Journal of International Scientific Publication:
Materials, Methods & Technologies, Volume 4, Part 1

ANALYSIS OF ELECTRICAL PROCESSES IN ALTERNATING VOLTAGE CONTROL SYSTEMS

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Abstract

One of the problems concerning the quality of electric power refers to amplitude control of supply voltage alternating in time. This paper presents an analysis of the problems of autotransformer discrete alternating voltage regulators (ADAVR) through simulation models while accounting for the specific features of a particular circuit design. These models are based on the non-linear parameters of the constructive components, such as: windings and ferromagnetic core in autotransformers, thyristor commutators, switch-off assemblies and load. The analysis has been basically made by the state variables method in the temporal field. A special algorithm has been developed for part-by-part solving of the obtained sparse matrix equations of cell structure, which have almost singular matrices. The obtained solutions show insignificant error accumulation from the computations and great stability in time. An automated computer program, AVTO, has also been developed to simulate ADRAV processes in MATLAB environment. The program operates with parameters of autotransformer windings, parameters of ferromagnetic core, parameters of thyristor switches and these of switch-off assemblies. The program analyzes all three intervals inherent to the commutation process and represents in series the behaviour of the individual quantities in time. The data from the simulated processes have been experimentally verified using a prototype and have shown a good correspondence. A system version for virtual design of discrete voltage regulators has been put forward.

Key words: *autotransformer discrete alternating voltage regulator, semiconductor commuting elements, thyristor, commutation process*

1. INTRODUCTION

Recently, there has been an increasing interest in a more precise parameter control of the electric power supplied to industries and homes [1]. An element of electric power quality is the range of alteration of the input supply voltage amplitude. The supply voltage control can be implemented through autotransformer discrete alternating voltage regulators (ADAVR) with semiconductor commuting elements (SCE) [2,3]. Design and construction of ADAVR with SCE require modern approaches, such as computer analysis and simulation of the complex processes occurring in devices of this class [1,2,3,4,5]. The major problem here is the development of adequate, precise models and algorithms for analysis which should enable the achievement of accurate solutions and true simulation of ADAVR responses in a variety of operative modes and in emergent situations as well [6,7,8]. The purpose of all this is economy of financial means and time during engineering and manufacturing of such products.

2. ANALYSIS

The amplitude range control of input supply voltage can be achieved through automatic switch-over of the transformer terminals (autotransformer). The terminals can be located on the side of the mains or on the side of the load [1]. Fig. 1 shows a circuit equivalent to one of the commonly used ADAVR with four SCE. The circuit includes the magnetic circuit parameters, commuting groups, switch-off assemblies, parameters of the separate sections of the winding and it takes into account the existing non-linearities. The model thus created enables detection of random commutations in time of adjacent SCE switched over in series.

During the computer simulation, the following real conditions of commutations were considered:

- commutation at a random moment;
- commutation implemented by switching over in series of adjacent switches with SCE.

Account has been taken of the specifics of thyristor switches, whereby one commutation process comprises three intervals. The heaviest ADAVR mode has also been studies through simulation, in the first interval when switch K_3 is closed and all others are open; in the second interval when switches K_3 and K_4 are closed; and in the third interval when only switch K_4 is closed.

The system equations of the three intervals are represented in series for R-load (1), for L-load (2) and for C-load (3), whereby in the first interval the mesh current method is applied in a complex form: the system is solved by the Gauss-Jordan method; in the second and third interval the state variables method is applied and the systems are solved by the Runge–Kutta fourth-order method (RK4 method) in the temporal field.

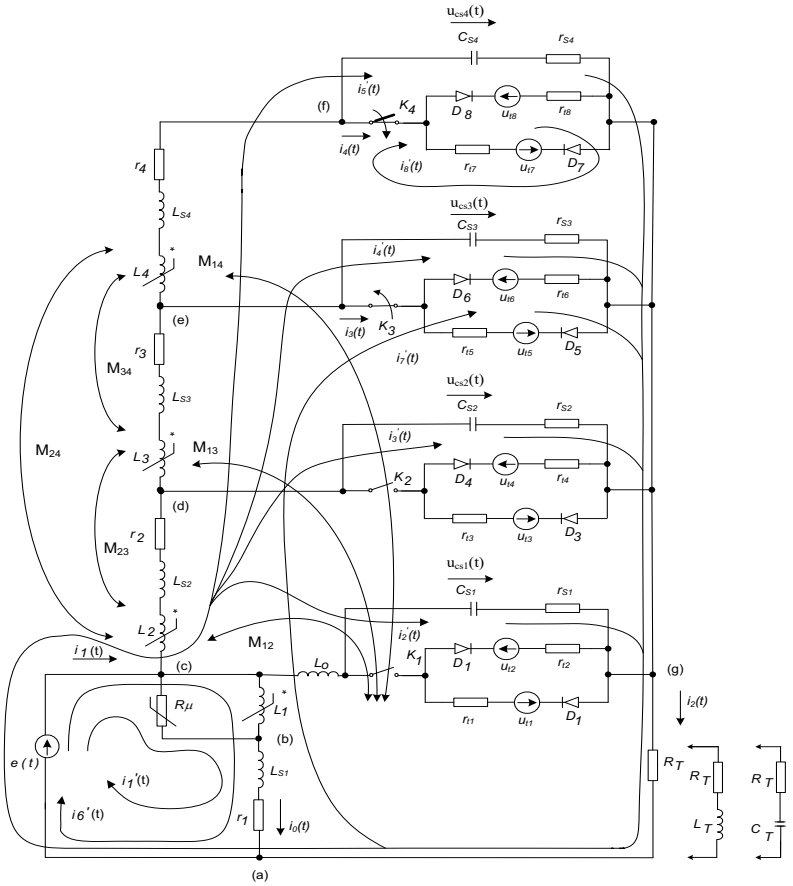


Fig.1. DAVR equivalent circuit with four SCE.

1st Interval (established move) mesh current method in a complex form for R-load

$$+(R_{\mu}+j\omega L_1)\dot{I}_1^{'}+j\omega L_1.\dot{I}_2^{'}-j\omega L_1.\dot{I}_3^{'}-j\omega(L_1+M_{12})\dot{I}_4^{'}-j\omega(L_1+M_{12}+M_{13})\dot{I}_5^{'}-$$
$$-j\omega(L_1+M_{12}+M_{13}+M_{14})\dot{I}_6^{'}-j\omega(L_1+M_{12}+M_{13})\dot{I}_7^{'}=0$$

$$+j\omega L_1.\dot{I}_1^{'}+[r_1+j\omega(L_{S1}+L_1)].I_2^{'}-[r_1+j\omega(L_{S1}+L_1)].I_3^{'}-[r_1+j\omega(L_{S1}+L_1+M_{12})].I_4^{'}-$$
$$-[r_1+j\omega(L_{S1}+L_1+M_{12}+M_{13})].I_5^{'}-[r_1+j\omega(L_{S1}+L_1+M_{12}+M_{13}+M_{14})].I_6^{'}-$$
$$-[r_1+j\omega(L_{S1}+L_1+M_{12}+M_{13})].\dot{I}_7^{'}=\dot{E}$$

$$-j\omega L_1.\dot{I}_1^{'}-[r_1+j\omega(L_{S1}+L_1)].I_2^{'}+\left[r_1+r_{S1}+R_T+j\omega(L_{S1}+L_1)-j\frac{1}{\omega C_{S1}}\right].\dot{I}_3^{'}+$$
$$+[r_1+R_T+j\omega(L_{S1}+L_1+M_{12})].\dot{I}_4^{'}+[r_1+R_T+j\omega(L_{S1}+L_1+M_{12}+M_{13})].\dot{I}_5^{'}+$$
$$+[r_1+R_T+j\omega(L_{S1}+L_1+M_{12}+M_{13}+M_{14})].\dot{I}_6^{'}+[r_1+R_T+j\omega(L_{S1}+L_1+M_{12}+M_{13})].\dot{I}_7^{'}=0$$

$$-j\omega(L_1+M_{12}).\dot{I}_1^{'}-[r_1+j\omega(L_{S1}+L_1+M_{12})].I_2^{'}+[r_1+R_T+j\omega(L_{S1}+L_1+M_{12})].I_3^{'}+$$
$$+\left[r_1+r_2+r_{S2}+R_T+j\omega(L_{S1}+L_1+L_{S2}+L_2+2M_{12})-j\frac{1}{\omega C_{S2}}\right].I_4^{'}+$$
$$+[r_1+r_2+R_T+j\omega(L_{S1}+L_1+L_{S2}+L_2+2M_{12}+M_{13}+M_{23})].I_5^{'}+$$
$$+[r_1+r_2+R_T+j\omega(L_{S1}+L_1+L_{S2}+L_2+2M_{12}+M_{13}+M_{14}+M_{23}+M_{24})].I_6^{'}+$$
$$+[r_1+r_2+R_T+j\omega(L_{S1}+L_1+L_{S2}+L_2+2M_{12}+M_{13}+M_{23})].I_7^{'}=0$$

