Energy-efficient half-bridge voltage converter for vehicle electrical systems

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***Annotation* – To increase energy efficiency, it is proposed to use semiconductor converters with a resonant topology, working with the soft-switching in the vehicle power circuits. The calculation method of a half-bridge resonant LLC converter is presented, the initial parameters and the results of the converter calculation by this method are given, based on the simulation, an analysis of the work is performed and the energy parameters of the converter are determined, its advantages are shown.**

Keywords – Resonant half-bridge converter, electrical equipment of transport, soft-switching, low power loss

I. Introduce

The development of existing, as well as the creation of new types of electric vehicles requires the improvement of power supply systems, reducing energy losses, which can be achieved by increasing the energy efficiency of semiconductor converters [1]. Almost any system uses power supply that convert the input voltage of a higher level to a lower voltage with the function of stabilizing the output current or voltage necessary to power control systems, auxiliary circuits, and battery charge [2].

It is known that one of the ways to increase the power density and improve the quality of electricity is to increase the operating frequency of the switching of semiconductor converters included in the power source. This entails a decrease in the overall dimensions of the power source due to a decrease in the size of the passive elements of the system, but it increases the dynamic switching loss for devices operating with "hard" key switching. Widely used circuits with pulse-width control with "hard" switched IGBT and MOSFET transistors have a limited conversion frequency. An increase in switching loss limits the frequency. In view of this, it is necessary to resort to the use of soft-switching of power semiconductor devices and resonant converter topologies [3].

II. Choose a topology of converter

The most attractive topology for the design and implementation of switching power supplies of small and medium power has a half-bridge resonant LLC converter with a serial resonant circuit. The converter, built according to this topology, provides high reliability with low dynamic losses when switching power transistors at high frequencies in a wide range of input voltages and large output currents [4].

A feature of this circuit (Fig. 1) is the resonant principle of switching transistors, in which the drain current and drain-source voltage at the time of switching are close to zero. The absence of current and voltage at the time of switching semiconductor elements leads to a reduction in losses.

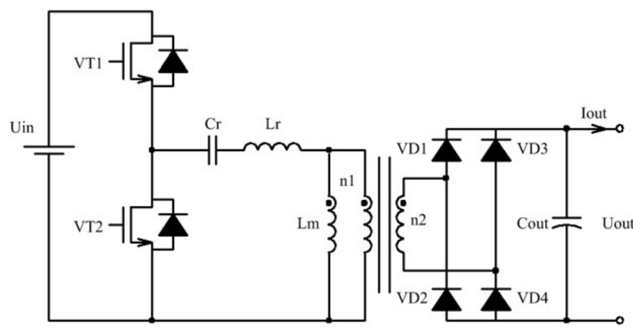

Fig. 1. Scheme of a half-bridge resonant converter with a series resonant circuit

The resonant inductor Lr and the resonant capacitor Cr are connected in series and form a resonant circuit connected in series with the load [5]. The resonant circuit and the load act as a voltage divider. When switching power transistors, the impedance of the resonant circuit changes. The input voltage Uin is divided between the resistance of the resonant circuit and the load resistance. Since this is a voltage divider, the direct current transfer coefficient is always less than one. At the resonant frequency, the impedance value of the series resonant circuit will be very small. All input voltage goes into the load. Thus, in a series resonant converter, the maximum gain occurs at the resonant frequency.

The installation of a inductor will certainly entail an increase in mass and dimensions, therefore, for devices with an output power of tens to hundreds of watts, the transformer dissipation inductance Lr is used, which should be 3-8 less than the magnetization inductance Lm. It is possible to achieve this effect by applying a partitioned method of winding transformer windings [6].

