

**EXPERIMENTAL STUDY OF THE COMMUTATION PROCESSES
IN DISCRETE ALTERNATING VOLTAGE REGULATOR**

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Abstract

Slow rates of electrical network renewal, extension of the connected consumers variety and the increased requirements for energy effectiveness persistently put the question for the need of power electronic devices for fast correction of the electrical energy quality parameters. Such devices are the discrete alternating voltage regulators. The present work is dedicated to experimental study of the commutation processes which appear during asynchronous automatic switching of multiple-winding autotransformer terminals. The obtained results will support the development of such devices and optimization of the algorithms for their control.

Key words: autotransformer, thyristor commutators, voltage regulator, control circuit

1. INTRODUCTION

The variety of devices and equipment connected to the distribution grid is constantly increasing. Their effective work also depends on the electrical energy quality (EEQ).

The characteristics of EEQ specified in the standard EN 50160 include the magnitude of the supply voltage U_n and its change. On one hand the allowed change of $U_n \pm 10\%$, and on the other hand the necessity of power electronic devices for fast correction of supply voltage changes, both define the actuality for development of discrete alternating voltage regulators (DAVR), [1].

DAVR based on a multiple-winding autotransformer and automatic switching of the windings with controllable thyristor switches (CTS) are well-known devices. One of the problems in their development is the algorithm for realization of the switching of two neighboring CTS, [6]. On principle, two approaches are possible:

- ✱ synchronous switching (at zero current);
- ✱ asynchronous switching at a random moment, when the magnitude of the supply voltage goes out from the allowed range of change.

Some disadvantages of the synchronous switching are:

- “zero current” in complex non-linear circuit with different number of connected reactive elements, according to the regime, hardly could be defined only with a single current detector for all commutations;
- as far as “zero current” is a qualitative condition, in the literature misses analysis for “region of insensitiveness” at a change of the current through the load from tens of miliamperes to tens of amperes, which will help to define requirements to the current detector parameters.

The present work is dedicated to experimental study of the commutation processes in DAVR with four CTS, working with variable induction (*CTS from the side of the load*) and asynchronous switching, [2]. The circuit diagram of DAVR is shown in fig.1, and the time diagram of the functional operation, which defines the commutation of the corresponding CTS – in fig.2, [3].

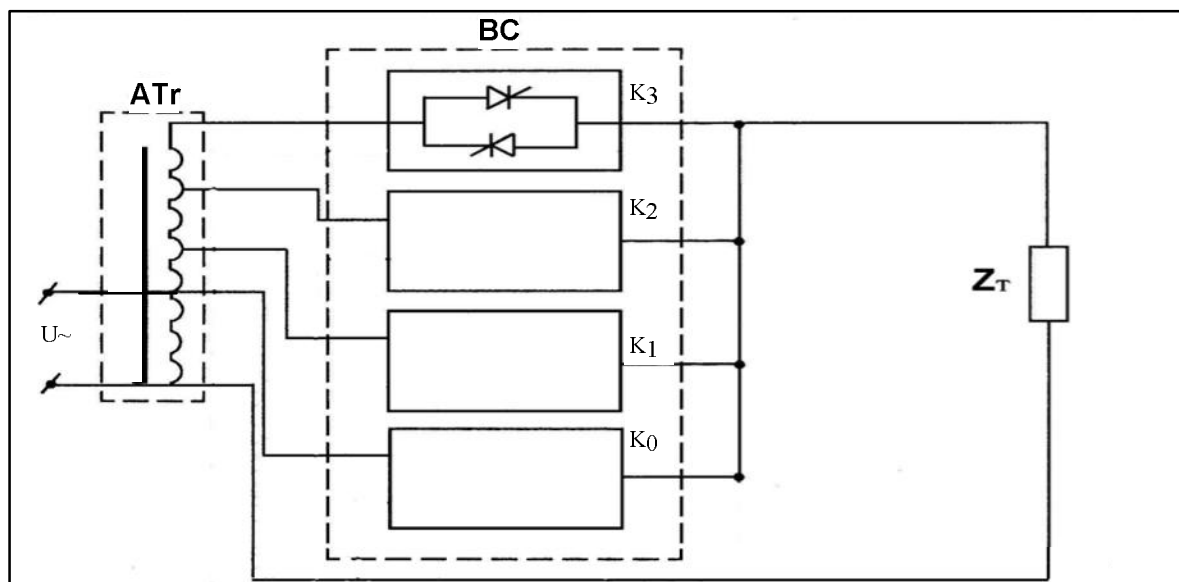


Fig. 1. Circuit diagram of DAVR with four CTS.

Turning on the respective switches K_0 - K_3 (*the shaded area is the time when applying the control pulses to the respective switches*) is shown on the next time diagrams. The output voltage, which is changing in the range $U_{out_{min}}$ - $U_{out_{max}}$, can also be traced on the relevant diagram. The choice of values of ΔU defines requirements to the number of autotransformer terminals, as well as to the number of semiconductor switches i.e. it influences over the price of DAVR.

where: ATr - is a step voltage autotransformer;

BC - is a commutating block, based on thyristor switches.

ΔU^* - fig. 2 is a hysteresis which improves the steady work of DAVR and decreases the number of commutations.

The circuit diagram of two neighboring CTS – (CTS_1 and CTS_2) is shown on fig.3.

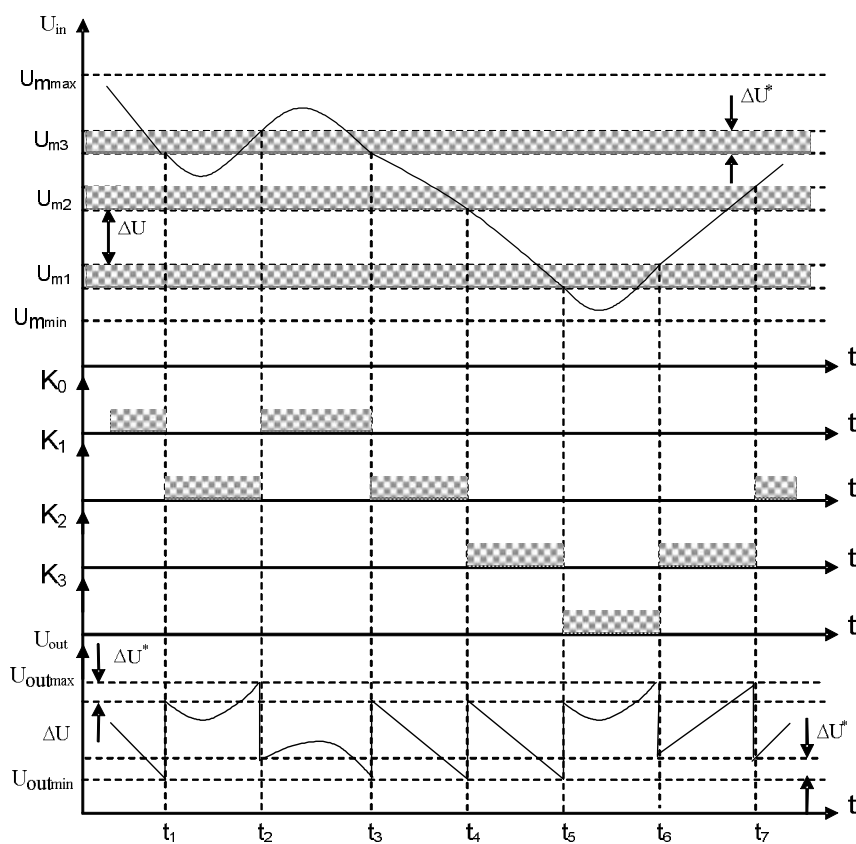


Fig. 2. Time diagram of the functional operation of DAVR.

