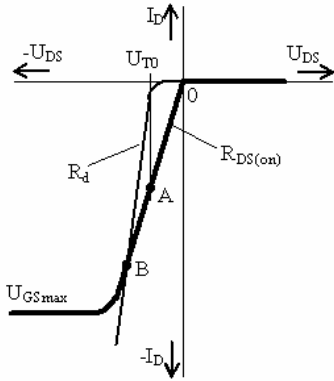


Fig. 1 V-A characteristic of MOSFET transistor and the body diode

In the third quadrant, the body diode is conductive, because it is polarized in forward direction. If the supply output voltage is polarized reverse, transistor works in the first quadrant of its static characteristics and transistor is closed. We can also see that the body diode is in the blocking state. MOSFET transistors are able to conduct current at zero voltage U_DS. This is not able in the diode due to its threshold voltage value.

Power losses of the MOSFET transistor for voltage drops from zero to the value of body diode threshold voltage, expresses the equation 1; losses from A to B are expressed in equation 2. These losses represent a voltage drop of synchronous rectifier:

$$\Delta P_1 = R_{DS(on)} \cdot I_D^2 \quad (1)$$

where:

$$\Delta P_2 = \frac{R_{DS(on)} \cdot R_d}{R_{DS(on)} + R_d} \cdot I_D^2 \quad (2)$$

The diode is characterized with permanent voltage drop due to its threshold voltage and the voltage drop due to the dynamic resistance R_d . Power losses of diode expresses equation 3:

$$\Delta P_3 = U_{T0} \cdot I_D + R_d \cdot I_D^2 \quad (3)$$

Fig. 2 shows a comparison of conduction losses for synchronous and diode rectifier.

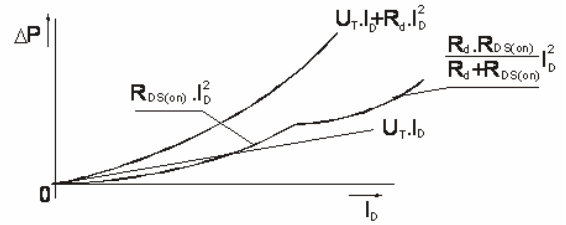


Fig. 2 Comparison of conduction losses

In addition to conduction losses, in semi-conductive structures we can calculate switching losses, control losses and loss in the rectifier commutation. These losses depend on the topology of the rectifier circuit. The energy required for charging and discharging of MOSFET input capacity generates control losses and they are increasing with increasing frequency.

3. CONTROL OF SYNCHRONOUS RECTIFIER

Basic topologies of synchronous rectifiers are derived from conventional. There are two types of control, external control and self-control of synchronous rectifier transistors. An example of external control is in Fig. 3. Control of synchronous rectifier MOSFET transistor contains control and driver circuit, which generates control signal. We must set precise timing of control signals, which is the most critical point of this work. Timing of control signals can be obtained by two ways. The first is to obtain control data from the primary side of converter, from control circuit of the converter. Galvanic isolation of control signal in the secondary side of converter from the primary one is needed. Precise timing of control signals to the gates of MOSFET is important. Additional control losses occur in the external control. The advantage of the external control is non-dependency of control signals due to load variations, simple gate protection and particularly accurate timing of control signals.

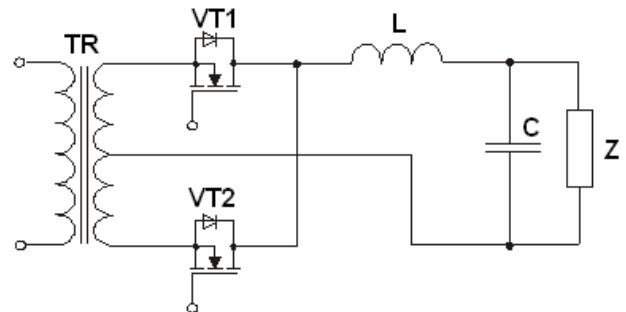


Fig. 3 Control of synchronous rectifier

In self-driven synchronous rectifiers voltage from secondary transformer side is directly used for transistor control. The self-driven synchronous rectifier is shown in

Fig. 4. With the power supply topology on the primary side of transformer the shape control curves are changing. Certain requirements are placed on the control curve.

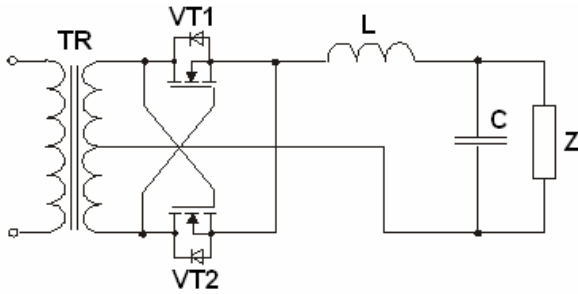


Fig. 4 Self-driven synchronous rectifier

The voltage levels must be high enough for safe switching of transistors, but not too high because of the security of the gates. Energy for control used to charge the parasitic capacity of MOSFET transistors can be used from the magnetizing or dispersion transformer inductance [1], [2].

