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Solid State Transformer for Connecting Consumers to the Medium Voltage Network

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***Abstract*—In this paper the authors describe and analyze an innovative solution for the development of an electronic transformer (Solid State Transformer - SST) with the voltage 10.0/0.230 kV. The transformer is designed to provide direct power to low-voltage consumers from the medium voltage network with the 50 Hz frequency. The proposed transformer permits bidirectional energy exchange. In order to stabilize the low voltage output, an original method has been adopted to manage the parameters of the control pulses for the transistors of the SST inverter. The primary winding of the high frequency transformer consists of 16 coils connected separately by means of two transistors. The design simplification of the transformer leads to the increase of energy efficiency indicators of the transformer and helps to reduce the high harmonics of the voltage and current in the power distribution network with a positive impact on power quality. It becomes possible to use this equipment to connect renewable energy sources, for example, the so-called micro-grids, to centralized power network of medium voltage.**

***Index Terms*—micro-grids, converter, power flow, SST electronic transformer, low-voltage stabilization.**

I. Introduction

The advancement of energy efficiency has been stated as a priority at an international scale, including in the field of electricity. According to [1], 70 % of primary energy resource potential is lost before it reaches the final consumer, and approximately 10 % of the energy that reaches the consumer is converted into useful work (for example, the light) and only 15-20 % of the fuel energy is transformed into mechanical torque of the vehicle. Because the electric power reaches the final consumer through the electric lines, it becomes obvious the need to solve the problem of energy loss associated with the transmission and distribution process.

According to the conclusions of international experts, losses of electricity of 4-5 % in the transport and distribution of electricity can be considered acceptable, and the level of about 10 % tolerable, taking into account the physical processes in electrical networks [2-4].

Losses in power networks are caused for technological reasons, deviations from the designed operating mode and commercial causes. Losses in electric power lines have the most significant proportion, of about (64-66) % [4], [5] of the total losses under load mode.

In order to decrease these losses, the following measures can be adopted: the increasing of the share of energy delivered from medium voltage networks (10, 20 kV); modernization of distribution networks by decreasing the length of portions of low voltage (0.4 kV); use of insulated wires with increased cross sectional area; compensation of the reactive power; use of individual power distribution transformers from medium voltage networks with the nominal power (6-10 kW) [6], [7]. These measures have already proved to be practical to use with the confirmation of their effectiveness in USA, Japan and EU.

The extension of such practices for the connection of the consumers by means of individual transformers mounted on pillars seems to be useful for the Republic of Moldova aiming to minimize losses within the distribution networks. However, we must mention that some transformers used in the USA and Japan for these purposes operate at the industrial frequency and have rather large mass and sizes per unit of installed power. In this context, the solution to substitute the transformers with classical construction with the so called electronic transformers with considerable smaller mass and sizes seems very promising [8], [9]. The electronic transformers known as Solid State Transformers (SST) usually have a working cycle with multiple stages of electric power conversion [10-14]. As a result, it becomes necessary to use multiple functional blocks, which naturally leads to higher volume equipment and higher manufacturing costs.

As an obvious trend in manufacturing of SST transformers one can indicate the use of SiC type transistors as semiconductor devices with technical indicators of increased performance, but at prices higher than the MOSFET transistors. So the increased costs may limit the wide spread of SST equipment in the medium voltage networks for direct power distribution.

The aim of the paper is to propose, describe and estimate the technical performance indices of the innovative solution to create an electronic single phase transformer type SST with 10/0.230 kV input/output voltage and active power in the range of 10-20 kW with bidirectional transfer of power.

II. The Problem Statement

It has been well known a set of solutions for the realization of converters of the type AC/AC [15], [17], which include more semiconductor devices (active elements), as well as passive elements: resistors, coils of inductance [17], filtering and commutation capacitors, transformers with multiple sectioned coils, diodes, high frequency alternating current rectifiers, low frequency

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converters [16].

The disadvantages of such solutions are as follows.