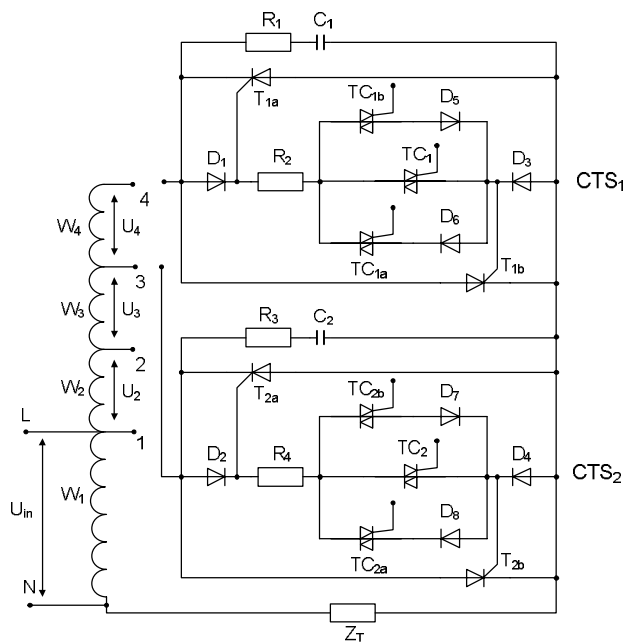


Fig. 3. Circuit diagram of DAVR with two CTS.

Peculiarities of CTS switching at decrease and increase of the input voltage are pointed below.

At decrease of the input supply voltage i.e. switching from a terminal with lower voltage of the autotransformer to a terminal with higher voltage the commutation process runs in the following sequence:

- for a respective half period it is accepted that T_{2b} has worked in CTS_2 ;
- simultaneously, the control voltage is switched off from CTS_2 , while T_{2b} keeps its conductivity, and it (*the control voltage*) is applied to the thyristors from CTS_1 , and this switches on T_{1b} ;
- when T_{1b} is on, there arise conditions for forced commutation of T_{2b} (reverse voltage anode-cathode is supplied to it), which does not depend on the commutation angle, the character and magnitude of the load and the commutation is done for few microseconds, [5].

Hence, in this case the asynchronous commutation process is performed without any problems.

At increase of the input supply voltage i.e. switching from a terminal with higher voltage to a terminal with lower voltage, the commutation process runs in the following sequence:

- it is assumed that for a respective half period T_{1a} has worked in CTS_1 ;
- simultaneously, the control voltage is switched off from CTS_1 , respectively from T_{1a} but it still keeps its conductivity, and it (*the control voltage*) is supplied to the thyristors from CTS_2 , which creates conditions for switching on of T_{2b} ;

Therefore, through the two connected in series conductive T_{1a} and T_{2b} is caused short circuit between two neighboring terminals of the autotransformer with a duration until the natural commutation of T_{1a} .

The purpose of the current work is a qualitative evaluation of the thyristors loading in CTS and the autotransformer at a short circuit mode, development of an algorithm for control which does not allow simultaneous switching on of two opposite connected to the load thyristors from two neighboring CTS, and synthesizing of a circuit for control of two CTS, which realizes the algorithms for control, [4].

2. ANALYSIS

In fig.4 at conducting CTS_1 – fig.3, is shown the current through CTS_1 and the voltage over winding W_4 – fig.3 with active load. The control pulses for T_{1a} and T_{1b} are formed at zero current and zero voltage. At the same conditions on fig.5 can be traced the dephasing between load and voltage and the formation of control pulses at zero current with RC load ($R=61,52\Omega$; $C=40\mu F$).

In fig.6 and fig.7 are presented current and voltage harmonic analyses of the supply voltage while DAVR operates with RC load ($R=61,52\Omega$; $C=40\mu F$). The obtained coefficients of the harmonic distortions THD are respectively 4,2% and 2,1%. These values satisfy the requirements in the standard EN 50160, where the allowed THD are up to 8%.

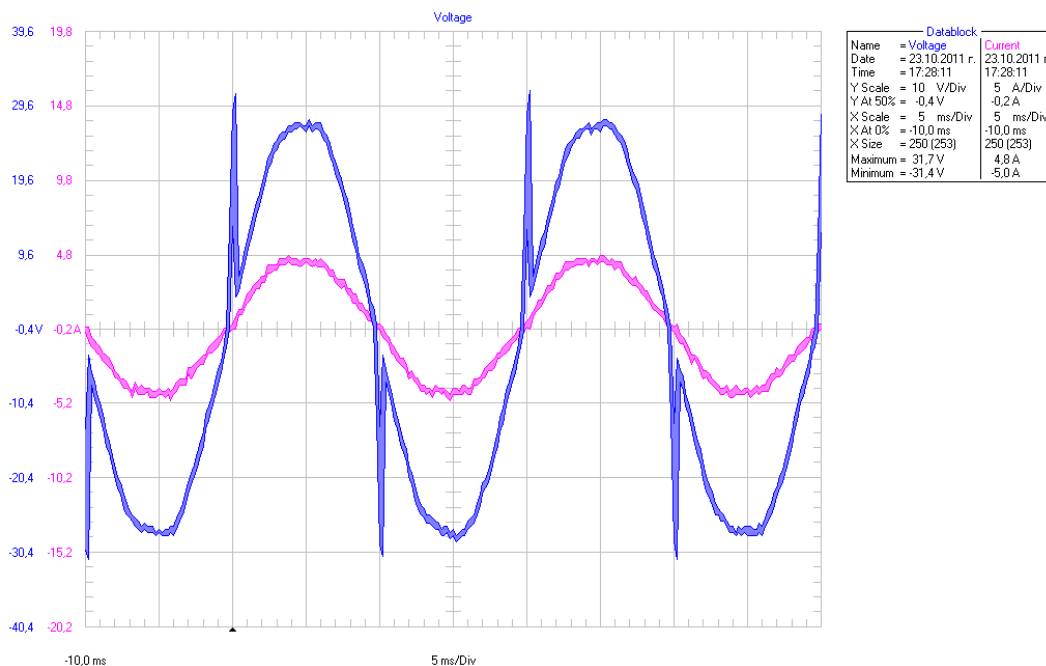


Fig. 4. Current through the conductive switch CTS_1 with R load. Dephasing between the current and the voltage and formation of control pulses at zero current.