$$-j\omega(L_1+M_{12}+M_{13}).\dot{I}_1^{'}-[r_1+j\omega(L_{S1}+L_1+M_{12}+M_{13})].I_2^{'}+[r_1+R_T+j\omega(L_{S1}+L_1+M_{12}+M_{13})].\dot{I}_3^{'}+$$
$$+[r_1+r_2+R_T+j\omega(L_{S1}+L_1+L_{S2}+L_2+2M_{12}+M_{13}+M_{23})].\dot{I}_4^{'}+$$
$$+\left[r_1+r_2+r_3+r_{S3}+R_T+j\omega(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+2M_{12}+2M_{13}+2M_{23})-j\frac{1}{\omega C_{S3}}\right].\dot{I}_5^{'}+$$
$$+[r_1+r_2+r_3+R_T+j\omega(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+2M_{12}+2M_{13}+M_{14}+2M_{23}+M_{24}+M_{34})].\dot{I}_6^{'}+$$
$$+[r_1+r_2+r_3+R_T+j\omega(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+2M_{12}+2M_{13}+2M_{23})].\dot{I}_7^{'}=0$$

$$-j\omega(L_1+M_{12}+M_{13}+M_{14}).\dot{I}_1^{'}-\left[r_1+j\omega\left(L_{S1}+L_1+M_{12}+M_{13}+M_{14}\right)\right].I_2^{'}+$$
$$+\left[r_1+R_T+j\omega\left(L_{S1}+L_1+M_{12}+M_{13}+M_{14}\right)\right].\dot{I}_3^{'}+$$
$$+\left[r_1+r_2+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+2M_{12}+M_{13}+M_{23}+M_{14}+M_{24}\right)\right].\dot{I}_4^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+2M_{12}+2M_{13}+2M_{23}+M_{14}+M_{24}+M_{34}\right)\right].\dot{I}_5^{'}+$$
$$+\left[\begin{array}{l} r_1+r_2+r_3+r_4+r_{S4}+R_T+ \\ +j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+L_{S4}+L_4+2M_{12}+2M_{13}+2M_{14}+2M_{23}+2M_{24}+2M_{34}\right)- \\ -j\dfrac{1}{\omega C_{S4}} \end{array}\right].\dot{I}_6^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+2M_{12}+2M_{13}+2M_{23}+M_{14}+M_{24}+M_{34}\right)\right].\dot{I}_7^{'}=0$$

$$-j\omega(L_1+M_{12}+M_{13}).\dot{I}_1^{'}-\left[r_1+j\omega\left(L_{S1}+L_1+M_{12}+M_{13}\right)\right].I_2^{'}+\left[r_1+R_T+j\omega\left(L_{S1}+L_1+M_{12}+M_{13}\right)\right].\dot{I}_3^{'}+$$
$$+\left[r_1+r_2+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+2M_{12}+M_{13}+M_{23}\right)\right].\dot{I}_4^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+2M_{12}+2M_{13}+2M_{23}\right)\right].\dot{I}_5^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+2M_{12}+2M_{13}+M_{14}+2M_{23}+M_{24}+M_{34}\right)\right].\dot{I}_6^{'}+$$
$$+\left[r_1+r_2+r_3+r_{t6}+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+2M_{12}+2M_{13}+2M_{23}\right)\right].\dot{I}_7^{'}=0$$

2nd Interval (first transitive process) the state variables method for R-load

$$+L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+0.\frac{di_3^{'}(t)}{dt}+0.\frac{di_4^{'}(t)}{dt}+0.\frac{di_5^{'}(t)}{dt}+L_{S1}.\frac{di_6^{'}(t)}{dt}-L_{S1}.\frac{di_7^{'}(t)}{dt}+0.\frac{di_8^{'}(t)}{dt}=$$
$$=-(r_1+R_\mu).i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)+0.i_5^{'}(t)-r_1.i_6^{'}(t)+r_1.i_7^{'}(t)+0.i_8^{'}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+L_0.\frac{di_2^{'}(t)}{dt}+0.\frac{di_3^{'}(t)}{dt}+0.\frac{di_4^{'}(t)}{dt}+0.\frac{di_5^{'}(t)}{dt}+0.\frac{di_6^{'}(t)}{dt}+0.\frac{di_7^{'}(t)}{dt}+0.\frac{di_8^{'}(t)}{dt}=$$
$$=0.i_1^{'}(t)-(r_{S1}+R_T).i_2^{'}(t)-R_T.i_3^{'}(t)-R_T.i_4^{'}(t)-R_T.i_5^{'}(t)+0.i_6^{'}(t)-R_T.i_7^{'}(t)+0.i_8^{'}(t)-u_{CS1}+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}).\frac{di_4^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}+M_{24}).\frac{di_5^{'}(t)}{dt}-M_{12}.\frac{di_6^{'}(t)}{dt}+$$
$$+(L_2+L_{S2}+M_{12}+M_{23}).\frac{di_8^{'}(t)}{dt}+M_{24}.\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+r_{S2}+R_T).i_3^{'}(t)-(r_2+R_T).i_4^{'}(t)-(r_2+R_T).i_5^{'}(t)+$$
$$+0.i_6^{'}(t)-(r_2+R_T).i_7^{'}(t)+0.i_8^{'}(t)-u_{CS2}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}).\frac{di_4^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{s3}+$$

$$+2.M_{23}+M_{24}).\frac{di_5^{'}(t)}{dt}-(M_{12}+M_{13}).\frac{di_6^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{12}+M_{13}).\frac{di_8^{'}(t)}{dt}=$$

$$=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+r_{S3}+R_T).i_4^{'}(t)-(r_2+r_3+R_T).i_5^{'}(t)+0.i_6^{'}(t)-(r_2+r_3+R_T).i_7^{'}(t)+$$

$$+0.i_8^{'}(t)-u_{CS3}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}+M_{24}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{24}+M_{34}).\frac{di_4^{'}(t)}{dt}+$$

$$(L_2+L_{S2}+L_3+L_{S3}+L_4+L_{S4}+2.M_{23}+2.M_{34}+2.M_{24}).\frac{di_5^{'}(t)}{dt}-(M_{12}+M_{13}+M_{14}).\frac{di_6^{'}(t)}{dt}+(L_2+L_{S2}+L_3+$$

$$+L_{S3}+2.M_{23}+M_{24}+M_{34}+M_{12}+M_{13}+M_{14}).\frac{di_7^{'}(t)}{dt}+(L_4+L_{S4}+M_{23}+M_{34}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-$$

$$-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+R_T).i_4^{'}(t)-(r_2+r_3+r_4+r_{S4}+R_T).i_5^{'}(t)+0.i_6^{'}(t)-(r_2+r_3+R_T).i_7^{'}(t)-r_4.i_8^{'}(t)-$$

$$-u_{CS4}(t)+e(t)$$

$$+L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}-M_{12}.\frac{di_3^{'}(t)}{dt}-(M_{12}+M_{13}).\frac{di_4^{'}(t)}{dt}-(M_{12}+M_{13}+M_{14}).\frac{di_5^{'}(t)}{dt}+(L_1+L_{S1}).\frac{di_6^{'}(t)}{dt}-$$

$$-(L_1+L_{S1}+M_{12}+M_{13}).\frac{di_7^{'}(t)}{dt}-M_{14}.\frac{di_8^{'}(t)}{dt}=-r_1.i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)+0.i_5^{'}(t)-r_1.i_6^{'}(t)+r_1.i_7^{'}(t)+$$

$$+0.i_8^{'}(t)+e(t)$$

$$-L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+M_{12}+M_{23}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{12}+M_{23}).\frac{di_4^{'}(t)}{dt}+$$

$$+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{12}+M_{13}+M_{14}+M_{24}+M_{34}).\frac{di_5^{'}(t)}{dt}-(L_1+L_{S1}+M_{12}+M_{13}).\frac{di_6^{'}(t)}{dt}+$$

$$+(L_1+L_{S1}+L_2+L_{S2}+L_3+L_{S3}+2.M_{12}+2.M_{13}+2.M_{23}).\frac{di_7^{'}(t)}{dt}+(M_{14}+M_{22}+M1_{23}).\frac{di_8^{'}(t)}{dt}=+r_1.i_1^{'}(t)-$$

$$-R_T.i_2^{'}(t)-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+R_T).i_4^{'}(t)-(r_2+r_3+R_T).i_5^{'}(t)+r_1.i_6^{'}(t)-(r_1+r_2+r_3+r_{t6(5)}+R_T).i_7^{'}+$$

$$+r_{t6(5)}.i_8^{'}(t)-sign\left[i_7^{'}(t)\right].u_{t6}$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+M_{24}.\frac{di_3^{'}(t)}{dt}+(M_{22}+M_{34}).\frac{di_4^{'}(t)}{dt}+(L_4+L_{S4}+M_{24}+M_{34}).\frac{di_5^{'}(t)}{dt}-M_{14}.\frac{di_6^{'}(t)}{dt}+$$

$$+(M_{14}+M_{24}+M_{34}).\frac{di_7^{'}(t)}{dt}+(L_4+L_{S4}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)-r_4.i_5^{'}(t)+0.i_6^{'}(t)+$$

$$+r_{t6(5)}.i_7^{'}(t)-(r_4+r_{t6(5)}+r_{t8(7)}).i_8^{'}(t)-sign\left[i_8^{'}(t)\right]u_{t8}+sign.\left[i_7^{'}(t)\right]u_{t6}$$

$$C_{S1}.\frac{du_{CS1}(t)}{dt} = i_2^{'}(t)$$
$$C_{S2}.\frac{du_{CS2}(t)}{dt} = i_3^{'}(t)$$
$$C_{S3}.\frac{du_{CS3}(t)}{dt} = i_4^{'}(t)$$
$$C_{S4}.\frac{du_{CS4}(t)}{dt} = i_5^{'}(t)$$