III. Operation Diagramm

For a deeper understanding of the principles of operation and calculation of the converter, we consider the process of current flow in the primary winding of the transformer at full load at the resonant switching frequency of the transistors, presented in the form of a graph in figure 2. At the initial time t < t0 the lower transistor VT2 is open [7]. The parasitic diode of the transistor VT2 is switched on in the forward direction, the parasitic capacitor of the transistor VT1 (output capacitance, Coss) is charged to the value of the input voltage supplied to the half-bridge. At time t0 – t1 both transistors are switched off. Is the recharge capacities of the transistors of the magnetization current. Due to the fact that this process must be completed before the dead time ends, the magnetization current must be large enough. At time t1 – t2, the transistor VT1 is switched on. The magnetization current is negative and flows through the internal parasitic diode of the transistor VT1 in the opposite direction. When the transistor turns on, the drain-source voltage will be close to zero. Switching occurs at zero voltage. At time t2 – t3 transistor VT1 is open. Energy is transferred to the load. The current of the resonance circuit is due to the influence of the resonance inductance and magnetization inductance and has a sinusoidal shape. The sinusoidal current of the resonant circuit flows through the transformer and forms a sinusoidal current on the secondary winding. At the end of the switching cycle, the current flowing through the diodes VD1 and VD4 will be zero. Switching occurs on the secondary winding of the transformer at zero current. At time t3-t4, the current in the primary winding of the transformer is due to the magnetization current. The parasitic capacitor of the transistor VT1 is charged, the parasitic capacitor of the transistor VT2 is discharged. Processes are repeated at time intervals back to the first half of the cycle.

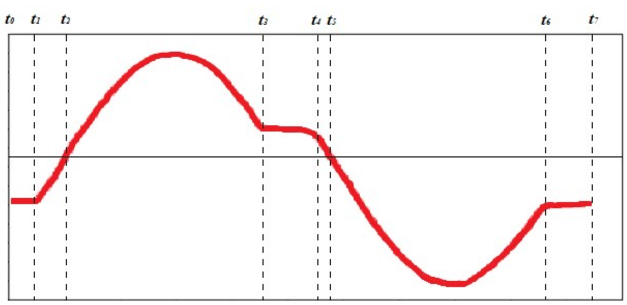

Fig. 2. Timing diagram of the current in the primary winding of the transformer

Next, we calculate a half-bridge resonant LLC converter [8] with a serial resonant circuit. According to the results, we will assemble a computer model of the converter and check the correctness of the work.

IV. Converter Calculation

The calculation is performed as follows. The equivalent load resistance (R_{ac}) on the primary winding of the transformer is calculated:

$$R_{ac} = \frac{8n^2}{\pi^2} \cdot R_{out}, \quad (1)$$

R_{out} – the value of the output resistance (load), n-coefficient of transformation.

Due to the presence of magnetization inductance (*Lm*) and scattering inductance (*Lr*) in the transformer, the resonance frequency is defined as:

$$\omega_p = \frac{1}{\sqrt{L_p C_{zvs}}}, \quad (2)$$

L_p - the sum of magnetizing inductance and leakage inductance of the primary winding of the transformer (L_{lkp}), C_{zvs} – the capacitance required for switching transistors at zero voltage [9], calculated by the following expression:

$$C_{zvs} = 2 \cdot C_{oss} + C_r, \quad (3)$$

C_{oss} – transistor output capacitance, C_r – capacitance value of the resonant capacitor.

The scattering inductance of the primary winding of the transformer is determined from the expression:

$$L_{lkp} = L_r - \frac{L_m (n^2 L_{lks})}{L_m + (n^2 L_{lks})}, \quad (4)$$

L_{lks} – the value of the scattering inductance of the secondary winding of the transformer.

The q-factor of the oscillating circuit is defined as the ratio of the characteristic (wave) resistance to the active:

$$Q = \frac{\sqrt{L_r / C_{zvs}}}{R_{ac}} \quad (5)$$

At a switching frequency close to the resonance, the q-factor of the oscillating circuit does not change when the load changes. Therefore, when operating at idle, the frequency change is minimal.

The voltage gain when the converter is operating at a resonant frequency does not depend on the load and is determined by the following expression:

$$M_{\omega=\omega_0} = \frac{L_m}{L_p - L_r} = \frac{L_m + n^2 L_{lks}}{L_m} = \frac{L_m + L_{lkp}}{L_m} \quad (6)$$

To simplify the transformation, we introduce the coefficient *k*, which is equal to:

$$k = \frac{L_m}{L_{lkp}} \quad (7)$$

Then we get the gain at the resonant frequency:

$$M_{\omega=\omega_0} = \frac{k+1}{k} = \sqrt{\frac{L_p}{L_p - L_r}} \quad (8)$$

When designing the converter, it is necessary to take into account that at the maximum input voltage, the minimum gain must occur at the resonant frequency. The k value must be selected to obtain the minimum gain. High gain can be obtained with a relatively small coefficient k, but this negatively affects the coupling of the primary and secondary windings of the transformer and reduces efficiency. Selecting k = 5 ... 10 provides a gain of 1.1...1.2 when operating at a resonant frequency.