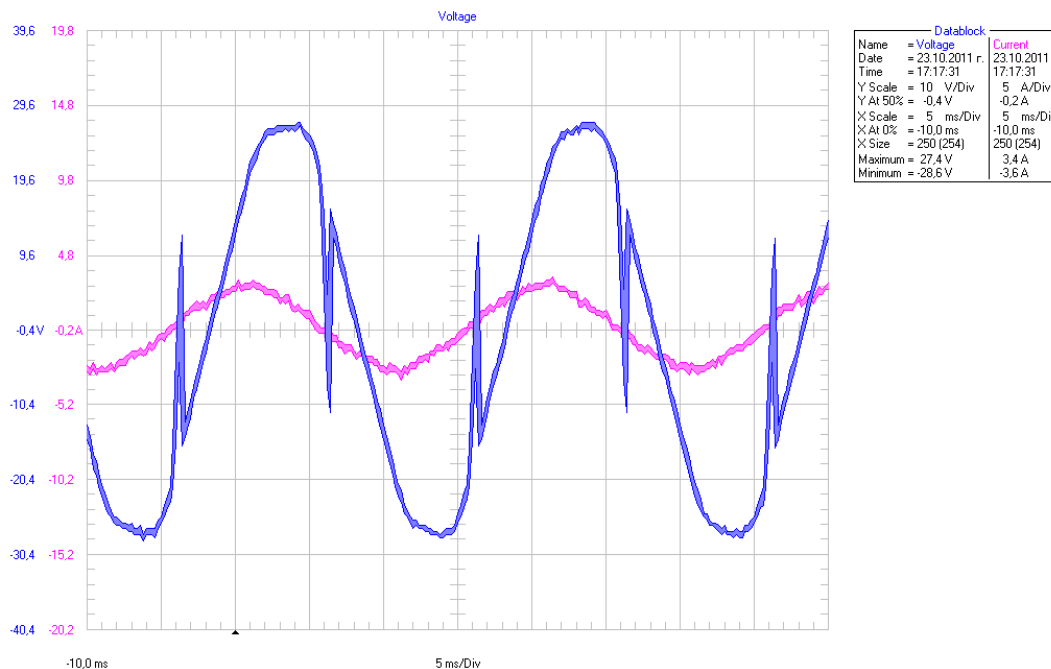


Fig. 5. Current through the conductive switch CTS_1 with RC load. Dephasing between the current and the voltage and formation of control pulses at zero current.

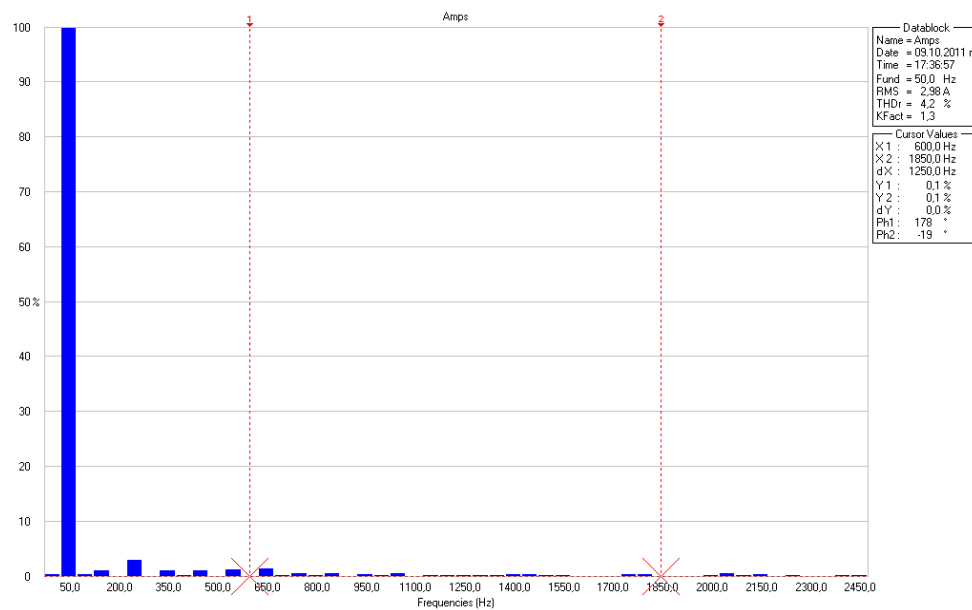


Fig. 6.Current harmonic analysis of the supply voltage during the operation of DAVR with RC load.

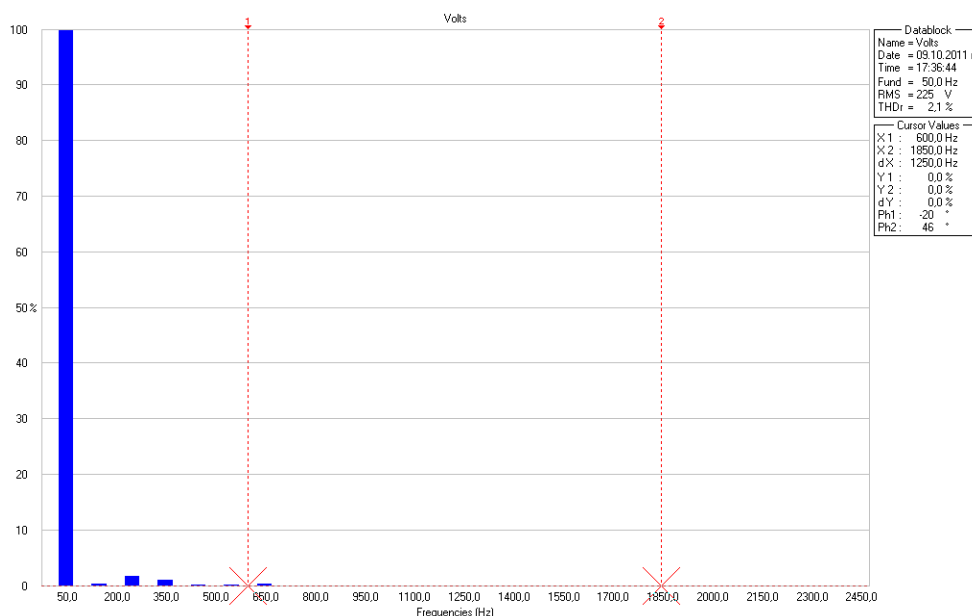


Fig. 7. Voltage harmonic analysis of the supply voltage during the operation of DAVR with RC load.

For prohibiting the simultaneous work of two connected opposite to the load thyristors from two neighboring CTS are possible two ways:

- Additional synchronization in which T_{1a} and T_{2a} can switch on only during one half period of the input supply voltage, and T_{1b} and T_{2b} - in the other half period.

This assumes introduction of TC_{1a} and D_6 for control of T_{1a} (TC_{2a} and D_8 – for T_{2a}) and TC_{1b} and D_5 for control of T_{1b} (TC_{2b} and D_7 – for T_{2b}) – fig.3.

- The operation at a sufficiently high angle of commutation, so that when switching off the control voltage from CTS_1 and applying such voltage to CTS_2 the current through the respective to be turned on thyristor, which is defined by U_4 and R_4 – fig.3, should be under its holding current.

Hence, the control circuit for conducting the experimental study follows to include three blocks:

- Block 1 for defining of the commutation angle – fig.8;
- Block 2 for realization of the CTS switching and meanwhile meeting two conditions – fig.10:
 - after a random moment in time;
 - at a certain angle of commutation in relation to the input supply voltage.
- Block 3 for synchronized or unsynchronized with the grid switching on and off of the thyristors from CTS – fig.10.

In fig.8 is shown Block 1 for pulses formation [5a] – fig.9 within one half period, which fixes the commutation angle according to the input supply voltage. In fig.9 is presented the time diagram of the module operation from fig.8.