3rd Interval (second transitive process) the state variables method for R-load

$$+L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+0.\frac{di_3^{'}(t)}{dt}+0.\frac{di_4^{'}(t)}{dt}+0.\frac{di_5^{'}(t)}{dt}+L_{S1}.\frac{di_6^{'}(t)}{dt}-L_{S1}.\frac{di_8^{'}(t)}{dt}=$$
$$=-(r_1+r_\mu).i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)+0.i_5^{'}(t)-r_1.i_6^{'}(t)+r_1.i_8^{'}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+L_0.\frac{di_2^{'}(t)}{dt}+0.\frac{di_3^{'}(t)}{dt}+0.\frac{di_4^{'}(t)}{dt}+0.\frac{di_5^{'}(t)}{dt}+0.\frac{di_6^{'}(t)}{dt}+0.\frac{di_8^{'}(t)}{dt}=$$
$$=0.i_1^{'}(t)-(r_{S1}+R_T).i_2^{'}(t)-R_T.i_3^{'}(t)-R_T.i_4^{'}(t)-R_T.i_5^{'}(t)+0.i_6^{'}(t)-R_T.i_8^{'}(t)-u_{CS1}+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}).\frac{di_4^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}+M_{24}).\frac{di_5^{'}(t)}{dt}-M_{12}.\frac{di_6^{'}(t)}{dt}+$$
$$+(L_2+L_{S2}+M_{12}+M_{23}+\quad+M_{24}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+r_{S2}+R_T).i_3^{'}(t)-(r_2+R_T).i_4^{'}(t)-(r_2+R_T).i_5^{'}(t)+$$
$$+0.i_6^{'}(t)-(r_2+R_T).i_8^{'}(t)-u_{CS2}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}).\frac{di_4^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+$$
$$+2.M_{23}+M_3+M_{24}).\frac{di_5^{'}(t)}{dt}-(M_{12}+M_{13}).\frac{di_6^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{12}+M_{13}+M_{24}+M_{34}).\frac{di_8^{'}(t)}{dt}=$$
$$=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+r_{S3}+R_T).i_4^{'}(t)-(r_2+r_3+R_T).i_5^{'}(t)+0.i_6^{'}(t)-(r_2+r_3+R_T).i_8^{'}(t)-u_{CS3}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}+M_{24}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{24}+M_{34}).\frac{di_4^{'}(t)}{dt}+$$
$$(L_2+L_{S2}+L_3+L_{S3}+L_4+L_{S4}+2.M_{23}+2.M_{24}+2.M_{34}).\frac{di_5^{'}(t)}{dt}-(M_{12}+M_{13}+M_{14}).\frac{di_6^{'}(t)}{dt}+(L_2+L_{S2}+L_3+$$
$$+L_{S3}+2.M_{23}+2.M_{24}+2.M_{34}+M_{12}+M_{13}+M_{14}+L_4+L_{S4}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+R_T).i_3^{'}(t)-$$
$$-(r_2+r_3+R_T).i_4^{'}(t)-(r_2+r_3+r_4+r_{S4}+R_T).i_5^{'}(t)+0.i_6^{'}(t)-(r_2+r_3+r_4+R_T).i_8^{'}(t)-u_{CS4}(t)+e(t)$$

$$+L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}-M_{12}.\frac{di_3^{'}(t)}{dt}-(M_{12}+M_{13}).\frac{di_4^{'}(t)}{dt}-(M_{12}+M_{13}+M_{14}).\frac{di_5^{'}(t)}{dt}+(L_1+L_{S1}).\frac{di_6^{'}(t)}{dt}-$$

$$-(L_1+L_{S1}+M_{12}+M_{13}+M_{14}).\frac{di_8^{'}(t)}{dt}=-r_1.i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)+0.i_5^{'}(t)-r_1.i_6^{'}(t)+r_1.i_8^{'}(t)+e(t)$$

$$-L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+M_{12}+M_{23}+M_{24}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{12}+M_{24}+M_{34}).\frac{di_4^{'}(t)}{dt}+$$

$$+(L_2+L_{S2}+L_3+L_{S3}+L_4+L_{S4}+2.M_{23}+M_{12}+M_{13}+M_{14}+2.M_{24}+2.M_{34}).\frac{di_5^{'}(t)}{dt}-(L_1+L_{S1}+M_{12}+M_{13}+M_{14}).\frac{di_6^{'}(t)}{dt}+$$

$$+(L_1+L_{S1}+L_2+L_{S2}+L_{S3}+2.M_{12}+2.M_{13}+2.M_{23}+L_4+L_{S4}+2.M_{14}+2.M_{24}+2.M_{34}).\frac{di_8^{'}(t)}{dt}=+r_1.i_1^{'}(t)-R_T.i_2^{'}(t)-$$

$$-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+R_T).i_4^{'}(t)-(r_2+r_3+r_4+R_T).i_5^{'}(t)+r_1.i_6^{'}(t)-(r_1+r_2+r_3+r_4+r_{t7(8)}+R_T).i_8^{'}-sign\left[i_8^{'}(t)\right].u_{t8(7)}$$

$$\begin{aligned}
&C_{S1}.\frac{du_{CS1}(t)}{dt}=i_2^{'}(t)\\
&C_{S2}.\frac{du_{CS2}(t)}{dt}=i_3^{'}(t)\\
&C_{S3}.\frac{du_{CS3}(t)}{dt}=i_4^{'}(t)\\
&C_{S4}.\frac{du_{CS4}(t)}{dt}=i_5^{'}(t)
\end{aligned}\qquad (1)$$

I 1st Interval (established move) mesh current method in a complex form for L-load

$$+(R_\mu+j\omega L_1)\dot{I}_1^{'}+j\omega L_1.\dot{I}_2^{'}-j\omega L_1.\dot{I}_3^{'}-j\omega(L_1+M_{12})\dot{I}_4^{'}-j\omega(L_1+M_{12}+M_{13})\dot{I}_5^{'}-$$

$$-j\omega(L_1+M_{12}+M_{13}+M_{14})\dot{I}_6^{'}-j\omega(L_1+M_{12}+M_{13})\dot{I}_7^{'}=0$$

$$+j\omega L_1.\dot{I}_1^{'}+\left[r_1+j\omega(L_{S1}+L_1)\right].I_2^{'}-\left[r_1+j\omega(L_{S1}+L_1)\right].I_3^{'}-\left[r_1+j\omega(L_{S1}+L_1+M_{12})\right].I_4^{'}-$$

$$-\left[r_1+j\omega(L_{S1}+L_1+M_{12}+M_{13})\right].I_5^{'}-\left[r_1+j\omega(L_{S1}+L_1+M_{12}+M_{13}+M_{14})\right].I_6^{'}-$$

$$-\left[r_1+j\omega(L_{S1}+L_1+M_{12}+M_{13})\right].\dot{I}_7^{'}=\dot{E}$$

$$-j\omega L_1.\dot{I}_1^{'}-\left[r_1+j\omega(L_{S1}+L_1)\right].I_2^{'}+\left[r_1+r_{S1}+R_T+j\omega(L_{S1}+L_1+L_T)-j\frac{1}{\omega C_{S1}}\right].\dot{I}_3^{'}+$$

$$+\left[r_1+R_T+j\omega(L_{S1}+L_1++L_T+M_{12})\right].\dot{I}_4^{'}+\left[r_1+R_T+j\omega(L_{S1}+L_1+M_{12}+L_T+M_{13})\right].\dot{I}_5^{'}+$$

$$+\left[r_1+R_T+j\omega(L_{S1}+L_1+L_T+M_{12}+M_{13}+M_{14})\right].\dot{I}_6^{'}+\left[r_1+R_T+j\omega(L_{S1}+L_1+L_T+M_{12}+M_{13})\right].\dot{I}_7^{'}=0$$

$$-j\omega(L_1+M_{12}).\dot{I}_1^{'}-\left[r_1+j\omega\left(L_{S1}+L_1+M_{12}\right)\right].I_2^{'}+\left[r_1+R_T+j\omega\left(L_{S1}+L_1+L_T+M_{12}\right)\right].I_3^{'}+$$
$$+\left[r_1+r_2+r_{S2}+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_T+2M_{12}\right)-j\frac{1}{\omega C_{S2}}\right].I_4^{'}+$$
$$+\left[r_1+r_2+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_T+2M_{12}+M_{13}+M_{23}\right)\right].I_5^{'}+$$
$$+\left[r_1+r_2+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_T+2M_{12}+M_{13}+M_{14}+M_{23}+M_{24}\right)\right].I_6^{'}+$$
$$+\left[r_1+r_2+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_T+2M_{12}+M_{13}+M_{23}\right)\right].I_7^{'}=0$$

$$-j\omega(L_1+M_{12}+M_{13}).\dot{I}_1^{'}-\left[r_1+j\omega\left(L_{S1}+L_1+M_{12}+M_{13}\right)\right].I_2^{'}+\left[r_1+R_T+j\omega\left(L_{S1}+L_1+L_T+M_{12}+M_{13}\right)\right].\dot{I}_3^{'}+$$
$$+\left[r_1+r_2+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_T+2M_{12}+M_{13}+M_{23}\right)\right].\dot{I}_4^{'}+$$
$$+\left[r_1+r_2+r_3+r_{S3}+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+L_T+2M_{12}+2M_{13}+2M_{23}\right)-j\frac{1}{\omega C_{S3}}\right].\dot{I}_5^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+L_T+2M_{12}+2M_{13}+M_{14}+2M_{23}+M_{24}+M_{34}\right)\right].\dot{I}_6^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_T+L_3+2M_{12}+2M_{13}+2M_{23}\right)\right].\dot{I}_7^{'}=0$$