Firstly, they include a big list of active and passive elements, some of them being operated for a given period of time of working cycle, performing just one function.

Secondly, some of the semiconductor devices operate only at high or low frequency. This leads to complicating the electric scheme of the electronic device, to the increase of losses, mass and dimensions of the AC/AC equipment.

In the known converters the semiconductor devices of alternating current usually work in active commutation mode [17], that has as a consequence the increase of energy losses and leads to the decrease of efficiency. In other known solutions the conversion cycle includes more stages as AC/DC, DC/DC, DC/AC. As a result of these, the indicated concept of these devices realization is considered to be a costly one.

This paper examines a technical solution for the realization of the solid-type transformer realized in the single-step concept of energy conversion, which allows the simplification of the electrical scheme with the reduction of the production costs and the energy losses as compared to the known solutions [9-12].

In order to achieve this goal, it is necessary to examine: the electrical scheme of AC/AC type converter; the operation mode of converter; the simulation of the operation regime of the AC/AC converter; making and testing the physical model.

III. THE TECHNICAL SOLUTION AND THE OPERATION PRINCIPLE OF THE CONVERTER

The convertor's electrical scheme

The converter of alternating voltage current into alternating voltage current (see Fig. 1) includes an alternative current source 1 connected with a number of 16 coils 3, as parts of the primary winding [18]. The coils 3 and the circuits formed of the capacitors 2 and semiconductor devices 4 and 5 are a functional element of the primary circuit of the transformer 7. Capacitors 2 execute the filter function for superior harmonics. The semiconductor devices 4 and 5 provide the energy transfer mode from low to high frequency. The energy transfer is carried out by the voltage converter, which includes one high frequency transformer 7, executed with air gap. This has a secondary coil 6 connected in series with a semiconductor device 8 and with the upper harmonics filter 9. In parallel with this filter a second supply source 10 is connected. Each semiconductor devices 4, 5 and 8 of alternating current is made of two transistors connected in opposite sense. All transistors contain shunt diode circuits.

The operation mode of convertor

There are two modes of operation of the converter when applying control pulses 21, 22, 23 and 24 (see Fig. 2) for semiconductor devices 4, 5 and 8. The first one is assured by adjusting the length of pulses 23 and 24 to the semiconductor device 5. The energy from alternating current source 1 in this mode has to stock in the magnetic field of the frequency transformer 7 and this regime is called "fly-back". The second mode is assured by adjusting the length of pulses 21 and 22 to the semiconductor device 4. In this regime the energy from the alternating current source 1 is transferred directly into the source 10 and this regime is called "forward".

Let us now analyze the operation of the converter on the positive duration of the sinusoidal signal of the source 1 (see Fig. 1).

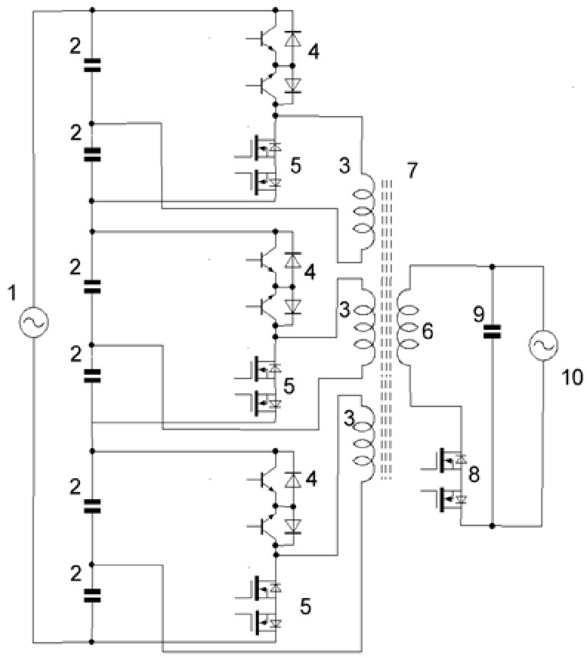

Figure 1.The equivalent electrical scheme of the converter of AC/AC type.