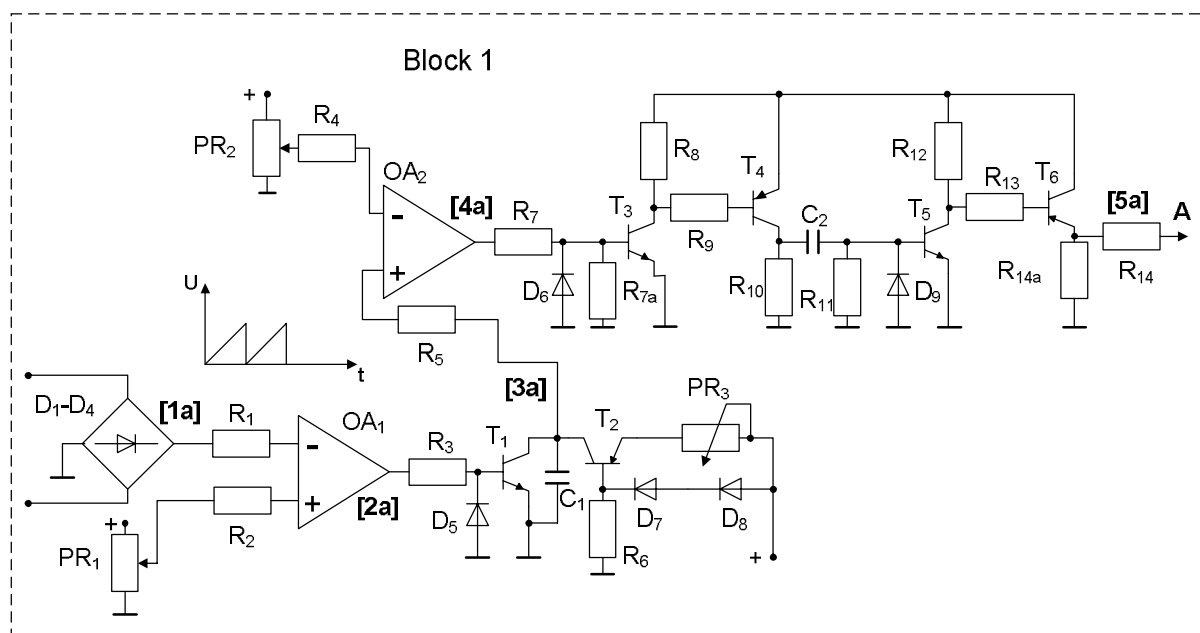


Fig. 8. Circuit diagram of block 1 – for pulses formation.

C_1 is charged linearly from the current generator – T_2 , PR_3 , R_6 , D_7 and D_8 , and discharges at the zero of the input supply voltage of T_1 , controlled by OA_1 .

The formed triangle-wave voltage [3a] – fig.9 is compared to the voltage from PR_2 with a comparator OA_2 and the pulses are formed [4a]. The leading edges of the last are turned into pulses which

synchronize the commutation angle with the grid – [5a], as their width is specified by C_2 , R_{11} and is in the range of 0,2ms.

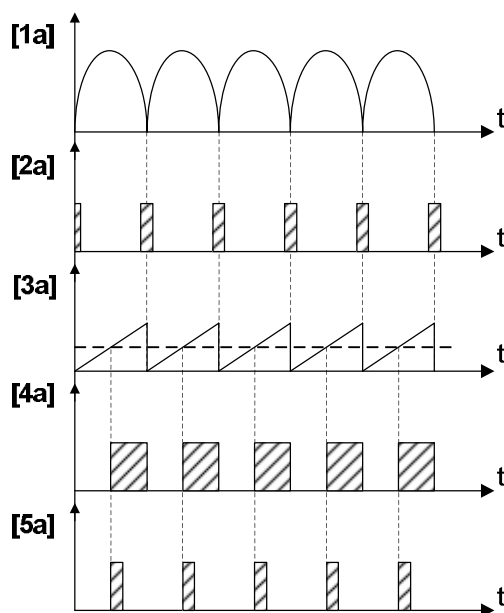


Fig. 9. Work time diagram of the module – block for pulses formation.

Block 2 - fig.10 carries out: feeding the pulses to CTS, which has to switch on [5] – fig.11 and turning off the pulse to CTS, which follows to switch off [6] – fig.11. Switching on one of the CTS and switching off the other CTS is performed at commutation angles with respect to the input supply voltage, which is specified by Block 1 – fig.8 ([5a] – fig.9) after closing the switch K_1 – fig.10 at a random moment. The direction of the switching from a terminal with higher voltage to one with lower voltage of the multiple-winding autotransformer or backwards is chosen with the switch K_2 .

Block 3 controls the operation of the light emitting diodes in the optically controlled triacs – fig.10.

At unsynchronized mode K_0 – fig.10 is switched off. Transistors T_{18} and T_{19} are in active mode during the whole time of operation of DAVR when switches K_3 и K_4 are opened; K_5 is in position K_{5b} . The work of T_{1a} and T_{1b} – $t_1 \div t_3$ and of T_{2a} and T_{2b} – $t_3 \div t_7$ can be followed on the time diagram in fig.11. At this working mode short circuit does not arise between two neighboring terminals of the multiple-winding autotransformer. Switching from a lower to a higher degree is done at t_8 at switching on of T_{1a} and forced commutation (*switching off*) of T_{2a} – fig.11. The opposite switching from a higher to a lower degree is performed at the zero of the input supply voltage - t_3 after formation of a pulse for switching at a moment t_2 – fig.11.

Switching from upper to lower voltage step is realized at zero current of the supply voltage - t_3 , after formation of a switching pulse at a moment t_2 – fig.11.

This mode is realized at the absence of dephasing between the load current and the input supply voltage, i.e. with an active load.

Consequently, a main interest of the experimental study in the paper is the switching from a higher to a lower degree of the multiple-winding autotransformer as a function of the commutation angle, the character and the magnitude of the load.