$$-j\omega(L_1+M_{12}+M_{13}+M_{14}).\dot{I}_1^{'}-\left[r_1+j\omega\left(L_{S1}+L_1+M_{12}+M_{13}+M_{14}\right)\right].I_2^{'}+$$
$$+\left[r_1+R_T+j\omega\left(L_{S1}+L_1+L_T+M_{12}+M_{13}+M_{14}\right)\right].\dot{I}_3^{'}+$$
$$+\left[r_1+r_2+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_T+2M_{12}+M_{13}+M_{23}+M_{14}+M_{24}\right)\right].\dot{I}_4^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+L_T+2M_{12}+2M_{13}+2M_{23}+M_{14}+M_{24}+M_{34}\right)\right].\dot{I}_5^{'}+$$
$$+\left[\begin{array}{l} r_1+r_2+r_3+r_4+r_{S4}+R_T+ \\ +j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+L_{S4}+L_4+L_T+2M_{12}+2M_{13}+2M_{14}+2M_{23}+2M_{24}+2M_{34}\right)- \\ -j\dfrac{1}{\omega C_{S4}} \end{array}\right].\dot{I}_6^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+L_T+2M_{12}+2M_{13}+2M_{23}+M_{14}+M_{24}+M_{34}\right)\right].\dot{I}_7^{'}=0$$

$$-j\omega(L_1+M_{12}+M_{13}).\dot{I}_1^{'}-\left[r_1+j\omega\left(L_{S1}+L_1+M_{12}+M_{13}\right)\right].I_2^{'}+\left[r_1+R_T+j\omega\left(L_{S1}+L_1+L_T+M_{12}+M_{13}\right)\right].\dot{I}_3^{'}+$$
$$+\left[r_1+r_2+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_T+2M_{12}+M_{13}+M_{23}\right)\right].\dot{I}_4^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+L_T+2M_{12}+2M_{13}+2M_{23}\right)\right].\dot{I}_5^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+L_T+2M_{12}+2M_{13}+M_{14}+2M_{23}+M_{24}+M_{34}\right)\right].\dot{I}_6^{'}+$$
$$+\left[r_1+r_2+r_3+r_{t6}+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+L_T+2M_{12}+2M_{13}+2M_{23}\right)\right].\dot{I}_7^{'}=0$$

2nd Interval (first transitive process) the state variables method for L-load

$$+L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+0.\frac{di_3^{'}(t)}{dt}+0.\frac{di_4^{'}(t)}{dt}+0.\frac{di_5^{'}(t)}{dt}+L_{S1}.\frac{di_6^{'}(t)}{dt}-L_{S1}.\frac{di_7^{'}(t)}{dt}+0.\frac{di_8^{'}(t)}{dt}=$$
$$=-(r_1+R_\mu).i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)+0.i_5^{'}(t)-r_1.i_6^{'}(t)+r_1.i_7^{'}(t)+0.i_8^{'}(t)+e(t)$$
$$+0.\frac{di_1^{'}(t)}{dt}+(L_0+L_T).\frac{di_2^{'}(t)}{dt}+L_T.\frac{di_3^{'}(t)}{dt}+L_T.\frac{di_4^{'}(t)}{dt}+L_T.\frac{di_5^{'}(t)}{dt}+0.\frac{di_6^{'}(t)}{dt}+L_T.\frac{di_7^{'}(t)}{dt}+0.\frac{di_8^{'}(t)}{dt}=$$
$$=0.i_1^{'}(t)-(r_{S1}+R_T).i_2^{'}(t)-R_T.i_3^{'}(t)-R_T.i_4^{'}(t)-R_T.i_5^{'}(t)+0.i_6^{'}(t)-R_T.i_7^{'}(t)+0.i_8^{'}(t)-u_{CS1}+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+L_T.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+L_T).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}+L_T).\frac{di_4^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}+M_{24}+L_T).\frac{di_5^{'}(t)}{dt}-M_{12}.\frac{di_6^{'}(t)}{dt}+$$
$$+(L_2+L_{S2}+M_{12}+M_{23}+L_T).\frac{di_7^{'}(t)}{dt}+M_{24}.\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+r_{S2}+R_T).i_3^{'}(t)-(r_2+R_T).i_4^{'}(t)-(r_2+R_T).i_5^{'}(t)+$$
$$+0.i_6^{'}(t)-(r_2+R_T).i_7^{'}(t)+0.i_8^{'}(t)-u_{CS2}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+L_T.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+L_T+M_{23}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+L_T+2.M_{23}).\frac{di_4^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+$$
$$+L_T+2.M_{23}+M_{34}+M_{24}).\frac{di_5^{'}(t)}{dt}-(M_{12}+M_{13}).\frac{di_6^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+L_T+2.M_{23}+M_{12}+M_{13}).\frac{di_7^{'}(t)}{dt}+$$
$$+(M_{24}+M_{33}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+r_{S3}+R_T).i_4^{'}(t)-(r_2+r_3+R_T).i_5^{'}(t)+0.i_6^{'}(t)-$$
$$-(r_2+r_3+R_T).i_7^{'}(t)+0.i_8^{'}(t)-u_{CS3}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+L_T.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+L_T+M_{23}+M_{24}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+L_T+2.M_{23}+M_{24}+M_{34}).\frac{di_4^{'}(t)}{dt}+$$
$$(L_2+L_{S2}+L_3+L_{S3}+L_4+L_{S4}+L_T+2.M_{23}+2.M_{34}+2.M_{24}).\frac{di_5^{'}(t)}{dt}-(M_{12}+M_{13}+M_{14}).\frac{di_6^{'}(t)}{dt}+(L_2+L_{S2}+L_3+$$
$$+L_{S3}+L_T+2.M_{23}+M_{24}+M_{34}+M_{12}+M_{13}+M_{14}).\frac{di_7^{'}(t)}{dt}+(L_4+L_{S4}+M_{23}+M_{34}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-$$
$$-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+R_T).i_4^{'}(t)-(r_2+r_3+r_4+r_{S4}+R_T).i_5^{'}(t)+0.i_6^{'}(t)-(r_2+r_3+R_T).i_7^{'}(t)-r_4.i_8^{'}(t)-u_{CS4}(t)+e(t)$$

$$+L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}-M_{12}.\frac{di_3^{'}(t)}{dt}-(M_{12}+M_{13}).\frac{di_4^{'}(t)}{dt}-(M_{12}+M_{13}+M_{14}).\frac{di_5^{'}(t)}{dt}+(L_1+L_{S1}).\frac{di_6^{'}(t)}{dt}-$$
$$-(L_1+L_{S1}+M_{12}+M_{13}).\frac{di_7^{'}(t)}{dt}-M_{14}.\frac{di_8^{'}(t)}{dt}=-r_1.i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)+0.i_5^{'}(t)-r_1.i_6^{'}(t)+r_1.i_7^{'}(t)+$$
$$+0.i_8^{'}(t)+e(t)$$

$$-L_{S1}.\frac{di_1^{'}(t)}{dt}+L_T.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+L_T+M_{12}+M_{23}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+L_T+2.M_{23}+M_{12}+M_{23}).\frac{di_4^{'}(t)}{dt}+$$

$$+(L_2+L_{S2}+L_3+L_{S3}+L_T+2.M_{23}+M_{12}+M_{13}+M_{14}+M_{24}+M_{34}).\frac{di_5^{'}(t)}{dt}-(L_1+L_{S1}+M_{12}+M_{13}).\frac{di_6^{'}(t)}{dt}+$$

$$+(L_1+L_{S1}+L_2+L_{S2}+L_3+L_{S3}+L_T+2.M_{12}+2.M_{13}+2.M_{23}).\frac{di_7^{'}(t)}{dt}+(M_{14}+M_{24}+M_{34}).\frac{di_8^{'}(t)}{dt}=+r_1.i_1^{'}(t)-$$

$$-R_T.i_2^{'}(t)-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+R_T).i_4^{'}(t)-(r_2+r_3+R_T).i_5^{'}(t)+r_1.i_6^{'}(t)-(r_1+r_2+r_3+r_{t6(5)}+R_T).i_7^{'}+r_{t6(5)}.i_8^{'}(t)-$$

$$-sign\left[i_7^{'}(t)\right].u_{t6}\left[u_{C_{S3}+r_{S3}}(t)\right]$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+M_{24}.\frac{di_3^{'}(t)}{dt}+(M_{22}+M_{34}).\frac{di_4^{'}(t)}{dt}+(L_4+L_{S4}+M_{24}+M_{34}).\frac{di_5^{'}(t)}{dt}-M_{14}.\frac{di_6^{'}(t)}{dt}+$$

$$+(M_{14}+M_{24}+M_{34}).\frac{di_7^{'}(t)}{dt}+(L_4+L_{S4}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)-r_4.i_5^{'}(t)+0.i_6^{'}(t)+$$

$$+r_{t6(5)}.i_7^{'}(t)-(r_4+r_{t6(5)}+r_{t8(7)}).i_8^{'}(t)-sign\left[i_8^{'}(t)\right]u_{t8}\left[u_{CS4+rS4}(t)\right]+sign\left[i_7^{'}(t)\right]u_{t6}\left[u_{CS3+rS4}(t)\right]$$