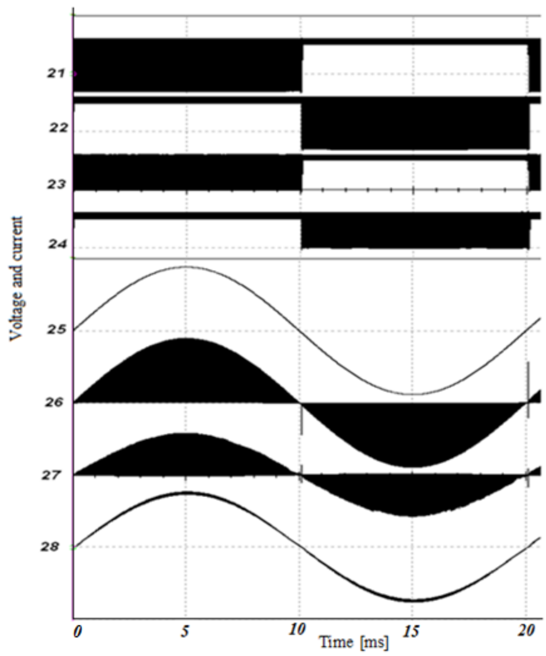

Figure 2.The control signal diagram of semiconductor devices for the convertor`s output voltage. The following notations were used for the applied signals: 21- at the upper transistors of the semiconductor devices 4 and 8 (two transistors connected in series; the grouped transistors are composed from one upper transistor and one bottom transistor); 22- at the bottom transistors of semiconductor devices 4 and 8; 23- at the upper transistors for semiconductor device 5; 24- at the bottom transistors for semiconductor device 5; 25- the current for medium voltage source 1; 26- the voltage in the common connection node of semiconductor devices 4 and 5; 27- the voltage in the common connection node of semiconductor devices 8, secondary coil 6 and high frequency transformer 7; 28- low voltage output of transformer in 10 (Fig.1).

When the sine signal reaches the zero value, the control

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pulses 22 and 24 (see Fig. 2) are applied to the bottom transistors of semiconductor devices 4, 5 and 8. These transistors are opened. In this case in the process of energy transfer from element 1 to the element 10 will be used only the upper transistors of semiconductor devices 4, 5 and 8 of the AC circuit.

We will consider that the voltage of alternating current sources 1 and 10 are sinusoidal. The analysis of the operation of the converter will be done for the positive wave of the sinusoidal signals.

The control pulse 32 (see Fig. 3 for t_0) is applied to the upper transistor of the semiconductor device 5, which opens this transistor. Following the opening of this transistor, there appears the circuit that includes source 1, the filter of superior harmonics 2, the primary coil 3, the semiconductor device 5 and the alternating current source 1. Under the influence of source 1 in this circuit will appear a current (see Fig. 3, curve 35), that ensures the energy transfers from source 1 to the magnetic field of high frequency transformer 7. This process will continue until the end of the control pulse 32 (see Fig. 3 for t_1) and the closing of the semiconductor device 5. The control pulse width 32 is determined by the relation:

$$\tau_{32} = T - \tau_{31},$$

where: τ_{32} - duration of control pulse applied to the semiconductor device 5; τ_{31} - duration of the control pulse applied to the semiconductor device 4; T - period of high frequency pulses, which values are determined by the frequency range 10 - 100 kHz.