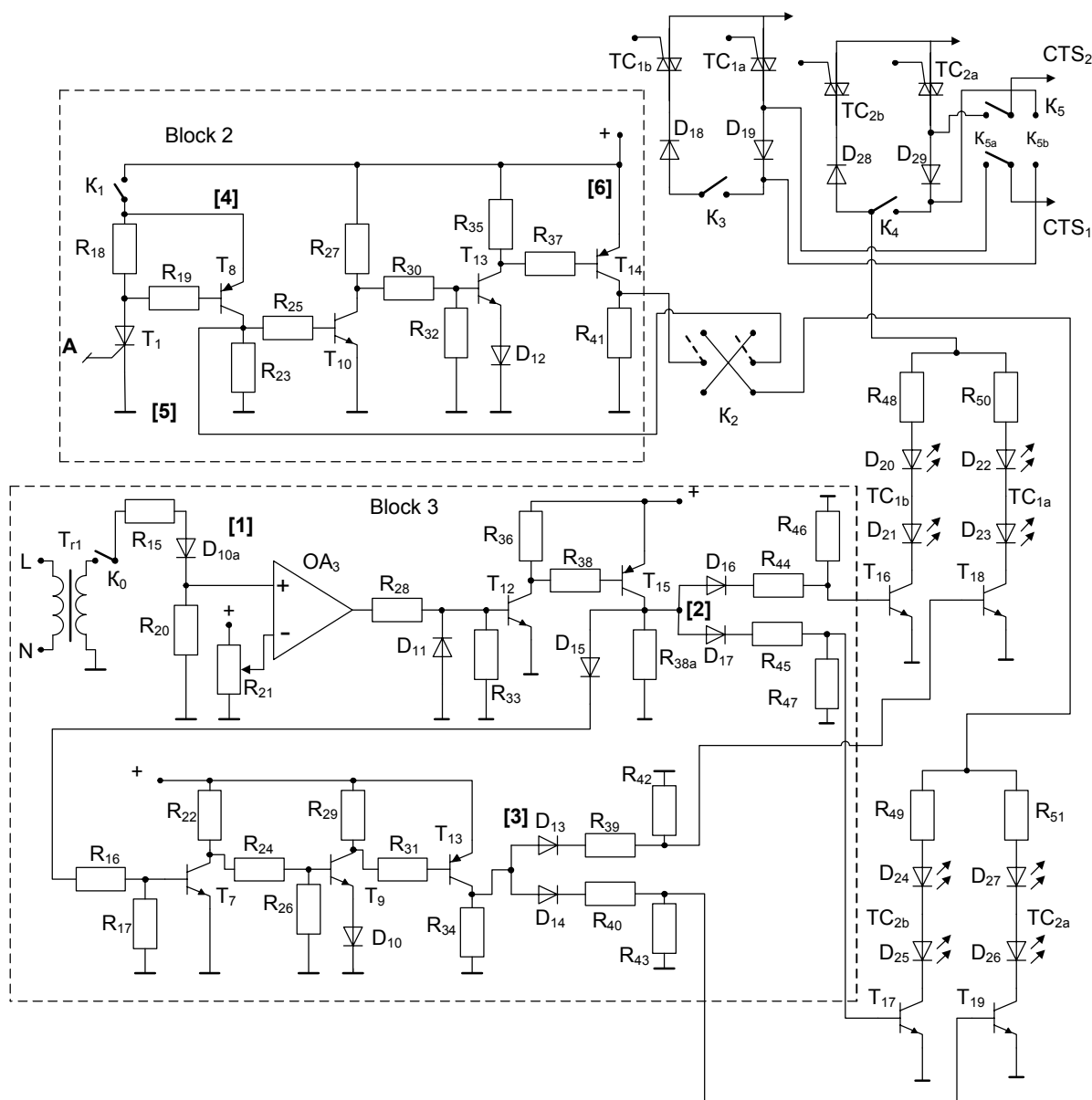


Fig. 10. Circuit diagram of block 2 – realizing of pulse forma to CTS, and block 3 – control of the light emitting diodes in the optically controlled triacs.

In fig.12 and fig.13 are presented oscillograms of the input current $i_{in}=i_m(t)$; the output current $i_{out}=i_{out}(t)$; and the current through CTS₂, which is switched on - $i_2=i_2(t)$ and the current through CTS₁, which is switched off - $i_1=i_1(t)$, at commutation angles 45° and 135° and a load $R=61,52\Omega$.

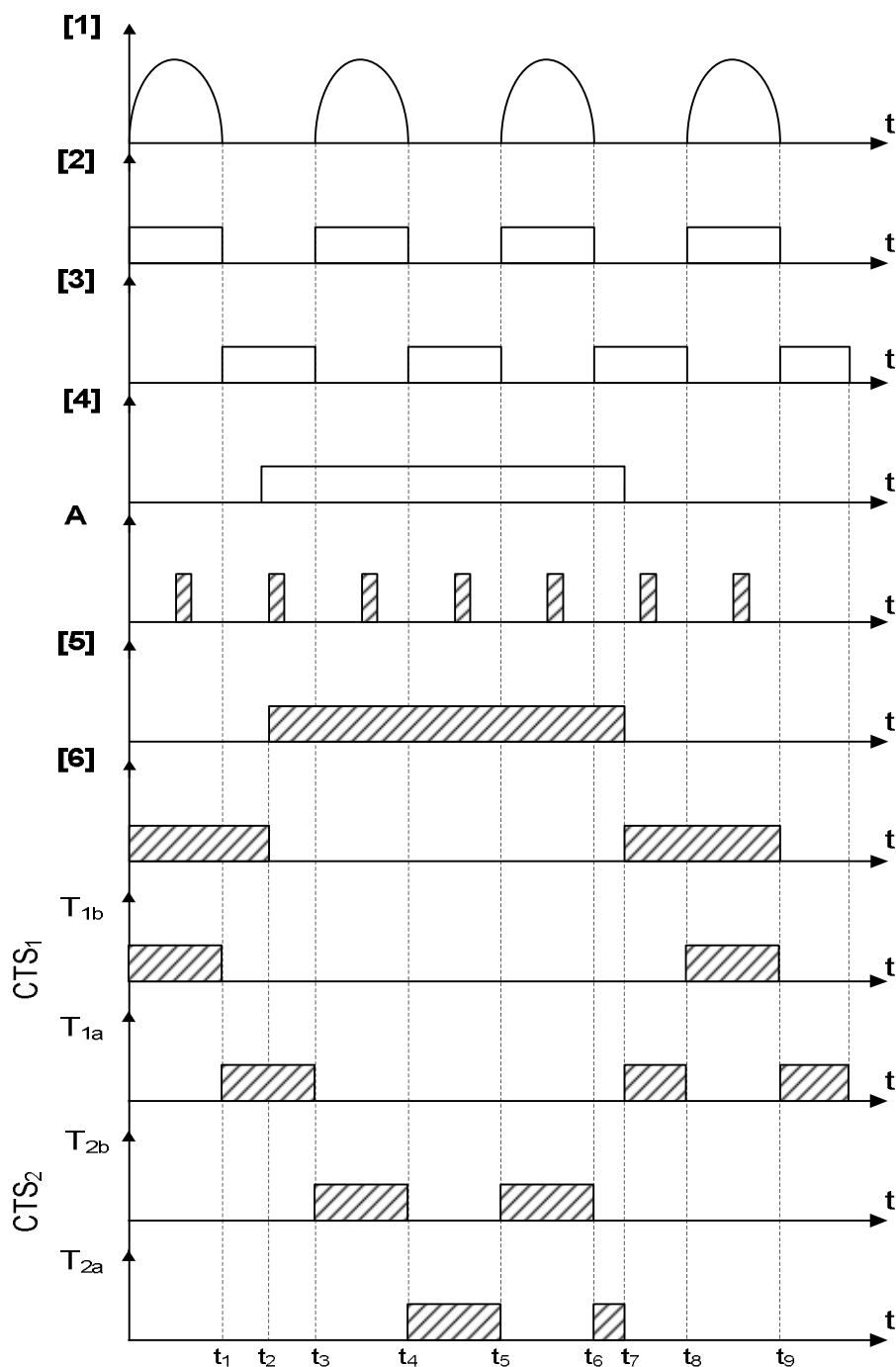


Fig. 11. Work time diagram of block 2 – feeds the pulses to CTS, and block 3 – control of the light emitting diodes in the optically controlled triacs.