4. OPTIMIZATION OF THE SYNCHRONOUS RECTIFIER CONFIGURATION

In previous chapter, the most generally used configurations of synchronous rectifiers are shown. As was mentioned such solution acts as very perspective idea for applications with high value of output current. Next figure shows dependency of converter's efficiency on output power/current. It can be seen that with the use of synchronous rectifier the efficiency rises by 7% at full load, what is valid for full operation range. This value can be further increased, when several optimization steps are acquired.

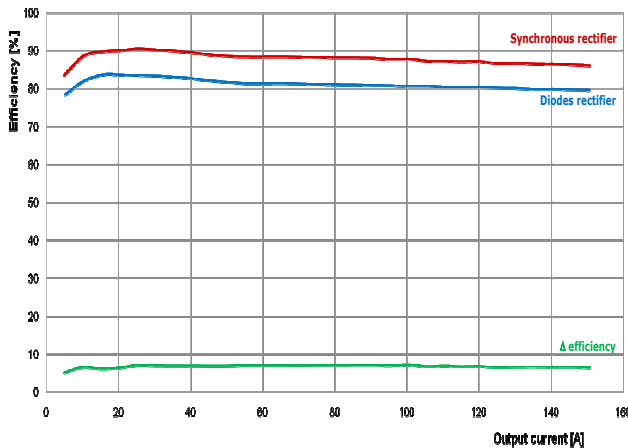


Fig. 5 Comparison of efficiency characteristics

We have been discovering various possibilities and for our purpose we found out next optimization steps:

- utilization of snubber circuit

- utilization of auxiliary diode
- utilization of spikiller

For these types, we have provided a lot of measurements, whereby main investigated parameter was efficiency. In next chapter we will show experimental results for various configurations of optimization proposals.

5. EXPERIMENTAL VERIFICATION

Experimental verifications were made on full bridge converter. Parameters of converter with synchronous rectifier are :

- Input Voltage 565 V
- Output Voltage 5 V, 10 V, 15 V
- Output Current up to 300 A
- Switching frequency 17 kHz

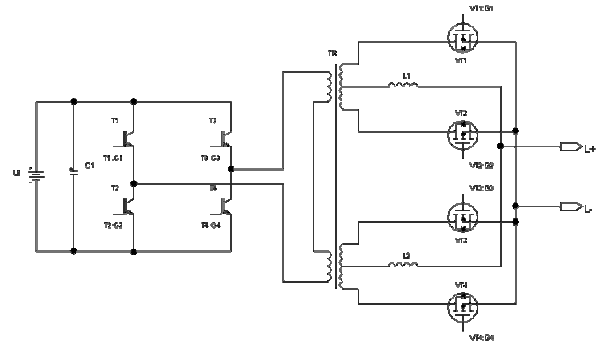


Fig. 6 Full-Bridge converter with synchronous rectifier

Fig. 6 principal schematic of power supply used for electroplating with the use of synchronous rectifier. The configuration is designed as current doubler, whereby several solution according to optimization process were connected to the transistors which are located on the secondary side.

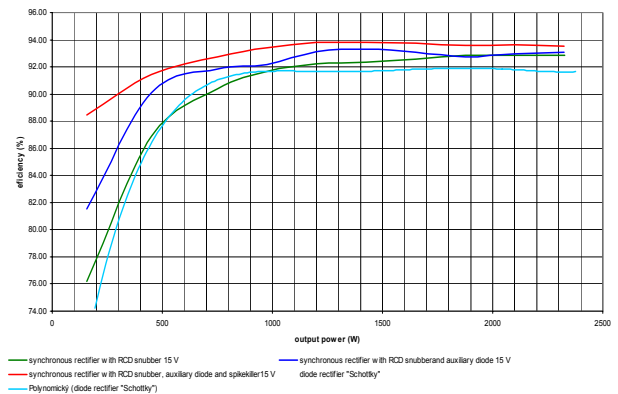


Fig. 7 Efficiency waveforms for various configuration of secondary rectifier for output voltage 15 V

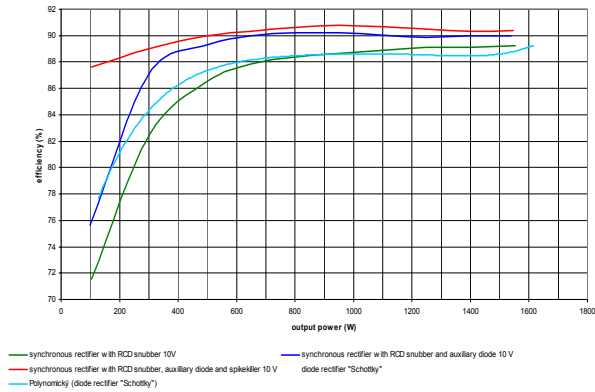


Fig. 8 Efficiency waveforms for various configuration of secondary rectifier for output voltage 10 V