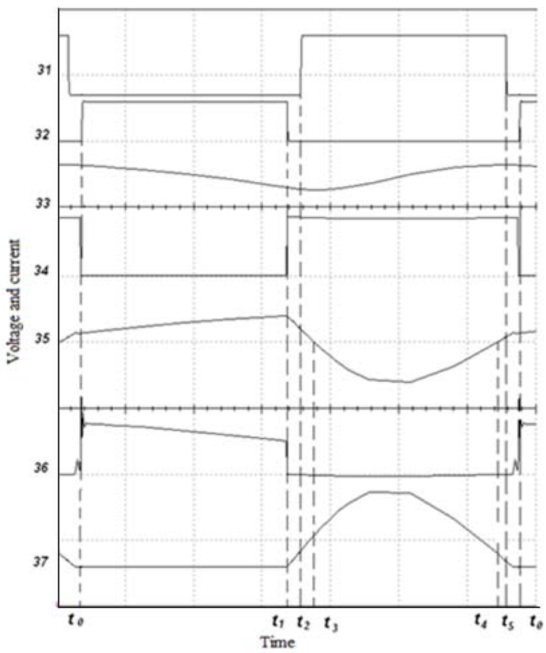

Figure 3.The diagram of commutation processes of semiconductor devices for the commutation mode when crossing zero value (ZCS mode), where notices are used: 32 - the shape of the control pulse applied to the semiconductor device 5; 33 - the shape of the voltage curve in the common connection node of the upper harmonics filters 2, inside the section N (see Fig. 1); 34 - the shape of the voltage pulse in the common connection node of the semiconductor devices 4 and 5 (Fig. 1); 35 - the shape of the pulse current flowing into the primary coil 3 of the high frequency transformer 7 (Fig. 1); 36 - the shape of the current pulse flowing into the primary coil 3; 37 - the shape of the voltage pulse in the common connection node of the semiconductor device 8 and the secondary coil 6 of the high frequency transformer 7 (Fig. 1)

The ratio of voltages of alternating current sources 1 and 10 depends on the ratio of control pulses width 31 and 32 applied to the semiconductor devices. In the case of deviation of the voltage value of the main source 1 (for example, from the nominal value 10 kV), one can receive the stabilization of low-voltage output of source 10 (for example 230 V) by changing the ratio of control pulse width 31 and 32 (Fig. 3). In order to obtain the stabilization of voltage output of source 10, the control pulse width 31 applied to the semiconductor device 4 will not change and the function of stabilization is assured by adjusting the control pulse width 32 applied to the semiconductor device 5.

When closing the semiconductor device 8, of the alternative current circuit, there will result two circuits. The first one includes the primary coil 3, the diode from the upper transistor which is part of the semiconductor device 4, medium voltage source 1, superior harmonics filter 2 and primary coil 3 of the high frequency transformer 7. The second circuit includes the secondary coil 6, the upper transistors diode of the semiconductor device 8, alternative current low voltage source 10 and secondary coil 6 of the high frequency transformer 7. The first circuit assures the limitation of commutation value of voltage of semiconductor devices under the limit of voltage of the alternating current source 1 (see Fig. 2, curve 26). The second circuit assures the transfer of energy stored in the magnetic field of the high frequency transformer 7 to the source of alternating current 10 (in this case the source 10 serves as a load).

When the upper transistor of semiconductor device 5 is closed, the control pulse 31 is applied to the upper transistors of semiconductor devices 4 and 8, the transistors have to open and make a short circuit for the upper diodes of semiconductor devices 4 and 8 (see Fig. 3 for t_2). This does not affect the process of energy transfer from the magnetic field of high frequency transformer 7 to the alternating current source 10.

When the current of primary coil 3 changes its polarity (see Fig. 3 curve 35 for t_3), the second mode of operation of converter begins (“forward” mode). Simultaneously with the process of energy transfer from the magnetic field of high frequency transformer 7 to the alternating current source 10 the new process begins. This process transfers the energy from the alternating current source 1 (through the circuit, composed of the source 1, the semiconductor device 4, the primary coil 3, the filter of superior harmonics 2, the source 1 and the circuit of the secondary coil 6 of high frequency transformer 7) to the alternating current source 10. It takes place until the current in the primary coil 3 (Fig. 3 curve 35 for t_4) changes its polarity.