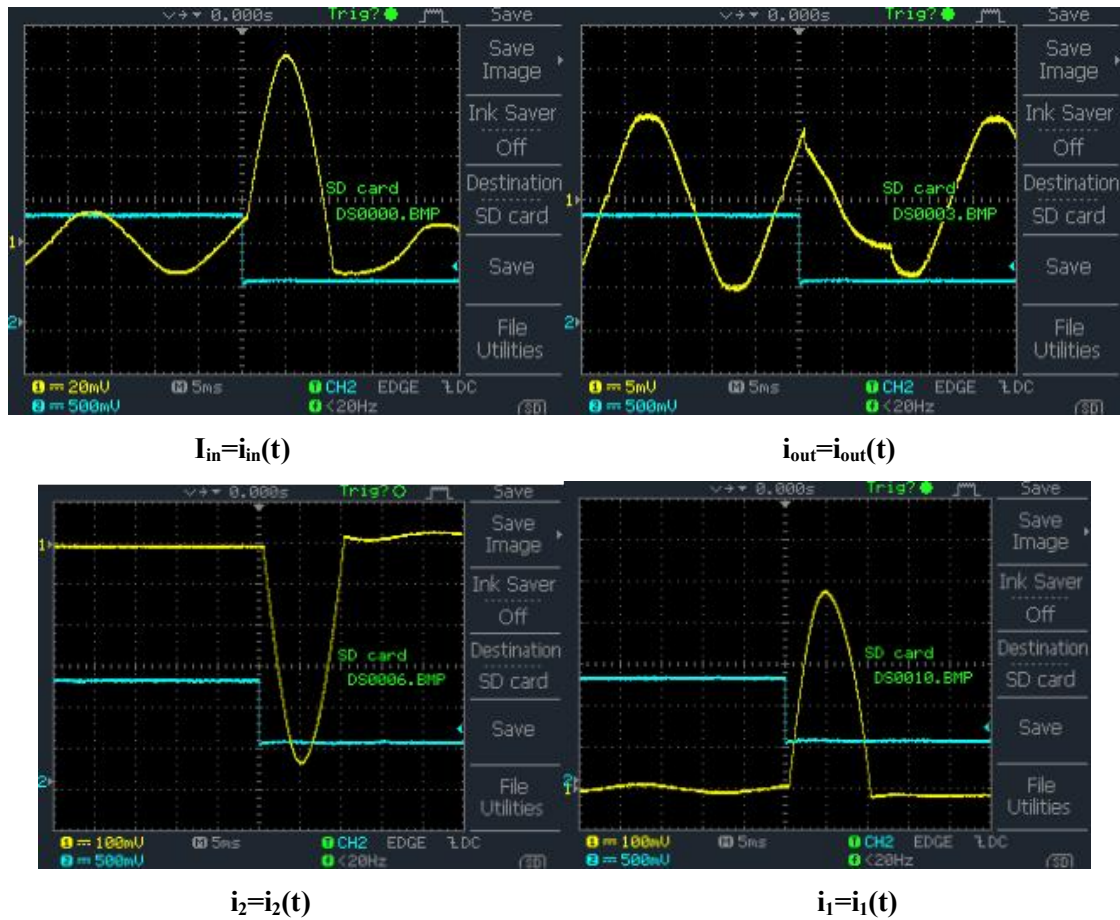
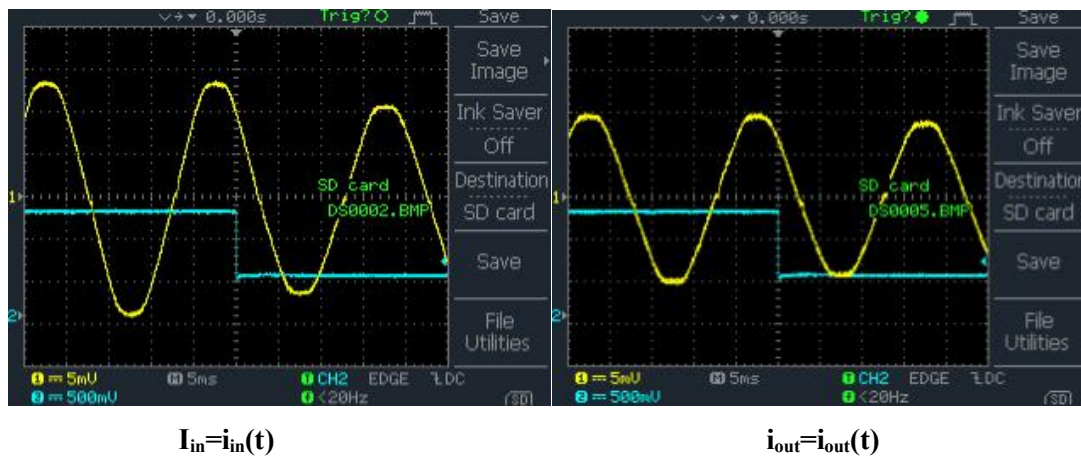


Fig. 12. Oscillograms of the currents in DAVR at a commutation angle 45° and R-load.

On the presented oscillograms the current channel – (*number one*) is in yellow, and the pulse forming channel – (*number two*) is in blue colour. For all oscillograms the time scale is 5ms/div.



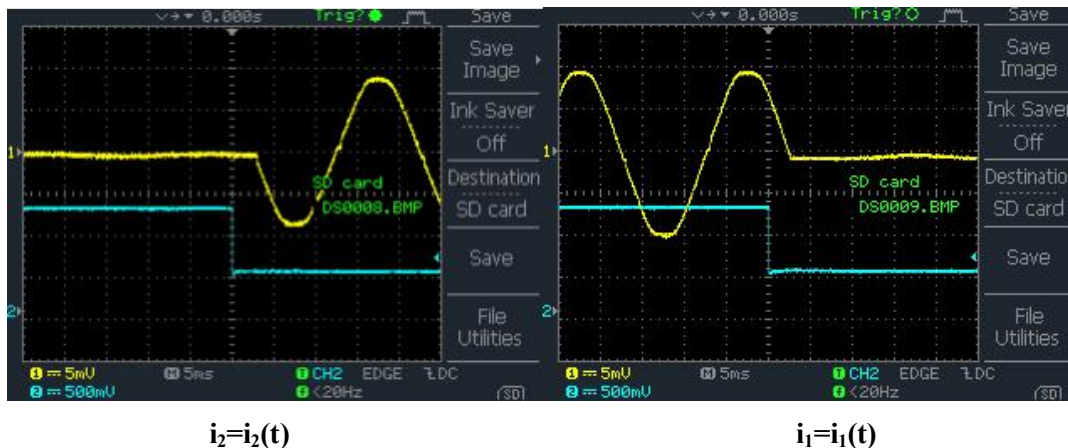


Fig. 13. Oscillograms of the currents in DAVR at a commutation angle 135° and R-load.

In fig.14 and 15 are shown oscillograms, which are analogical to those from fig.12 and 13 for RL load ($R=61,52\Omega$ and $L=2,1712H$ connected in parallel).

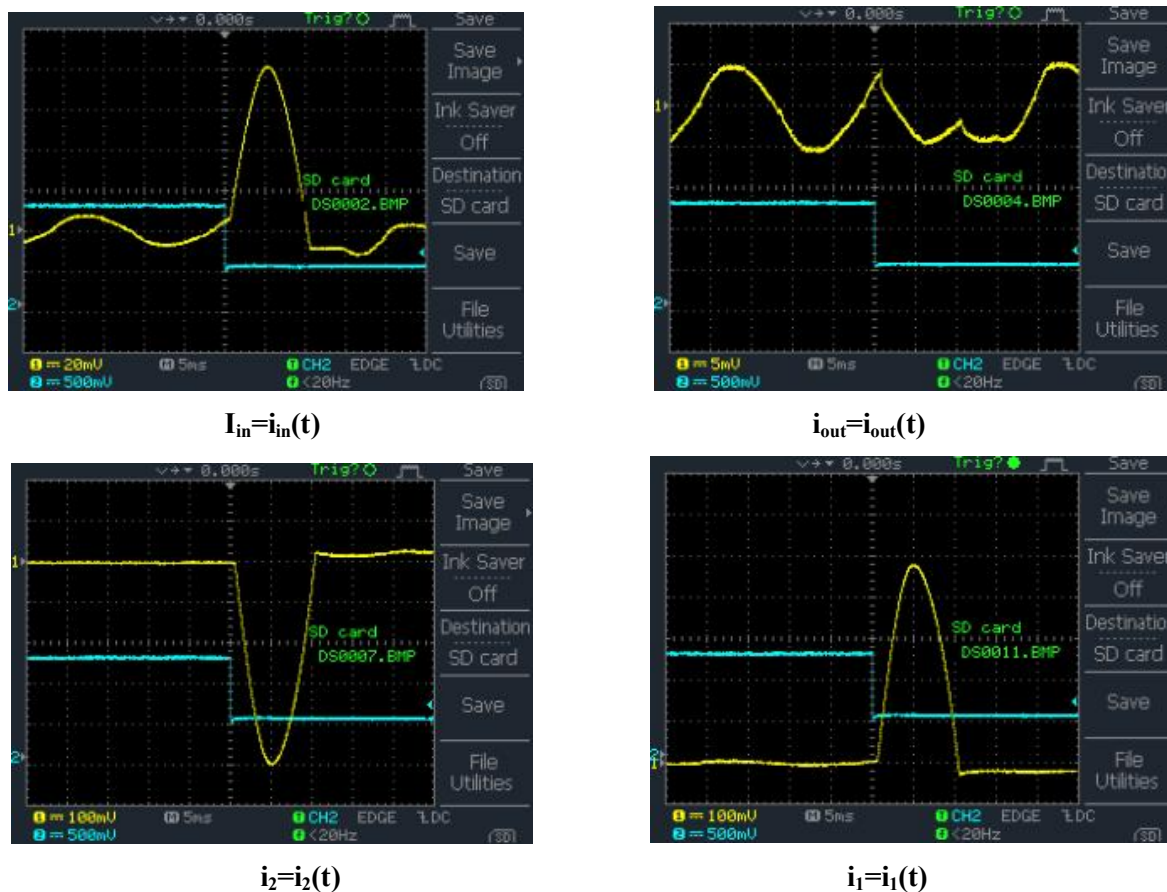


Fig. 14. Oscillograms of the currents in DAVR at a commutation angle 45° and RL-load.