$$C_{S1}.\frac{du_{CS1}(t)}{dt}=i_2^{'}(t)$$

$$C_{S2}.\frac{du_{CS2}(t)}{dt}=i_3^{'}(t)$$

$$C_{S3}.\frac{du_{CS3}(t)}{dt}=i_4^{'}(t)$$

$$C_{S4}.\frac{du_{CS4}(t)}{dt}=i_5^{'}(t)$$

3rd Interval (second transitive process) the state variables method for L-load

$$+L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+0.\frac{di_3^{'}(t)}{dt}+0.\frac{di_4^{'}(t)}{dt}+0.\frac{di_5^{'}(t)}{dt}+L_{S1}.\frac{di_6^{'}(t)}{dt}-L_{S1}.\frac{di_8^{'}(t)}{dt}=$$

$$=-(r_1+r_\mu).i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)+0.i_5^{'}(t)-r_1.i_6^{'}(t)+r_1.i_8^{'}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+(L_0+L_T).\frac{di_2^{'}(t)}{dt}+L_T.\frac{di_3^{'}(t)}{dt}+L_T.\frac{di_4^{'}(t)}{dt}+L_T.\frac{di_5^{'}(t)}{dt}+0.\frac{di_6^{'}(t)}{dt}+L_T.\frac{di_8^{'}(t)}{dt}=$$

$$=0.i_1^{'}(t)-(r_{S1}+R_T).i_2^{'}(t)-R_T.i_3^{'}(t)-R_T.i_4^{'}(t)-R_T.i_5^{'}(t)+0.i_6^{'}(t)-R_T.i_8^{'}(t)-u_{CS1}+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+L_T.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+L_T).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_T+M_{23}).\frac{di_4^{'}(t)}{dt}+(L_2+L_{S2}+L_T+M_{23}+M_{24}).\frac{di_5^{'}(t)}{dt}-$$

$$-M_{12}.\frac{di_6^{'}(t)}{dt}+(L_2+L_{S2}+L_T+M_{12}+M_{23}+M_{24}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+r_{S2}+R_T).i_3^{'}(t)-(r_2+R_T).i_4^{'}(t)-$$

$$-(r_2+R_T).i_5^{'}(t)+0.i_6^{'}(t)-(r_2+R_T).i_8^{'}(t)-u_{CS2}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+L_T.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+L_T+M_{23}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+L_T+2.M_{23}).\frac{di_4^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{s3}+L_T+$$

$$+2.M_{23}+M_{34}+M_{24}).\frac{di_5^{'}(t)}{dt}-(M_{12}+M_{13}).\frac{di_6^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{12}+M_{13}+L_T+M_{24}+M_{34}).$$

$$.\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+r_{S3}+R_T).i_4^{'}(t)-(r_2+r_3+R_T).i_5^{'}(t)+0.i_6^{'}(t)-(r_2+r_3+R_T).i_8^{'}(t)-u_{CS3}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+L_T.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+L_T+M_{23}+M_{24}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+L_T+2.M_{23}+M_{24}+M_{34}).\frac{di_4^{'}(t)}{dt}+$$

$$(L_2+L_{S2}+L_3+L_{S3}+L_4+L_{S4}+L_T+2.M_{23}+2.M_{24}+2.M_{34}).\frac{di_5^{'}(t)}{dt}-(M_{12}+M_{13}+M_{14}).\frac{di_6^{'}(t)}{dt}+(L_2+L_{S2}+L_3+$$

$$+L_{S3}+L_4+L_{S4}+L_T+2.M_{23}+2.M_{24}+2.M_{34}+M_{12}+M_{13}+M_{14}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+R_T).i_3^{'}(t)-$$

$$-(r_2+r_3+R_T).i_4^{'}(t)-(r_2+r_3+r_4+r_{S4}+R_T).i_5^{'}(t)+0.i_6^{'}(t)-(r_2+r_3+r_4+R_T).i_8^{'}(t)-u_{CS4}(t)+e(t)$$

$$+L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}-M_{12}.\frac{di_3^{'}(t)}{dt}-(M_{12}+M_{13}).\frac{di_4^{'}(t)}{dt}-(M_{12}+M_{13}+M_{14}).\frac{di_5^{'}(t)}{dt}+(L_1+L_{S1}).\frac{di_6^{'}(t)}{dt}-$$

$$-(L_1+L_{S1}+M_{12}+M_{13}+M_{14}).\frac{di_8^{'}(t)}{dt}=-r_1.i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)+0.i_5^{'}(t)-r_1.i_6^{'}(t)+r_1.i_8^{'}(t)+e(t)$$

$$-L_{S1}.\frac{di_1^{'}(t)}{dt}+L_T.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+L_T+M_{12}+M_{23}+M_{24}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+L_T+2.M_{23}+M_{12}+M_{24}+M_{34}).\frac{di_4^{'}(t)}{dt}+$$

$$+(L_2+L_{S2}+L_3+L_{S3}+L_4+L_{S4}+L_T+2.M_{23}+M_{12}+M_{13}+M_{14}+2.M_{24}+2.M_{34}).\frac{di_5^{'}(t)}{dt}-(L_1+L_{S1}+M_{12}+M_{13}+M_{14}).\frac{di_6^{'}(t)}{dt}+$$

$$+(L_1+L_{S1}+L_2+L_{S2}+L_{S3}+L_T+2.M_{12}+2.M_{13}+2.M_{23}+L_4+L_{S4}+2.M_{14}+2.M_{24}+2.M_{34}).\frac{di_8^{'}(t)}{dt}=+r_1.i_1^{'}(t)-R_T.i_2^{'}(t)-$$

$$-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+R_T).i_4^{'}(t)-(r_2+r_3+r_4+R_T).i_5^{'}(t)+r_1.i_6^{'}(t)-(r_1+r_2+r_3+r_4+r_{t7(8)}+R_T).i_8^{'}-sign\left[i_8^{'}(t)\right].u_{t8(7)}$$

$$C_{S1}.\frac{du_{CS1}(t)}{dt}=i_2^{'}(t)$$
$$C_{S2}.\frac{du_{CS2}(t)}{dt}=i_3^{'}(t)$$
$$C_{S3}.\frac{du_{CS3}(t)}{dt}=i_4^{'}(t) \qquad (2)$$
$$C_{S4}.\frac{du_{CS4}(t)}{dt}=i_5^{'}(t)$$

1st Interval (established move) mesh current method in a complex form for C-load

$$+(R_\mu+j\omega L_1)\dot{I}_1^{'}+j\omega L_1.\dot{I}_2^{'}-j\omega L_1.\dot{I}_3^{'}-j\omega(L_1+M_{12})\dot{I}_4^{'}-j\omega(L_1+M_{12}+M_{13})\dot{I}_5^{'}-$$
$$-j\omega(L_1+M_{12}+M_{13}+M_{14})\dot{I}_6^{'}-j\omega(L_1+M_{12}+M_{13})\dot{I}_7^{'}=0$$

$$+ j\omega L_1.\dot{I}_1^{'} + \left[r_1 + j\omega\left(L_{S1} + L_1\right)\right].I_2^{'} - \left[r_1 + j\omega\left(L_{S1} + L_1\right)\right].I_3^{'} - \left[r_1 + j\omega\left(L_{S1} + L_1 + M_{12}\right)\right].I_4^{'} -$$
$$- \left[r_1 + j\omega\left(L_{S1} + L_1 + M_{12} + M_{13}\right)\right].I_5^{'} - \left[r_1 + j\omega\left(L_{S1} + L_1 + M_{12} + M_{13} + M_{14}\right)\right].I_6^{'} -$$
$$- \left[r_1 + j\omega\left(L_{S1} + L_1 + M_{12} + M_{13}\right)\right].\dot{I}_7^{'} = \dot{E}$$

$$- j\omega L_1.\dot{I}_1^{'} - \left[r_1 + j\omega\left(L_{S1} + L_1\right)\right].I_2^{'} + \left[r_1 + r_{S1} + R_T + j\omega\left(L_{S1} + L_1\right) - j\left(\frac{1}{\omega C_{S1}} + \frac{1}{\omega C_T}\right)\right].\dot{I}_3^{'} +$$
$$+ \left[r_1 + R_T + j\omega\left(L_{S1} + L_1 + M_{12}\right) - j\frac{1}{\omega C_T}\right].\dot{I}_4^{'} + \left[r_1 + R_T + j\omega\left(L_{S1} + L_1 + M_{12} + M_{13}\right) - j\frac{1}{\omega C_T}\right].\dot{I}_5^{'} +$$
$$+ \left[r_1 + R_T + j\omega\left(L_{S1} + L_1 + M_{12} + M_{13} + M_{14}\right) - j\frac{1}{\omega C_T}\right].\dot{I}_6^{'} + \left[r_1 + R_T + j\omega\left(L_{S1} + L_1 + M_{12} + M_{13} - j\frac{1}{\omega C_T}\right)\right].\dot{I}_7^{'} = 0$$

$$- j\omega\left(L_1 + M_{12}\right).\dot{I}_1^{'} - \left[r_1 + j\omega\left(L_{S1} + L_1 + M_{12}\right)\right].I_2^{'} + \left[r_1 + R_T + j\omega\left(L_{S1} + L_1 + M_{12}\right) - j\frac{1}{\omega C_T}\right].I_3^{'} +$$
$$+ \left[r_1 + r_2 + r_{S2} + R_T + j\omega\left(L_{S1} + L_1 + L_{S2} + L_2 + 2M_{12}\right) - j\left(\frac{1}{\omega C_{S2}} + \frac{1}{\omega C_T}\right)\right].I_4^{'} +$$
$$+ \left[r_1 + r_2 + R_T + j\omega\left(L_{S1} + L_1 + L_{S2} + L_2 + 2M_{12} + M_{13} + M_{23}\right) - j\frac{1}{\omega C_T}\right].I_5^{'} +$$
$$+ \left[r_1 + r_2 + R_T + j\omega\left(L_{S1} + L_1 + L_{S2} + L_2 + 2M_{12} + M_{13} + M_{14} + M_{23} + M_{24}\right) - j\frac{1}{\omega C_T}\right].I_6^{'} +$$
$$+ \left[r_1 + r_2 + R_T + j\omega\left(L_{S1} + L_1 + L_{S2} + L_2 + 2M_{12} + M_{13} + M_{23}\right) - j\frac{1}{\omega C_T}\right].I_7^{'} = 0$$