With the selected factor k, the minimum voltage gain at the maximum input voltage is defined as:

$$M_{\min} = \frac{L_m + n^2 L_{lks}}{L_m} = \frac{L_m + L_{lkp}}{L_m} = \frac{k+1}{k} \quad (9)$$

The maximum voltage gain is equal to:

$$M_{\max} = \frac{U_{in\max}}{U_{in\min}} \cdot M_{\min} \quad (10)$$

The transformation coefficient is equal to:

$$n = \frac{N_p}{N_s} = \frac{U_{in\max}}{2(U_{out} + 2U_F)} \cdot M_{\min}, \quad (11)$$

U_F – output diode voltage drop.

The capacitance of the resonant capacitor is determined by the formula:

$$C_{zvs} = \frac{1}{2\pi \cdot Q \cdot f_0 \cdot R_{ac}} \quad (12)$$

The scattering inductance is determined by the following expression:

$$L_r = \frac{1}{(2\pi \cdot f_0)^2 \cdot C_{zvs}} \quad (13)$$

The inductance of the primary winding of the transformer is:

$$L_p = \frac{(k+1)^2}{(2k+1)} \cdot L_r \quad (14)$$

Using the formulas (1-14), the calculation of the half-bridge resonant transducer was performed. The initial parameters for the calculation are presented in table 1. The calculated values of the Converter parameters are given in table 2.

Table 1. The initial parameters for the calculation.

Name of parameter	**Value**
Minimum input voltage (U_{inmin}), V	350
Nominal input voltage (U_{inmnom}), V	380
Maximum input voltage (U_{inmax}), V	400
Nominal output voltage (U_{out}), V	24
Nominal output current (I_{out}), A	5
Resonant frequency (f_r), kHz	80

Table 2. Calculated values of parameters of a semi-bridge resonant transducer with a serial resonant circuit.

Name of parameter	**Value**
Coefficient (k)	7
Minimum voltage gain (M_{min})	1,143
Maximum voltage gain (M_{max})	1,306
Transformation ratio (n)	9
Equivalent resistance (R_{ac}), Ohm	314
Quality factor (Q)	0,505
Resonant Capacity (C_r), nF	8,2
Leakage inductance (L_r), uH	329
Inductance of the primary winding of the transformer (L_p), uH	1406

V. Modeling Results

To verify the calculation methodology and analyze the operation of the converter, computer simulation was performed. The model was developed in the LTSpice environment taking into account the models in Matlab / Simulink [10]. The advantage of the LTSpice program is that it integrates a library with ready-made PSpice models of real elements. The simulation results are as close as possible to those that will be when using these elements in the finished device.

A computer model of a half-bridge resonant LLC converter is shown in figure 3. Transistors are used as power switches R6020PNG (C_{oss} = 2 nF), output diodes – diodes Schottky RBR30NS30A.

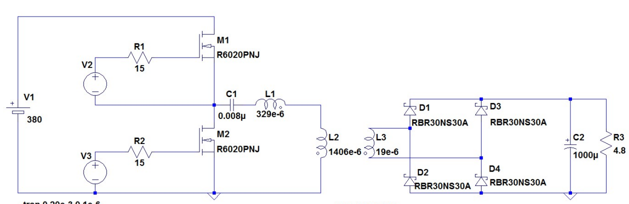

Fig. 3. Computer model half-bridge resonant LLC converter

Figure 4 shows the output waveforms of the voltage and current of a half-bridge resonant LLC converter. It can be seen from the graphs that the voltage stabilizes at +24 V at an output current of 5 A. A bridge rectification circuit is selected as the output rectifier, because when applying this circuitry solution, the transformer design has only one secondary winding, which greatly simplifies its calculation and design and winding styling.