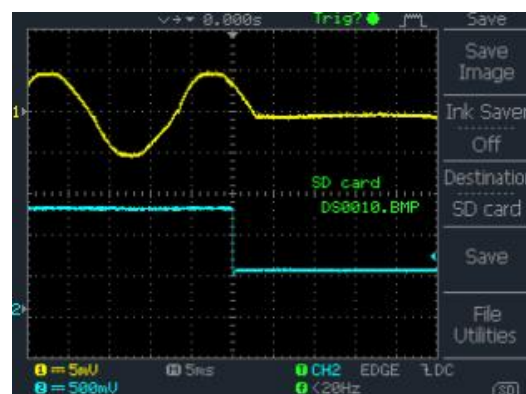
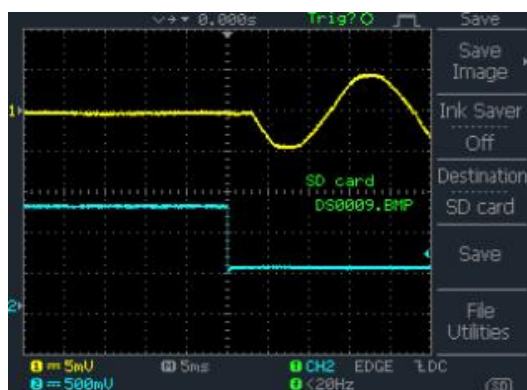
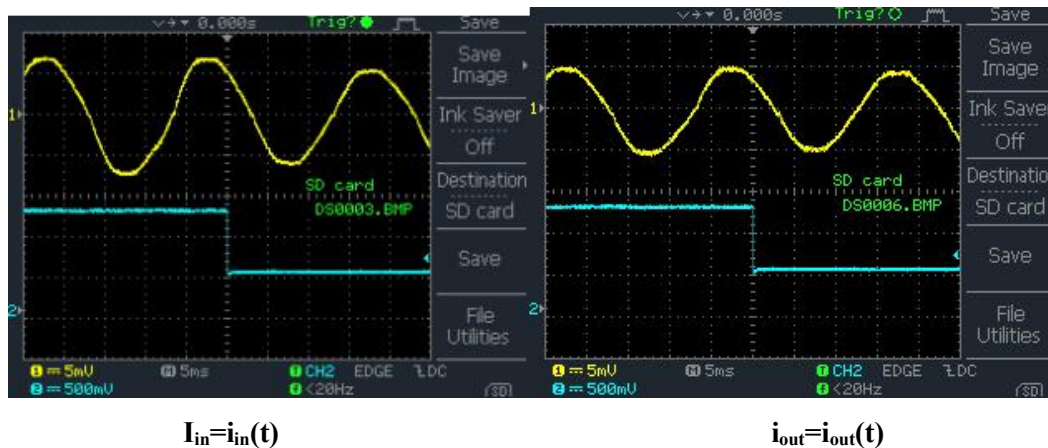
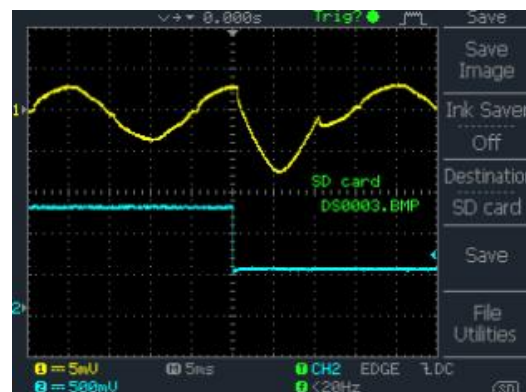
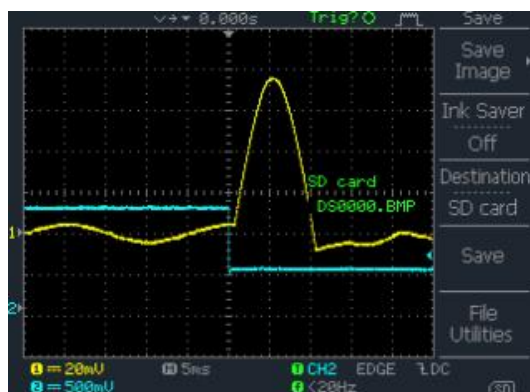
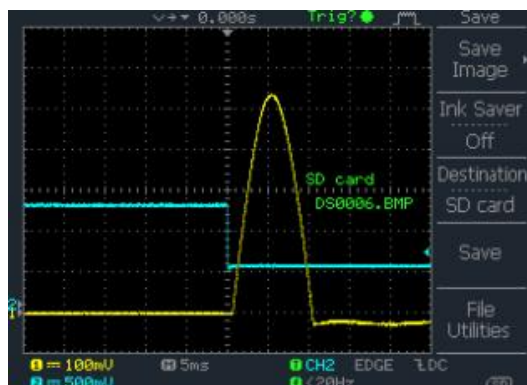


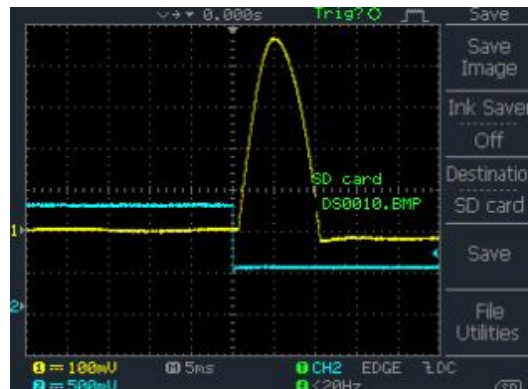
Fig. 15. Oscillograms of the currents in DAVR at a commutation angle 135° and RL-load.

In fig.16 and fig.17 are presented oscillograms for RC load ($R=61,52\Omega$ и $C=40\mu F$, connected in series) and commutation angles 45° and 135° .



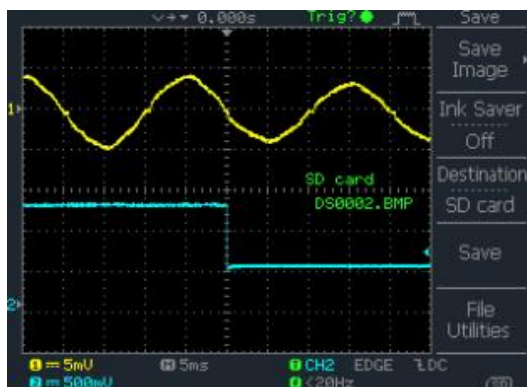


$$i_2=i_2(t)$$



$$i_1=i_1(t)$$

Fig. 16. Oscillograms of the currents in DAVR at a commutation angle 45° and RC-load.