$$- j\omega\left(L_1 + M_{12} + M_{13}\right).\dot{I}_1^{'} - \left[r_1 + j\omega\left(L_{S1} + L_1 + M_{12} + M_{13}\right)\right].I_2^{'} + \left[r_1 + R_T + j\omega\left(L_{S1} + L_1 + M_{12} + M_{13} - j\frac{1}{\omega C_T}\right)\right].\dot{I}_3^{'} +$$
$$+ \left[r_1 + r_2 + R_T + j\omega\left(L_{S1} + L_1 + L_{S2} + L_2 + 2M_{12} + M_{13} + M_{23}\right) - j\frac{1}{\omega C_T}\right].\dot{I}_4^{'} +$$
$$+ \left[r_1 + r_2 + r_3 + r_{S3} + R_T + j\omega\left(L_{S1} + L_1 + L_{S2} + L_2 + L_{S3} + L_3 + 2M_{12} + 2M_{13} + 2M_{23}\right) - j\left(\frac{1}{\omega C_{S3}} + \frac{1}{\omega C_T}\right)\right].\dot{I}_5^{'} +$$
$$+ \left[r_1 + r_2 + r_3 + R_T + j\omega\left(L_{S1} + L_1 + L_{S2} + L_2 + L_{S3} + L_3 + 2M_{12} + 2M_{13} + M_{14} + 2M_{23} + M_{24} + M_{34}\right) - j\frac{1}{\omega C_T}\right].\dot{I}_6^{'} +$$
$$+ \left[r_1 + r_2 + r_3 + R_T + j\omega\left(L_{S1} + L_1 + L_{S2} + L_2 + L_{S3} + L_3 + 2M_{12} + 2M_{13} + 2M_{23}\right) - j\frac{1}{\omega C_T}\right].\dot{I}_7^{'} = 0$$

$$-j\omega(L_1+M_{12}+M_{13}+M_{14}).\dot{I}_1^{'}-\left[r_1+j\omega\left(L_{S1}+L_1+M_{12}+M_{13}+M_{14}\right)\right].I_2^{'}+$$
$$+\left[r_1+R_T+j\omega\left(L_{S1}+L_1+M_{12}+M_{13}+M_{14}-j\frac{1}{\omega C_T}\right)\right].\dot{I}_3^{'}+$$
$$+\left[r_1+r_2+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+2M_{12}+M_{13}+M_{23}+M_{14}+M_{24}-j\frac{1}{\omega C_T}\right)\right].\dot{I}_4^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+2M_{12}+2M_{13}+2M_{23}+M_{14}+M_{24}+M_{34}-j\frac{1}{\omega C_T}\right)\right].\dot{I}_5^{'}+$$
$$+\left[\begin{array}{l} r_1+r_2+r_3+r_4+r_{S4}+R_T+ \\ +j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+L_{S4}+L_4+2M_{12}+2M_{13}+2M_{14}+2M_{23}+2M_{24}+2M_{34}\right)-j\left(\frac{1}{\omega C_{S4}}+\frac{1}{\omega C_T}\right) \end{array}\right].\dot{I}_6^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+2M_{12}+2M_{13}+2M_{23}+M_{14}+M_{24}+M_{34}-j\frac{1}{\omega C_T}\right)\right].\dot{I}_7^{'}=0$$

$$-j\omega(L_1+M_{12}+M_{13}).\dot{I}_1^{'}-\left[r_1+j\omega\left(L_{S1}+L_1+M_{12}+M_{13}\right)\right].I_2^{'}+\left[r_1+R_T+j\omega\left(L_{S1}+L_1+M_{12}+M_{13}\right)-j\frac{1}{\omega C_T}\right].\dot{I}_3^{'}+$$
$$+\left[r_1+r_2+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+2M_{12}+M_{13}+M_{23}\right)-j\frac{1}{\omega C_T}\right].\dot{I}_4^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+2M_{12}+2M_{13}+2M_{23}\right)-j\frac{1}{\omega C_T}\right].\dot{I}_5^{'}+$$
$$+\left[r_1+r_2+r_3+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+2M_{12}+2M_{13}+M_{14}+2M_{23}+M_{24}+M_{34}\right)\right].\dot{I}_6^{'}+$$
$$+\left[r_1+r_2+r_3+r_{t6}+R_T+j\omega\left(L_{S1}+L_1+L_{S2}+L_2+L_{S3}+L_3+2M_{12}+2M_{13}+2M_{23}\right)-j\frac{1}{\omega C_T}\right].\dot{I}_7^{'}=0$$

2nd Interval (first transitive process) the state variables method for C-load

$$+L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+0.\frac{di_3^{'}(t)}{dt}+0.\frac{di_4^{'}(t)}{dt}+0.\frac{di_5^{'}(t)}{dt}+L_{S1}.\frac{di_6^{'}(t)}{dt}-L_{S1}.\frac{di_7^{'}(t)}{dt}+0.\frac{di_8^{'}(t)}{dt}=$$
$$=-(r_1+R_\mu).i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)+0.i_5^{'}(t)-r_1.i_6^{'}(t)+r_1.i_7^{'}(t)+0.i_8^{'}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+L_0.\frac{di_2^{'}(t)}{dt}+0.\frac{di_3^{'}(t)}{dt}+0.\frac{di_4^{'}(t)}{dt}+0.\frac{di_5^{'}(t)}{dt}+0.\frac{di_6^{'}(t)}{dt}+0.\frac{di_7^{'}(t)}{dt}+0.\frac{di_8^{'}(t)}{dt}=$$
$$=0.i_1^{'}(t)-(r_{S1}+R_T).i_2^{'}(t)-R_T.i_3^{'}(t)-R_T.i_4^{'}(t)-R_T.i_5^{'}(t)+0.i_6^{'}(t)-R_T.i_7^{'}(t)+0.i_8^{'}(t)-u_{CS1}+$$
$$+u_{CT1}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}).\frac{di_4^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}+M_{24}).\frac{di_5^{'}(t)}{dt}-M_{12}.\frac{di_6^{'}(t)}{dt}+$$
$$+(L_2+L_{S2}+M_{12}+M_{23}).\frac{di_7^{'}(t)}{dt}+M_{24}.\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+r_{S2}+R_T).i_3^{'}(t)-(r_2+R_T).i_4^{'}(t)-(r_2+R_T).i_5^{'}(t)+$$
$$+0.i_6^{'}(t)-(r_2+R_T).i_7^{'}(t)+0.i_8^{'}(t)-u_{CS2}(t)+u_{CT1}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}).\frac{di_4^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+$$
$$+2.M_{23}+M_{34}+M_{24}).\frac{di_5^{'}(t)}{dt}-(M_{12}+M_{13}).\frac{di_6^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{12}+M_{13}).\frac{di_8^{'}(t)}{dt}=$$
$$=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+r_{S3}+R_T).i_4^{'}(t)-(r_2+r_3+R_T).i_5^{'}(t)+0.i_6^{'}(t)-(r_2+r_3+R_T).i_7^{'}(t)+$$
$$+0.i_8^{'}(t)-u_{CS3}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}+M_{24}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{24}+M_{34}).\frac{di_4^{'}(t)}{dt}+$$
$$(L_2+L_{S2}+L_3+L_{S3}+L_4+L_{S4}+2.M_{23}+2.M_{34}+2.M_{24}).\frac{di_5^{'}(t)}{dt}-(M_{12}+M_{13}+M_{14}).\frac{di_6^{'}(t)}{dt}+(L_2+L_{S2}+L_3+$$
$$+L_{S3}+2.M_{23}+M_{24}+M_{34}+M_{12}+M_{13}+M_{14}).\frac{di_7^{'}(t)}{dt}+(L_4+L_{S4}+M_{23}+M_{34}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-$$
$$-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+R_T).i_4^{'}(t)-(r_2+r_3+r_4+r_{S4}+R_T).i_5^{'}(t)+0.i_6^{'}(t)-(r_2+r_3+R_T).i_7^{'}(t)-r_4.i_8^{'}(t)-$$
$$-u_{CS4}(t)+u_{CT}(t)+e(t)$$

$$+L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}-M_{12}.\frac{di_3^{'}(t)}{dt}-(M_{12}+M_{13}).\frac{di_4^{'}(t)}{dt}-(M_{12}+M_{13}+M_{14}).\frac{di_5^{'}(t)}{dt}+(L_1+L_{S1}).\frac{di_6^{'}(t)}{dt}-$$
$$-(L_1+L_{S1}+M_{12}+M_{13}).\frac{di_7^{'}(t)}{dt}-M_{14}.\frac{di_8^{'}(t)}{dt}=-r_1.i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)+0.i_5^{'}(t)-r_1.i_6^{'}(t)+r_1.i_7^{'}(t)+$$
$$+0.i_8^{'}(t)+e(t)$$

$$-L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+M_{12}+M_{23}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{12}+M_{23}).\frac{di_4^{'}(t)}{dt}+$$