In the following moment the control pulse 31 applied to the upper transistor of semiconductor device 4 comes to an end (see Fig. 3 for t_5). As it can be seen (see Fig. 3, curve 34 for t_4 and t_5) the commutation and closing process of upper transistor of semiconductor device 4 occurs at a voltage equal to zero, so the losses of energy decrease which leads to the increasing efficiency of the convertor. Beginning with the moment t_0 the new control pulse 32 is applied to the semiconductor device 5 and the process of operation of the convertor repeats in the new working cycle until the instantaneous value of voltage of alternating current source

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1 decreases to zero (see Fig. 2, curve 25).

The transition to the negative alternating voltage of the sine wave signal of the source 1 (see Fig. 1) takes place in the zero point of the sine wave voltage of the source 1 (see Fig. 2, curve 25). For the bottom transistors of semiconductor devices 4, 5 and 8 the control pulses 22 and 24 come to the end (see Fig. 2) and the control pulses 21 and 23 are applied to the upper transistors of the same semiconductor devices (4, 5 and 8), which open these transistors. During the negative sine wave in the process of energy transfer from source 1 to the source 10 only the bottom transistors of semiconductor devices 4, 5 and 8 will take part. The process of semiconductor device commutation is similar to the case of positive sine wave.

IV. The Simulation Results of Operation Regime of AC/AC Converter

Based on the diagram presented in Fig.1, an MULTISIM model was developed to simulate the operation of the single-phase transformer at active load. Electronic controlled semiconductor devices, type IKW25N120H3 (in Fig. 1, notation 4) and C2M0160120 (notations 5 and 8) with rated voltage 1,200V were selected. The IKW25N120H3 transistors have better performance indices in the opening mode and the C2M0160120 transistors in the closing mode (when the circuit breaks).

Another purpose of the simulations was to estimate disturbances in the current and voltage curves of the transformer due to its high frequency operation as well as to assess the impact of the C_{f2} capacitance on the output signals of the transformer SST 10/0.230 kV.

Parameters of passive elements RLC and diodes of the simulation model of the transformer SST 10/0.230 kV are shown in Fig. 4. In order to simplify the simulation model of the transformer SST 10/0.230 kV, in MULTISIM software, the transistors Q4, Q5 and Q8 of the type C2C0160120 were used (Fig.4).

The mathematical model of the transistor C2C0160120 was taken from the manufacturer's site. The simulation of the operation mode was carried out aiming to verify the quality of the commutation processes of the semiconductor devices in the commutation regime passing through zero (ZCS), drawing the output current and voltage curves, including the deviation of voltage in the power supply network (10 kV). The zero voltage switching of the transistors is considered in order to ensure minimal losses [19], [20]. The operating diagrams for transistors of the converter are shown in Fig. 3.

In Fig. 5 are presented the curves of input voltage U_1, output voltage U_2, input current I_1 and output current I_2 for a resistive load (RLOAD1) and for different values of the filtering capacitor (for superior harmonics) in the output circuit of transformer.

The absorbed current from the network is of approx. $I_{1.nom}$ = 2 A at the voltage of 10 kV and in the nominal power mode, the injected current in the load at the voltage of 0.230 kV is of approx. $I_{2.nom}$ = 90 A. Electronically the transformer is programmed with the limitation mode of short circuit current (SC) at the level of approx. $I_{SC} = 1.2 * I_{2nom}$.

Based on the simulation results, it can be stated that the energy quality in the primary circuit of the transformer is not affected. The use of relative small capacities ($C2$ = 0.25 μF) ensures good filtration of superior current harmonics occurring during operation of Q4 and Q5 electronic switching devices. The distortion of the voltage and current curves in the mains is not practically visible.

Considering the simulation results one can state that the quality of the energy in the primary circuit of the transformer is not affected, the distortions of the voltage curves, as well as the current curves in the power supply network are not noticeable.