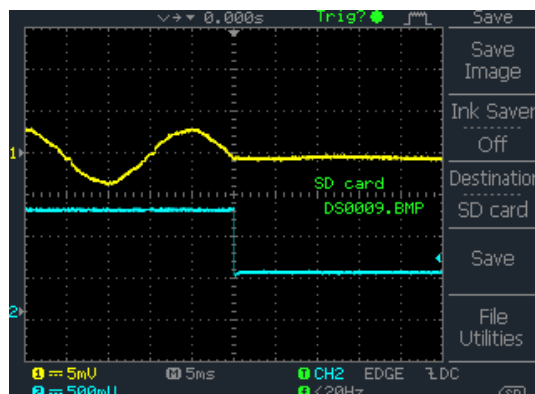
$$I_{in}=i_{in}(t)$$



$$i_{out}=i_{out}(t)$$



$$i_2=i_2(t)$$



$$i_1=i_1(t)$$

Fig. 17. Oscillograms of the currents in DAVR at a commutation angle 135° and RC-load.

In fig. 18 and 19 is presented the harmonic content of the input and the output current with RC load ($R=61,52\Omega$ and $C=40\mu F$, connected in parallel) and a commutation angle 45° .

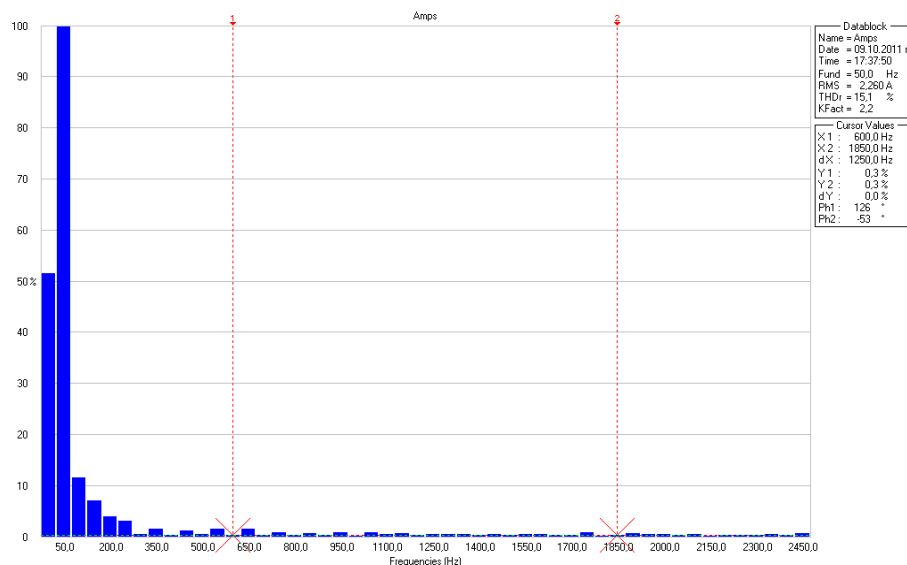


Fig. 18. Harmonic content of the input current of DAVR with RC load.

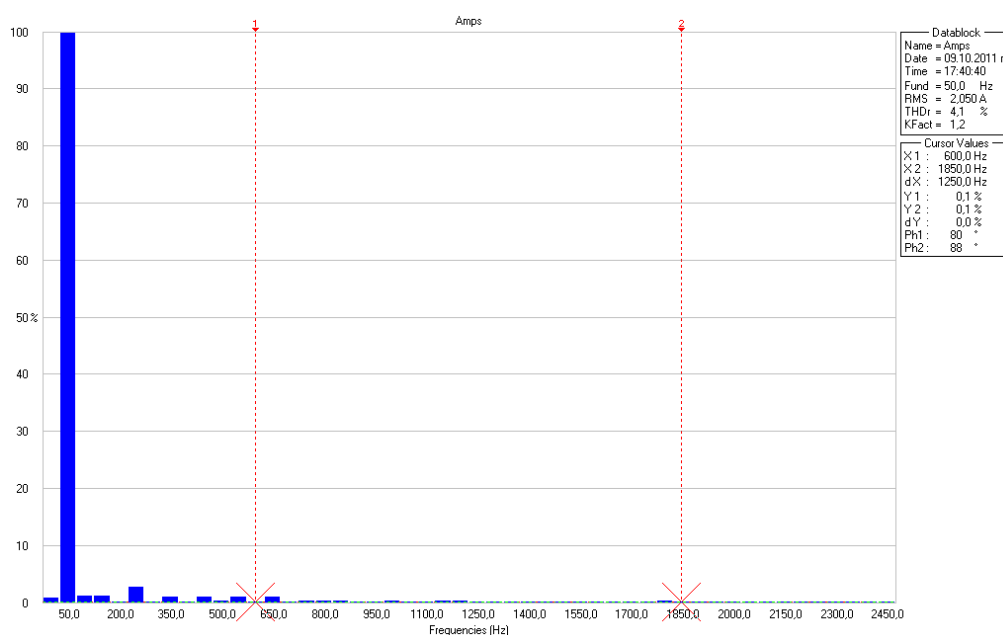


Fig. 19. Harmonic content of the input voltage of DAVR with RC load.

Table 1 presents the obtained results for the amplitudes and duration of the current overload of CTS for different types of loads, commutation angle and switching degrees (at different input voltage) of the autotransformer voltage regulator. The data in the table show that for the analytical modeling it is best to describe the processes when switching DAVR from degree 2 to 3.

Table 1. Type of load, commutation time and angle of DAVR at different input voltage.

Type of load	U _{in} =160V. K ₃ - switching off, and K ₂ - switching on.		U _{in} =180V. K ₂ - switching off, and K ₁ - switching on.		U _{in} =200V. K ₁ - switching off, and K ₀ - switching on.	
	Maximum current	Commutation time	Maximum current	Commutation time	Maximum current	Commutation time
	<i>A</i>	<i>ms</i>	<i>A</i>	<i>ms</i>	<i>A</i>	<i>mS</i>
Commutation angle	switch K ₂ - K ₃	switch K ₂ - K ₃	switch K ₁ - K ₂	switch K ₁ - K ₂	switch K ₀ - K ₁	switch K ₀ - K ₁
R – 45°	520	10	540	7,5	700	7
R – 90°	380	7,5	480	7	620	6,5
R – 135°	0	0	0	0	0	0
RL – 45°	500	10	520	7	680	8
RL – 90°	380	7,5	440	6	640	7
RL – 135°	0	0	0	0	0	0
RC– 45°	540	10	520	8	800	8
RC– 90°	380	7,5	460	6,5	640	7
RC – 135°	0	0	0	0	0	0

CONCLUSIONS

The conducted experimental study allows to be summarized:

1. The presented graphics in fig.13, 15 and 17 reveal that there occurs no short circuit between two neighboring terminals of the multiple-winding autotransformer when switching from a higher to a lower degree at commutation angle bigger than 135° and this does not depend on the character or magnitude of the load. Therefore, there is no overload of the thyristors and the autotransformer. The coefficient of the harmonic distortions is within the admissible range – fig.18.
2. At a commutation angle higher than 135° the switching does not perform at a moment defined by the commutation angle, but after it – at the range of the half period at zero current. The realization of such mode demands synchronization with the input supply voltage which is easy to be fulfilled schematically.
3. The obtained results for the amplitudes and duration of the current overloading point that in analytical modeling it is best to be described the processes at switching of DAVR from degree 2 to 3 – fig.3, since there are included most reactive elements.

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