$$+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{12}+M_{13}+M_{14}+M_{24}+M_{34}).\frac{di_5^{'}(t)}{dt}-(L_1+L_{S1}+M_{12}+M_{13}).\frac{di_6^{'}(t)}{dt}+$$

$$+(L_1+L_{S1}+L_2+L_{S2}+L_3+L_{S3}+2.M_{12}+2.M_{13}+2.M_{23}).\frac{di_7^{'}(t)}{dt}+(M_{14}+M_{24}+M_{34}).\frac{di_8^{'}(t)}{dt}=+r_1.i_1^{'}(t)-$$

$$-R_T.i_2^{'}(t)-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+R_T).i_4^{'}(t)-(r_2+r_3+R_T).i_5^{'}(t)+r_1.i_6^{'}(t)-(r_1+r_2+r_3+r_{t6(5)}+R_T).i_7^{'}+$$

$$+r_{t6(5)}.i_8^{'}(t)+u_{CT}(t)-sign\left[i_7^{'}(t)\right].u_{t6}\left[u_{C_{S3}+r_{S3}}(t)\right]$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+M_{24}.\frac{di_3^{'}(t)}{dt}+(M_{22}+M_{34}).\frac{di_4^{'}(t)}{dt}+(L_4+L_{S4}+M_{24}+M_{34}).\frac{di_5^{'}(t)}{dt}-M_{14}.\frac{di_6^{'}(t)}{dt}+$$

$$+(M_{14}+M_{24}+M_{34}).\frac{di_7^{'}(t)}{dt}+(L_4+L_{S4}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)-r_4.i_5^{'}(t)+0.i_6^{'}(t)+$$

$$+r_{t6(5)}.i_7^{'}(t)-(r_4+r_{t6(5)}+r_{t8(7)}).i_8^{'}(t)-sign\left[i_8^{'}(t)\right].u_{t8}\left[u_{CS4+rS4}(t)\right]+sign\left[i_7^{'}(t)\right].u_{t6}\left[u_{CS3+rS4}(t)\right]$$

$$C_{S1}.\frac{du_{CS1}(t)}{dt}=i_2^{'}(t)$$

$$C_{S2}.\frac{du_{CS2}(t)}{dt}=i_3^{'}(t)$$

$$C_{S3}.\frac{du_{CS3}(t)}{dt}=i_4^{'}(t)$$

$$C_{S4}.\frac{du_{CS4}(t)}{dt}=i_5^{'}(t)$$

$$C_T.\frac{du_{CT}(t)}{dt}=i_2^{'}(t)+i_3^{'}(t)+i_4^{'}(t)+i_5^{'}(t)+i_7^{'}(t)$$

3rd Interval (second transitive process) the state variables method for C-load

$$+L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+0.\frac{di_3^{'}(t)}{dt}+0.\frac{di_4^{'}(t)}{dt}+0.\frac{di_5^{'}(t)}{dt}+L_{S1}.\frac{di_6^{'}(t)}{dt}-L_{S1}.\frac{di_8^{'}(t)}{dt}=$$

$$=-(r_1+r_\mu).i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)+0.i_5^{'}(t)-r_1.i_6^{'}(t)+r_1.i_8^{'}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+L_0.\frac{di_2^{'}(t)}{dt}+0.\frac{di_3^{'}(t)}{dt}+0.\frac{di_4^{'}(t)}{dt}+0.\frac{di_5^{'}(t)}{dt}+0.\frac{di_6^{'}(t)}{dt}+0.\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-$$

$$-(r_{S1}+R_T).i_2^{'}(t)-R_T.i_3^{'}(t)-R_T.i_4^{'}(t)-R_T.i_5^{'}(t)+0.i_6^{'}(t)-R_T.i_8^{'}(t)-u_{CS1}+u_{CT}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}).\frac{di_4^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}+M_{24}).\frac{di_5^{'}(t)}{dt}-M_{12}.\frac{di_6^{'}(t)}{dt}+$$

$$+(L_2+L_{S2}+M_{12}+M_{23}+M_{24}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+r_{S2}+R_T).i_3^{'}(t)-(r_2+R_T).i_4^{'}(t)-(r_2+R_T).i_5^{'}(t)+$$

$$+0.i_6^{'}(t)-(r_2+R_T).i_8^{'}(t)-u_{CS2}(t)+u_{CT}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}).\frac{di_4^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{34}$$

$$+M_{24}).\frac{di_5^{'}(t)}{dt}-(M_{12}+M_{13}).\frac{di_6^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{12}+M_{13}+M_{24}+M_{34}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-$$

$$-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+r_{S3}+R_T).i_4^{'}(t)-(r_2+r_3+R_T).i_5^{'}(t)+0.i_6^{'}(t)-(r_2+r_3+R_T).i_8^{'}(t)-u_{CS3}(t)+u_{CT}(t)+e(t)$$

$$+0.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+M_{23}+M_{24}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{24}+M_{34}).\frac{di_4^{'}(t)}{dt}+$$

$$(L_2+L_{S2}+L_3+L_{S3}+L_4+L_{S4}+2.M_{23}+2.M_{24}+2.M_{34}).\frac{di_5^{'}(t)}{dt}-(M_{12}+M_{13}+M_{14}).\frac{di_6^{'}(t)}{dt}+(L_2+L_{S2}+L_3+$$

$$+L_{S3}+2.M_{23}+2.M_{24}+2.M_{34}+M_{12}+M_{13}+M_{14}+L_4+L_{S4}).\frac{di_8^{'}(t)}{dt}=0.i_1^{'}(t)-R_T.i_2^{'}(t)-(r_2+R_T).i_3^{'}(t)-$$

$$-(r_2+r_3+R_T).i_4^{'}(t)-(r_2+r_3+r_4+r_{S4}+R_T).i_5^{'}(t)+0.i_6^{'}(t)-(r_2+r_3+r_4+R_T).i_8^{'}(t)-u_{CS4}(t)+u_{CT}(t)+e(t)$$

$$+L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}-M_{12}.\frac{di_3^{'}(t)}{dt}-(M_{12}+M_{13}).\frac{di_4^{'}(t)}{dt}-(M_{12}+M_{13}+M_{14}).\frac{di_5^{'}(t)}{dt}+(L_1+L_{S1}).\frac{di_6^{'}(t)}{dt}-$$

$$-(L_1+L_{S1}+M_{12}+M_{13}+M_{14}).\frac{di_8^{'}(t)}{dt}=-r_1.i_1^{'}(t)+0.i_2^{'}(t)+0.i_3^{'}(t)+0.i_4^{'}(t)+0.i_5^{'}(t)-r_1.i_6^{'}(t)+r_1.i_8^{'}(t)+e(t)$$

$$-L_{S1}.\frac{di_1^{'}(t)}{dt}+0.\frac{di_2^{'}(t)}{dt}+(L_2+L_{S2}+M_{12}+M_{23}+M_{24}).\frac{di_3^{'}(t)}{dt}+(L_2+L_{S2}+L_3+L_{S3}+2.M_{23}+M_{12}+M_{24}+M_{34}).\frac{di_4^{'}(t)}{dt}+$$

$$+(L_2+L_{S2}+L_3+L_{S3}+L_4+L_{S4}+2.M_{23}+M_{12}+M_{13}+M_{14}+2.M_{24}+2.M_{34}).\frac{di_5^{'}(t)}{dt}-(L_1+L_{S1}+M_{12}+M_{13}+M_{14}).\frac{di_6^{'}(t)}{dt}+$$

$$+(L_1+L_{S1}+L_2+L_{S2}+L_{S3}+2.M_{12}+2.M_{13}+2.M_{23}+L_4+L_{S4}+2.M_{14}+2.M_{24}+2.M_{34}).\frac{di_8^{'}(t)}{dt}=+r_1.i_1^{'}(t)-R_T.i_2^{'}(t)-$$

$$-(r_2+R_T).i_3^{'}(t)-(r_2+r_3+R_T).i_4^{'}(t)-(r_2+r_3+r_4+R_T).i_5^{'}(t)+r_1.i_6^{'}(t)-(r_1+r_2+r_3+r_4+r_{i7(8)}+R_T).i_8^{'}+u_{_{CT}}(t)-sign\left[i_8^{'}(t)\right]u_{t8(7)}$$

$$C_{S1}.\frac{du_{CS1}(t)}{dt}=i_2^{'}(t)$$

$$C_{S2}.\frac{du_{CS2}(t)}{dt}=i_3^{'}(t)$$

$$C_{S3}.\frac{du_{CS3}(t)}{dt}=i_4^{'}(t) \qquad (3)$$

$$C_{S4}.\frac{du_{CS4}(t)}{dt}=i_5^{'}(t)$$

$$C_T.\frac{du_{CT}(t)}{dt}=i_2^{'}(t)+i_3^{'}(t)+i_4^{'}(t)+i_5^{'}(t)+i_8^{'}(t)$$

Fig. 2, 3 and 4 show the graphs of the circuit for the three intervals of the commutation process.

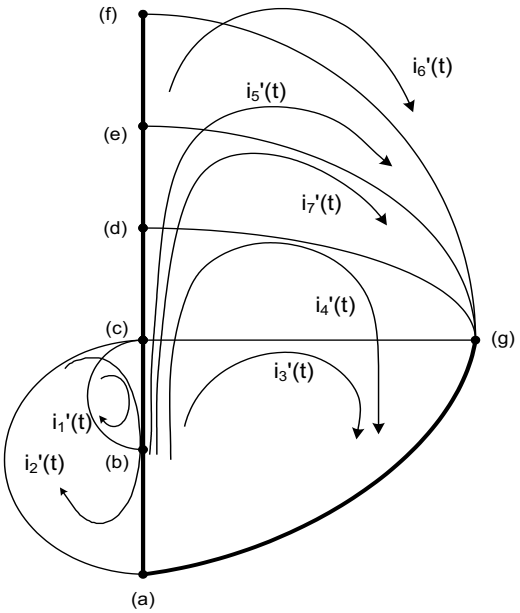


Fig. 2. Graph of the circuit for 1st interval.