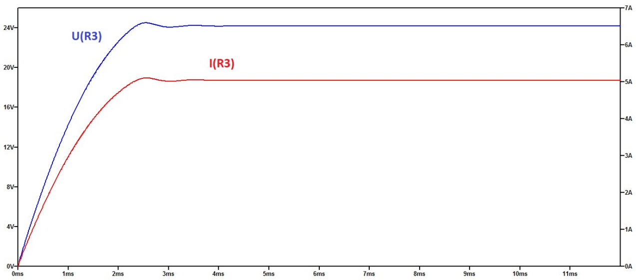

Fig. 4. The form of output voltage and current converter

The shape of the current through the transistor and the drain-source voltage are shown in Figure 5. From the graphs it can be seen that the transistor is turned on at the moment when the drain-source voltage is absent. This leads to the fact that the transistor operates with minimal power loss.

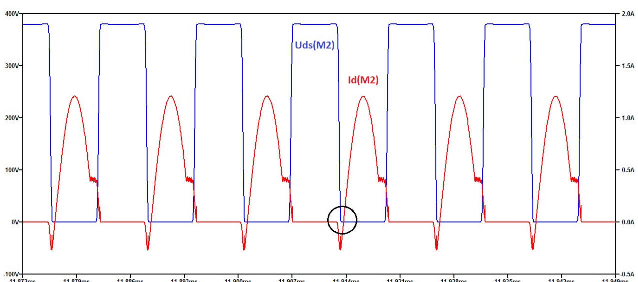

Fig. 5. The form of voltage and current on the transistor at the time of switching

Figure 6 shows a graph of the current through the primary winding of the transformer. The current has an almost sinusoidal shape. In this mode of operation, the transformer does not overheat, the level of electromagnetic interference is much lower than in converters operating on the principle of “hard” switching of transistors.

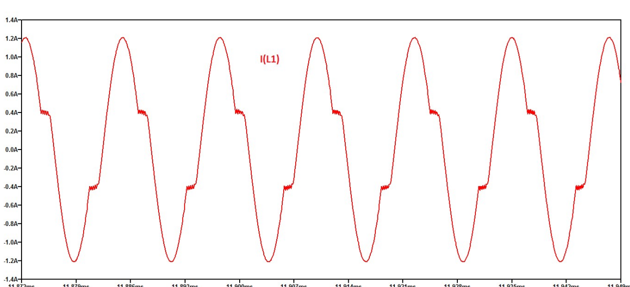

Fig. 6. The form of current throuth the primary winding of the transformer

Figure 7 shows the average power values at the load (left) and in the input circuit (right). Converter efficiency is 96.45%.

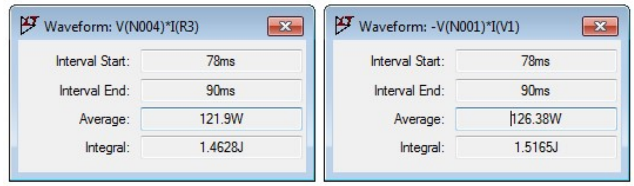

Fig. 7. The values of power on the load and power consumed from the network

VI. Conclusion

Modeling of a half-bridge resonant LLC converter in the LTSpice environment shows that the parameters of the resonant oscillatory circuit calculated by the above method allow achieving soft-switching of transistors when operating at a given load. Switching transistors occurs at a time when the drain-source voltage is zero, which significantly reduces the power loss on the semiconductor elements.

According to the above methodology, the calculations of the converters for power up to 6.6 kW were performed. Experimental studies have shown that the use of a transformer dissipation inductance as a resonant inductor at an output power of more than 1 kW is impractical due to the enhanced proximity effect and increased additional losses in conductors. To reduce losses, it is necessary to increase the distance between the windings, which leads to an increase in the overall dimensions of the transformer and complicates its calculation.

The use of the presented converter, as well as power sources having a similar topology, will significantly increase the energy efficiency of electrical equipment for passenger, general industrial, and special vehicles, increase the power density in a unit volume, and also achieve acceptable thermal operating modes of devices with minimal dimensions.

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