Synchronous Rectification in High-Frequency MagAmp Power Converters

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Abstract: **The paper describes new approaches to high-efficient high-frequency power supply design for specialized computer systems, which require high load current at low output voltage. It is suggested to use semiconductor power converters based on high-frequency magnetic amplifiers. Paper shows the ways to increase converter's efficiency due to the use of a synchronous rectifier based on MOSFETs.**

Keywords: **high-frequency magnetic amplifier, synchronous rectifier, power converter, high level of the load current.**

I. INTRODUCTION

Modern specialized computer systems require high-quality and high-efficient power supply for their proper functioning. Reliability of such system is determined first of all by the reliability of its power supply. One of the peculiarities of specialized computer systems is that they consume high currents (dozens, often hundreds amperes) at low input voltage (3.3V, 5V, etc.) This results in strict requirements to power converters that are used as power supplies for such systems. They include high level of reliability, efficiency, specific power along with high quality of output voltage and its dynamic characteristics in the whole range of change of the load current. Moreover, operation of such power converters should cause the lowest possible level of both conductive and radiative electromagnetic interferences.

Nowadays, power supplies for specialized computer systems are realized as high-frequency power converters. Their efficiency is mostly defined with the operation modes of the high-frequency output rectifier, as the largest part of power converter losses at high level of load current is caused by the rectifier diodes.

Technical characteristics of modern rectifying diodes (including Schottky diodes) for low output voltage applications allow to provide satisfactory efficiency for high-frequency semiconductor low and medium power DC power converters.

With the appearance of high-frequency MOSFETs develops a new rectifier topology: synchronous rectifier. Its novelty consists in the use of a MOSFET instead of a rectifying diode, which is controlled in a function of voltage of high-frequency power transformer secondary winding (synchronously with this voltage) [1-3]. Works [4-7] describe digital solutions for synchronous rectifier control. The current paper introduces a simplified topology of a power converter with synchronous rectifier which does not require digital controllers.

Modern semiconductor component manufacturers specify MOSFETs for synchronous rectifiers as a separate category, and work on decreasing their channel resistance in the conducting state. For instance, this parameter equals 0.2 mΩ for recent synchronous rectifier MOSFETs by International Rectifier [8].

II. FUNDAMENTALS OF MAGAMP POWER CONVERTERS DESIGN

MagAmp is just a coil wound on a core of amorphous alloy with a relatively rectangular hysteresis loop (fig. 1) [9-11]. A MagAmp, used as a switch, can block and delay the applied voltage. However, MagAmp cannot interrupt the current once started. Hence, MagAmps are used in pulse circuits where they are assisted by diode rectifiers, which cut off the current as the applied voltage changes polarity.

When the voltage of negative polarity is applied to MagAmp, its core demagnetizes (corresponds to 1-2 slope in fig. 1; $t_1 \ldots t_2$ in fig. 2). The MagAmp core is unsaturated and due to high resistance there flows no current through its winding. When the input voltage changes its polarity to positive, MagAmp requires a certain volt-sec, which is the integral of voltage over time, to be applied to its terminals for the magnetic flux to build up in the core and reach the saturation level (interval 2-3 in fig. 1; $t_2 \ldots t_3$ in fig. 2).

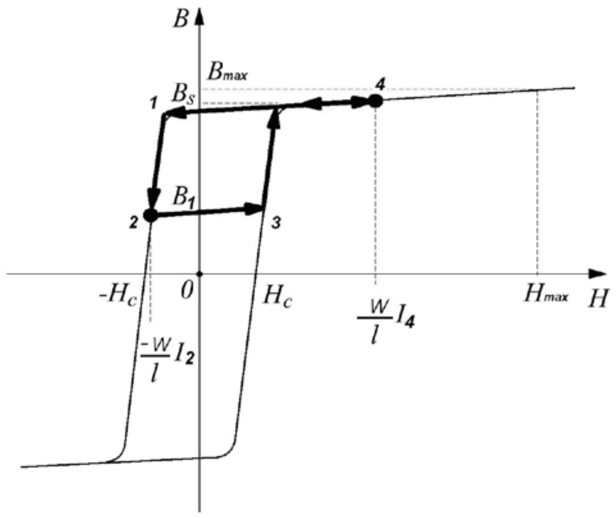

Fig. 1. Hysteresis loop of MagAmp core material

When the magnetic inductance reaches the saturation level (slope 3-4 in fig. 1), the MagAmp resistance approaches zero, which allows the current to flow trough MagAmp's winding (interval 4-1 in fig. 1; $t_3 \ldots t_4$ in fig. 2).