When connecting in parallel with the load R_{LOAD1} (Fig.1), a condenser C_{f2} with the capacities of 1.0 μF and 4.0 μF, there will result a significant decrease of the output signal distortion of the transformer (Fig. 5b, 5c).

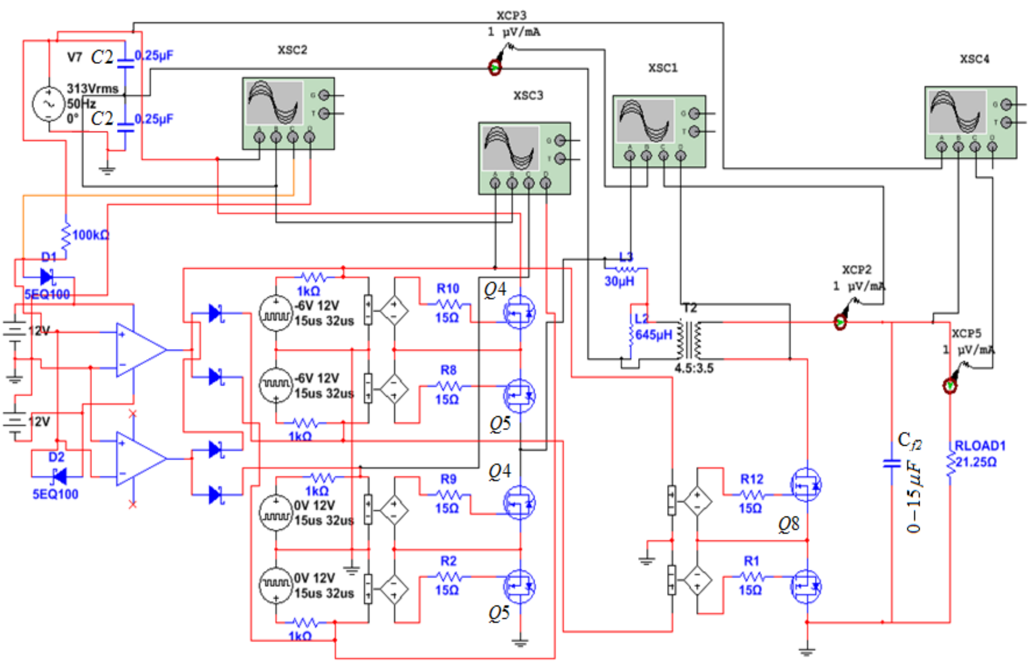

Figure 4.The converter model in MULTISIM medium

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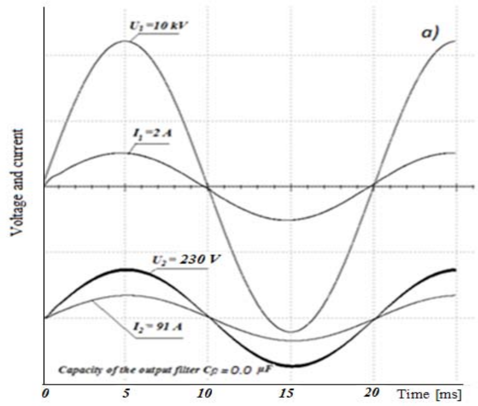

Figure 5a. The curves of voltage and current of the transformer for different values of the capacitance of filtering capacitor C_{f2}=0.0 μ*F* (*a*)

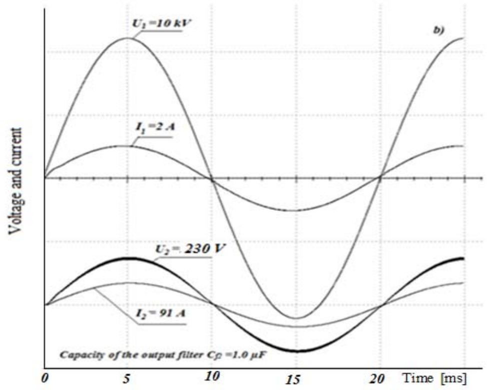

Figure 5b. The curves of voltage and current of the transformer for different values of the capacitance of filtering capacitor C_{f2}=1.0 μ*F* (*b*)