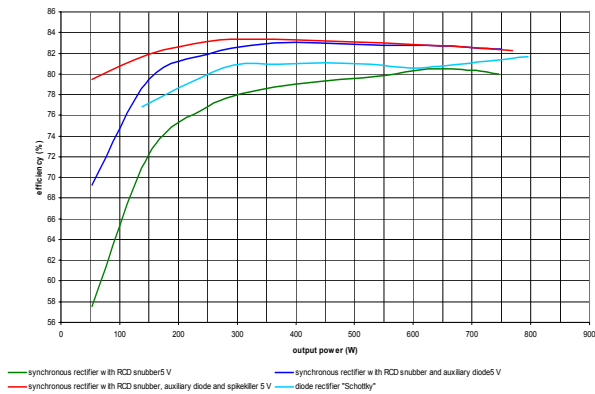


Fig. 9 Efficiency waveforms for various configuration of secondary rectifier for output voltage 5 V

For synchronous rectifier switches, one of the newest family of transistors from IR were used. It deals about MOSFET IRFS3004 with these parameters: $I_D=240A$ $U_{DS}=40V$ $R_{DS(ON)(MAX)}=1,25m\Omega$. Driving signals for synchronous rectifier were taken from main control board of full bridge part. These signals were galvanic isolated from primary part of converter, through high frequency driving transformer. As a driver, the new circuit was made, because commercial available circuits are not sufficient for our application due to high value of transistors input capacitance

Fig.7 to Fig.9 are showing results from the experimental measurements. the red line is efficiency waveform for the configuration of synchronous rectifier with RCD snubber, auxiliary diode and spikekiller. Blue line is related to efficiency waveform for configuration of synchronous rectifier with additional snubber circuit and auxiliary rectifier. Green waveform is valid for synchronous rectifier just with RCD snubber, and cyan waveform is related to diode rectifier. From previous results can be seen that efficiency is highly dependent on output voltage of converter. The lower the value of output voltage, the lower value of efficiency is. Anyway, important result is that with the use of combination of each optimization proposal, the efficiency reach very high values almost in the whole operating range (from 5% of output power up

to 100%). Therefore it can be said that optimization process has fulfilled its expectations. Next figure is showing experimental set-up.

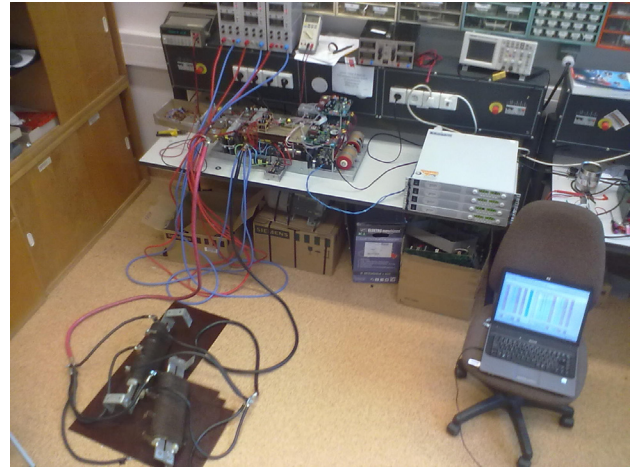


Fig. 10 Experimental set-up

Fig. 8 shows thermal images of devices used in rectifiers. The temperature of diode at 150A load was $101^{\circ}C$, while temperature of MOSFET transistor in synchronous rectifier was $61^{\circ}C$ at the same load.

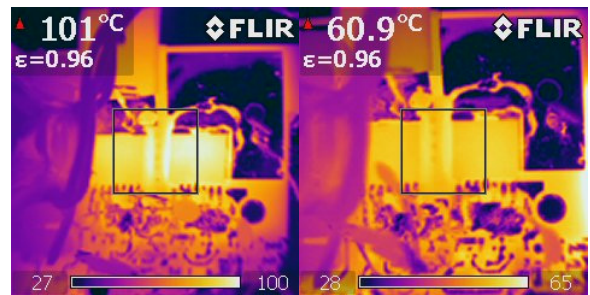


Fig. 11 Thermal image of diode (left) and synchronous rectifier (right)

6. CONCLUSION

The main goal of these experiments was increasing efficiency of switching power supply, using synchronous rectifier. Utilization of the synchronous rectifier is advisable for power supplies for electroplating, with switching frequency higher than 20 kHz. Increase of efficiency is approx. 7.3% if compared to diode rectifier. Used topology for this synchronous rectifier is suitable for high currents, because the current always flows through only one transistor to reduce the losses. The results of this experiment will help in the design of the source with output current of thousands of amps for electroplating industry.

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