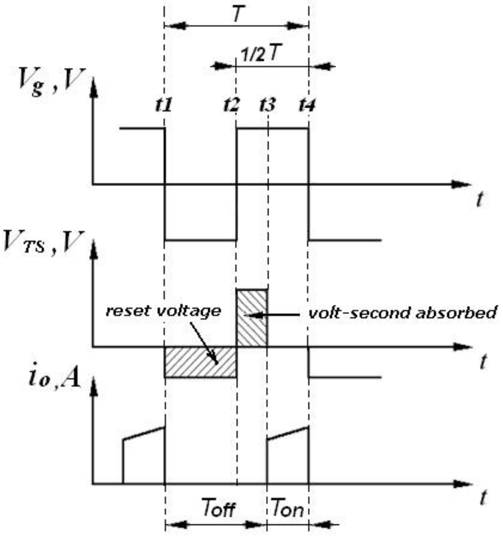

Fig. 2. Ideal MagAmp waveforms: V_g – transformer secondary winding voltage, V_{MS} – MagAmp switch voltage; i_o – MagAmp switch output current

In fig. 3 there is presented a functional scheme of a DC voltage regulator based on high-frequency magnetic amplifiers, which contains an unregulated high-frequency transistor voltage inverter 1, power transformer, push-pull centre-tapped rectifier, controlled MagAmps, output filter 2, load, control circuit 3, demagnetizing diodes [11].

However, providing a high level of output current in such voltage regulator is followed by the increase of losses on the diodes of high-frequency rectifier. This leads to a significant decrease of efficiency.

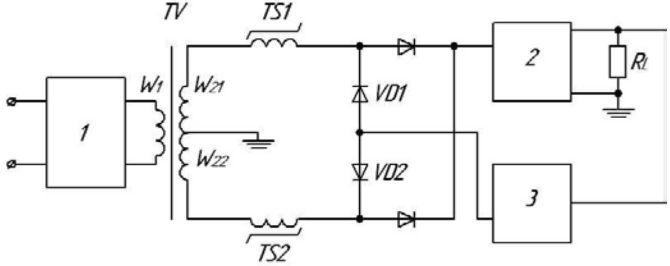

Fig. 3. Functional scheme of a DC voltage regulator based on high-frequency magnetic amplifiers

III. MAGAMP POWER CONVERTER WITH SYNCHRONOUS RECTIFIER

It is suggested to substitute diodes of the output rectifier with MOSFETs, with a possibility of their synchronous control from the respective high-frequency transformer secondary windings. The functional scheme of such power converter is shown in fig. 4 [12].

The DC voltage regulator operates in the following way. When the control half-period takes place, voltage of negative polarity is applied to the winding of MagAmp TS1. During this time interval, MOSFET VT1 of the high-frequency push-pull rectifier is in unconducting state (the voltage of negative polarity from the secondary winding W_{c1} is applied to its gate). Demagnetizing diode VD1 is conducting. Thus, the current flows through the control circuit 2, demagnetizing diode VD1, controlled MagAmp TS1, secondary winding W2 of high-frequency power transformer TV. This current is a function of the error signal obtained after comparison of regulator DC output voltage and reference voltage, and the change of the transformer secondary winding voltage due to the voltage change in the primary grid. The current causes demagnetization of MagAmp core from the saturation induction B_s to some induction B_1. The demagnetization depth is regulated with this stabilizing feedback. When the polarity of the input voltage changes to positive, remagnetization of the controlled MagAmp TS1 begins from the memorized level of induction B_1.When the controlled MagAmp TS1 operates in control half-period, the controlled MagAmp TS2 operates in a different mode – working half-period. During this time interval the rectifier MOSFET VT2 conducts (the voltage of positive polarity from the secondary winding W_{c2} is applied to its gate). The demagnetizing diode VD2 in not conducting. The current flows through secondary winding W2 of the power transformer TV, the winding of MagAmp TS2, rectifier MOSFET VT2, inductor L, capacitor C, load R_L. The working half-period consists of two subintervals. During the first subinterval the core of MagAmp TS2 remagnetizes from the memorized level of inductance to saturation inductance B_s. The time required for this remagnetization is considerably shorter than the demagnetization time of the control half-period due to no limitations of the remagnetization velocity (the load resistance is considerably smaller than the equivalent resistance of the control circuit). That's why the MagAmp core saturates within the half-period of the working frequency. During this time subinterval the current flows through inductor L, load R_L, and reverse diode VD3, the discharge current of the output LCD filter's capacitor C flows through the load R_L as well. After reaching saturation, the resistance of controlled MagAmp TS2 approaches zero, and the circuit current is defined with the load resistance R_L (second subinterval). Changing the depth of demagnetization of the controlled MagAmps TS1 and TS2 from $+B_s$ to $–B_s$ during the control half-period, we get the pulse-width modulation within a half-period of commutation high frequency during working half-period. This provides output voltage stabilization at change of the load current within its whole range. There also is a much lower level of losses in high-frequency rectifier due to significantly smaller resistance of channels of MOSFETs VT1, VT2 in conducting state, compared to the losses on diodes (when they are used in the rectifier) as a result of both direct voltage drop and, often, unsatisfactory frequency characteristics of diodes. Decrease of the equivalent resistance of the regulator allows obtaining higher level of load current along with high efficiency, if the operation modes of all topology components are agreed.