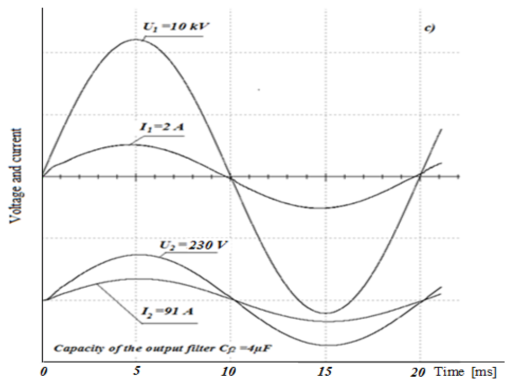

Figure 5c.The curves of voltage and current of the transformer for different values of the capacitance of filtering capacitor C_{f2}=4.0 μ*F*(*c*)

V. The Results of Experimental Tests

According to the proposed solutions, the laboratory sample was manufactured and a software control algorithm was developed using the microcontroller AT90PWM312.

In Fig. 6 is presented the constructive realization for the ferromagnetic element of the high frequency transformer 7 (78,125 kHz) with the apparent power S = 20 kVA.

Taking into account the basic concept of manufacturing the electronic transformer, such a treatment of the methodology of performed tests do not affect the essence of the operation process.

At the stage of tests of robustness of the equipment all coils of the primary winding were connected in parallel. The aim of a connection was to perform the first tests at the nominal voltage for one coil of the transformer in the laboratory conditions, as well as to comply with the requirements of labor security. The purpose of these tests was to experimentally verify the soft switching of electronic devices at different loading quota of the SST 10/0.230 kV transformers. The theoretical switching curves are presented in Fig. 3. These curves were considered as standard signals.

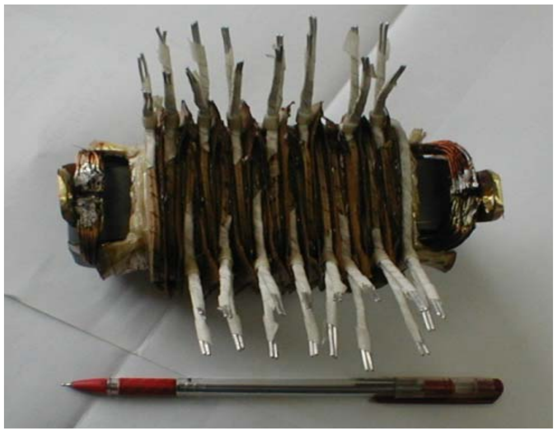

Figure 6. The picture of laboratory sample of high frequency transformer

From the diagrams shown in Fig. 7a-7c we can confirm that the commutation process of semiconductor devices takes place in the resonance regime of currents for all the range of variation of active load in domain 0 to 20 kW.

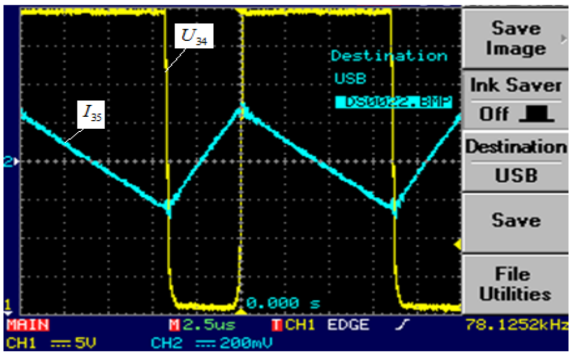

Figure 7a.The voltage U_{34} and current I_{35} of semiconductor devices in idle running mode, where notices: U_{34} - the shape of the voltage pulse in the common connection node of the electronic devices 4 and 5 (Fig. 1); I_{35} - the shape of the pulse current flowing into the primary coil 3 of the high frequency transformer 7 (Fig. 1)

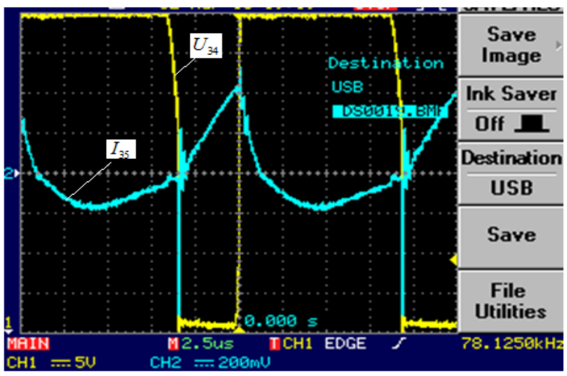

Figure 7b.The voltage and currents of semiconductor devices at a load equal to $P = 0.33P_{nom,}$ where notices: U_{34} - the shape of the voltage pulse in the common connection node of the electronic devices 4 and 5 (Fig. 1); I_{35} - the shape of the pulse current flowing into the primary coil 3 of the high frequency transformer 7 (Fig. 1)

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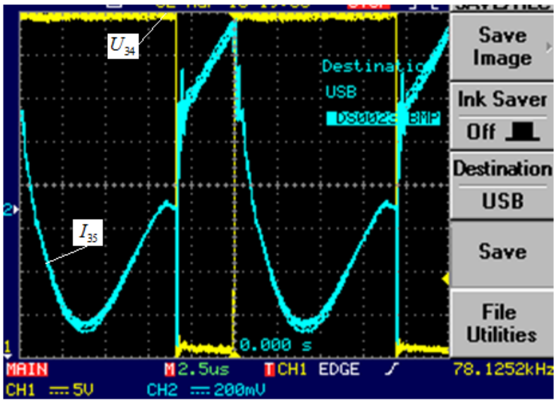

Figure 7c.The voltage and currents of semiconductor devices at a load equal to $P = 1.0P_{nom}$, where notices: U_{34} - the shape of the voltage pulse in the common connection node of the electronic devices 4 and 5 (Fig. 1); I_{35} - the shape of the pulse current flowing into the primary coil 3 of the high frequency transformer 7 (Fig. 1)

The experimental tests were performed for the case of the deviation of input network medium voltage within the limits 9.0 - 11.0 kV, which corresponds to the ± 10% deviation. The deviation of the low-voltage output was set at 230V ± 1 V. Experimentally the deviation of the output voltage did not exceed ± 0.5%. The deviation of the output voltage when the load is deflected in the range 0 - 20 kW does not exceed ± 0.5%. The overall efficiency of the tested sample constitutes 98%.

VI. Conclusion

The innovation of this proposed solution is to decrease the number of stages of energy conversion in the AC/AC equipment in comparison with known solutions and to simplify the topology of the functional scheme, which results in lower costs of transformer production and allows decreasing energy losses in this equipment. Simultaneously, it simplifies the requirements for connection to centralized network, because the existence of the neutral conductor is not mandatory in this case.

Mathematical simulations have confirmed the truthfulness of the concept of SST transformer realization, as well as quality indices of the output current and voltage (corresponding to the quality requirements of electric energy). The transformer possesses the advantage to stabilize the output low-voltage during the voltage deviations in power supply network. The output voltage stabilization is based on the original process of adjusting the control pulses parameters of the semiconductor devices of SST inverter. Experimentally, it was determined that the deviation of the output low-voltage does not exceed 0.5% in case of 10% deviation of the input medium voltage. This indicator is the same when the load changes from zero to the nominal power P_{nom} of the transformer.

The experimental test results confirm the functionality of the equipment, including the opportunity of realization of semiconductor devices commutation mode when current passes through zero (ZCS mode). The simplification of the topology of the SST transformer contributes to the increase of the energy efficiency indicators (by about 0.8%) compared to the TMG type transformer of the same power.

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