However, in such voltage regulator, the losses on the output filter reverse diode VD3 (about 1/3 of the load current flows through it) do not allow achieving maximum possible efficiency.

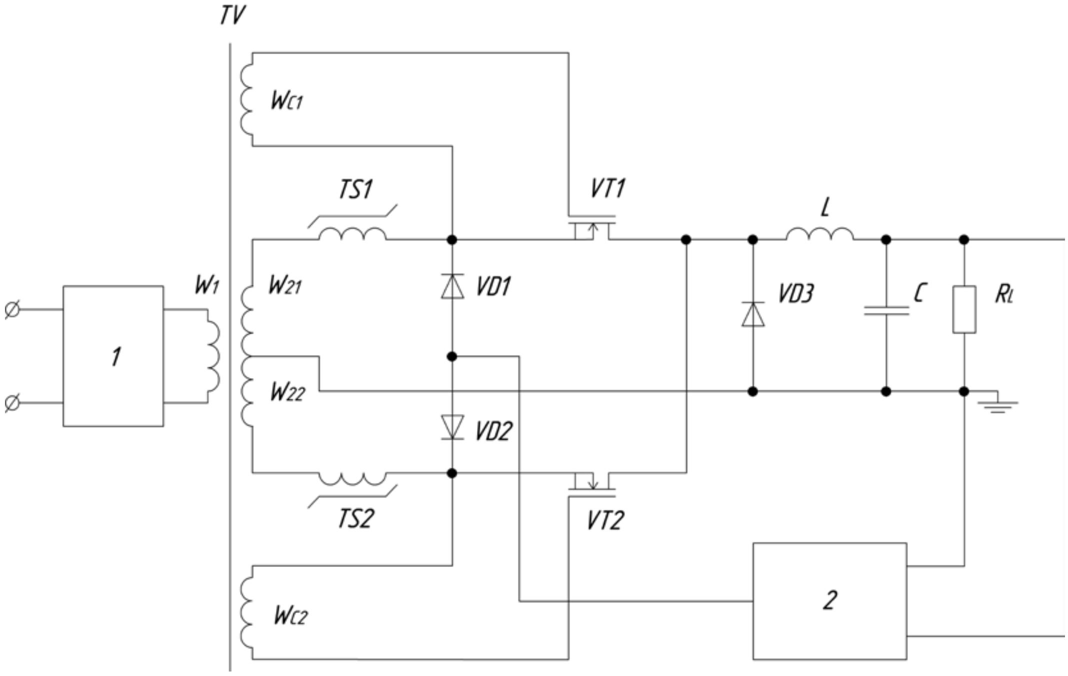

Fig. 4. The functional scheme of MagAmp power converter with synchronous rectifier

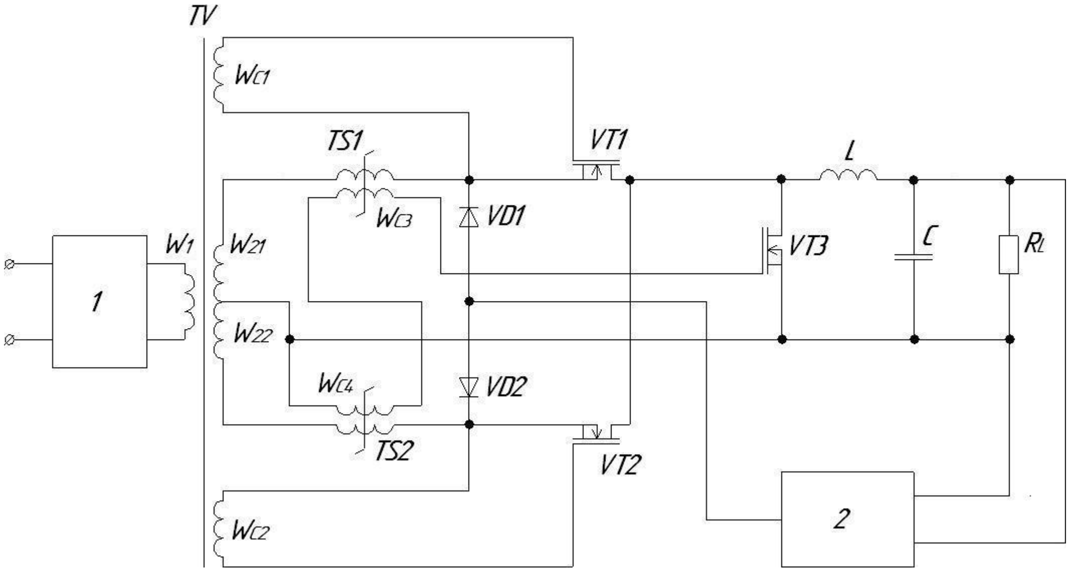

Fig. 5. The functional scheme of MagAmp power converter with synchronous rectifier with MOSFET instead of output LCD filter diode

It is suggested to substitute the output filter reverse diode with a MOSFET, that would be controlled in a function of voltages of additionally placed respective windings of controlled MagAmps.

The functional scheme of DC voltage regulator is shown in fig. 5 [13]. The waveforms that illustrate the principle of its operation are presented in fig. 6.

The advantage of using a synchronous rectifier in a power converter based on high-frequency MagAmps is that the load current starts flowing through it when its MOSFETs are already in conducting state. This is due to MagAmp operation principle. As a result, the converter's dynamic losses are decreased.

For instance, according to the experimental research, efficiency of the power converter based on high-frequency MagAmps with output parameters of 24V, 10A, where diodes have been used in the output rectifier and output filter, constituted 92% [14]. Its input active power was equal to 260.87 W. Which means the losses were equal to 20,87W, and about a half of those were the power losses in the output rectifier and filter. The use of MOSFETs with the open channel resistance of 0.2 mΩ in synchronous rectifier and output filter allows to significantly decrease these losses. The efficiency of such power converter is expected to be ≥95%. The efficiency tends to grow when designing power converters with higher output power.

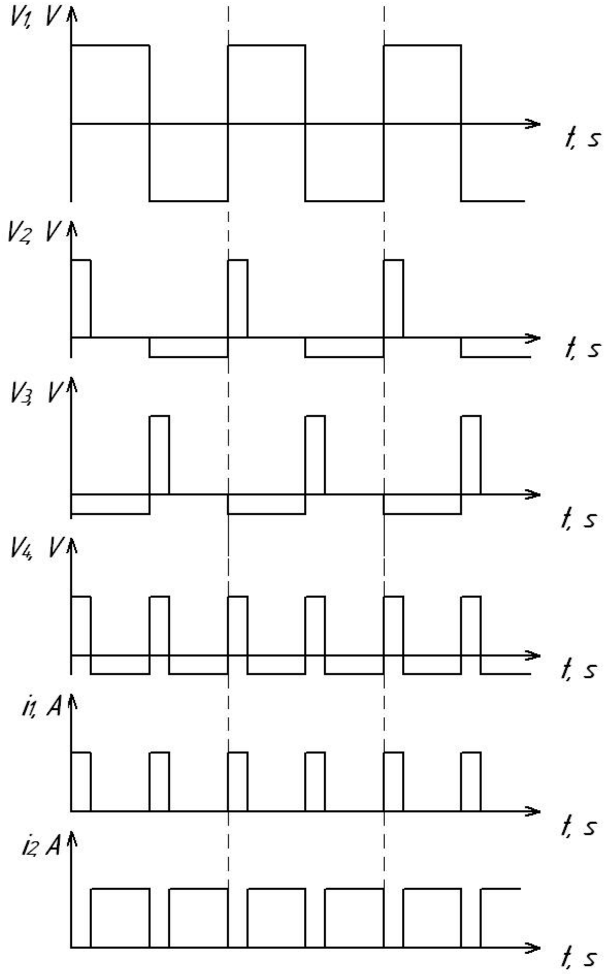

Fig. 6. Theoretical waveforms of MagAmp power converter with synchronous rectifier with MOSFET instead of output LCD filter diode

IV. CONCLUSION

Thus, the high level of load current along with high efficiency of the suggested DC voltage regulator are obtained due to:

1) the use of MOSFETs in the push-pull centre-tapped rectifier, which are synchronously controlled from the corresponding high-frequency power transformer secondary windings;

2) the use of MOSFET instead of reverse diode in output filter, which is controlled from the additionally placed corresponding windings of controlled MagAmps.

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