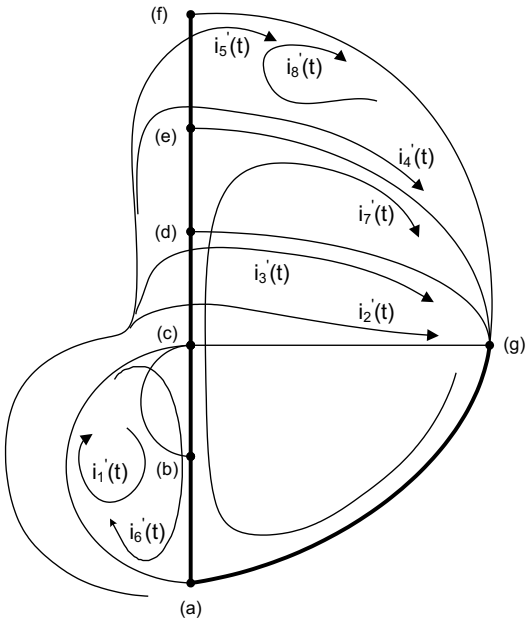


Fig. 3. Graph of the circuit for 2nd interval.

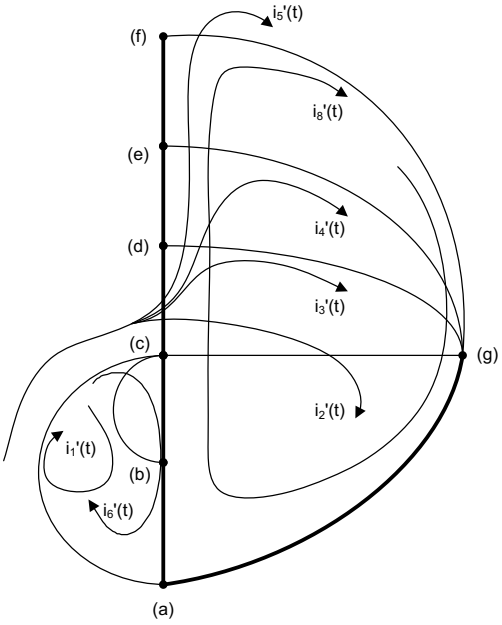


Fig. 4. Graph of the circuit for 3rd interval.

In the first interval, ADAVR still operates in an established alternating-current mode, where the electrical balance is described by the mesh current method in a complex form. The number of the

independent loops is seven and the system of equations consists of seven equations with seven unknowns. The general form of the system assumes the following matrix form:

$$[Y_1].[\dot{I}'] = [\dot{E}], \tag{4}$$

where $[Y_1]$ is a complex conductivity matrix of ADAVR with dimensions 7 rows and 7 columns (i.e. 7x7); $[\dot{I}']$ is the matrix column of mesh currents $\dot{I}_1'; \dot{I}_2'; \ldots \dot{I}_7'$ with dimensions 7x1; $[\dot{E}]$ is the matrix-column of the complexes of the mesh e.m.f. with dimensions 7x1. The numerical method, chosen for solving equation (4) is the Gauss-Jordan method, and the matrix $[Y_1]$ is not singular, regardless of the selection version of the independent loops of the circuit. Therefore, there are no particular difficulties to determine the initial response of ADAVR until the moment when switch K_4 gets closed.

In the second interval, the first transitive process in ADAVR can be observed providing that switches K_3 and K_4 are closed. The analysis is made by the state variables method, where eight of the state variables are mesh currents $i_1'(t); i_2'(t); \ldots; i_7'(t); i_8'(t)$, and the other four are the voltages over the switch-off capacitors $u_{cs1}(t); \ldots; u_{cs4}(t)$. The analysis is made in the temporal field, whereby the system of equations contains twelve equations with twelve unknowns. The matrix of the system of equations is almost singular. This leads to error accumulation during the computations for some specific values of the commutation phase of switch K_4. No alteration of the independent loops in the various versions results in improvement of the matrix type of the system of equations, i.e. it remains almost singular. Nonetheless, the independent loops are chosen in the form shown in fig.1 and fig.3. In this situation, the general matrix form of the system of equations is as follows:

$$[A_2]\frac{d}{dt}[x(t)] = [B_2].[x(t)] + [e_2(t)], \tag{5}$$

where the matrices $[A_2]$ and $[B_2]$ have dimensions 12x12 and consist of nine submatrices:

$$[A_2] = \left[\begin{array}{c|c|c} A_{11} & A_{12} & A_{13} \\ \hline A_{21} & A_{22} & A_{23} \\ \hline A_{31} & A_{32} & A_{33} \end{array}\right], \quad [B_2] = \left[\begin{array}{c|c|c} B_{11} & B_{12} & B_{13} \\ \hline B_{21} & B_{22} & B_{23} \\ \hline B_{31} & B_{32} & B_{33} \end{array}\right]. \tag{6}$$

The matrices [x(t)] and $[e_2(t)]$ have dimensions 12x1 and each of them consists of three submatrices:

$$[x(t)] = \begin{bmatrix} X_{11}(t) \\ \overline{X_{21}(t)} \\ \overline{X_{31}(t)} \end{bmatrix}, \quad [e_2(t)] = \begin{bmatrix} E_{11}(t) \\ \overline{E_{21}(t)} \\ \overline{E_{31}(t)} \end{bmatrix}. \tag{7}$$

Here matrix [x(t)] contains the state variables in the order as listed above, and matrix $[e_2(t)]$ contains the input e.m.f.e(t) and the drops u_{t5}, u_{t6}, u_{t7} and u_{t8} over the thyristor switches K_3 and K_4 in a saturated state.

The dimensions of the submatrices are as follows:

$[A_{11}]$ и $[B_{11}]$ са 5x5; $[A_{12}]$ и $[B_{12}]$ са 5x3; $[A_{13}]$ и $[B_{13}]$ са 5x4;

$[A_{21}]$ и $[B_{21}]$ са 3x5; $[A_{22}]$ и $[B_{22}]$ са 3x3; $[A_{23}]$ и $[B_{23}]$ са 3x4;

$[A_{31}]$ и $[B_{31}]$ са 4x5; $[A_{32}]$ и $[B_{32}]$ са 4x3; $[A_{33}]$ и $[B_{33}]$ са 4x4;

$[X_{11}(t)]$ и $[E_{11}(t)]$ са 5x1; $[X_{21}(t)]$ и $[E_{21}(t)]$ са 3x1; $[X_{31}(t)]$ и $[E_{31}(t)]$ са 4x1.

The matrices $[A_2]$ and $[B_2]$ are sparse, i.e. they have over 30% zero elements, and the following submatrices are also zero ones: $[A_{13}]$; $[A_{23}]$; $[A_{31}]$; $[A_{32}]$; $[B_{23}]$; $[B_{31}(:,1)]$; $[B_{32}]$; $[B_{33}]$; $[E_{31}(t)]$. In addition, submatrices $[A_{33}]$, $[B_{13}]$, $[B_{31}]$ are diagonal. The submatrices of the state variables have the following form:

$$[X_{11}(t)]=\begin{bmatrix} i_1'(t) \\ i_2'(t) \\ ..... \\ i_5'(t) \end{bmatrix};\quad [X_{21}(t)]=\begin{bmatrix} i_6'(t) \\ i_7'(t) \\ i_8'(t) \end{bmatrix};\quad [X_{31}(t)]=\begin{bmatrix} u_{cs1}(t) \\ u_{cs2}(t) \\ u_{cs3}(t) \\ u_{cs4}(t) \end{bmatrix}. \tag{8}$$

The algorithm, used in order to avoid the fact that matrix $[A_2]$ is almost singular, consists in breaking down equation (5) into three matrix equations containing the submatrices listed above, and solving them one after another. With each step forward in time, the following matrix equations are solved:

$$1)\ [A_{22}]\frac{d}{dt}[X_{21}(t)]=[B_{22}].[X_{21}(t)]+[E_{21}(t)], \tag{9}$$

whereby equation (9) is multiplied on the left and right by the opposite matrix $[A_{22}]^{-1}$ and then the approximate values of the first derivatives $\frac{d}{dt}[X_{21}(t)]$ are substituted in the next matrix equation:

$$2)\ [A_{11}]\frac{d}{dt}[X_{11}(t)]=[B_{11}|B_{12}|B_{13}].[X(t)]-[A_{12}]\frac{d}{dt}[X_{21}(t)]+[E_{11}(t)], \tag{10}$$

whereby equation (10) is multiplied on the left and right with the opposite matrix $[A_{11}]^{-1}$ and then RK4 method is applied. The obtained solution is substituted in the next matrix equation:

$$3)\ [A_{33}]\frac{d}{dt}[X_{31}(t)]=[B_{31}(:;2:5)].[X_{11}(t)], \tag{11}$$

whereby equation (11) is multiplied on the left and right by the opposite matrix $[A_{33}]^{-1}$ and then RK4 method is applied. The obtained solution is substituted in the last matrix equation:

$$4)\ [A_{22}]\frac{d}{dt}[X_{21}(t)]=-[A_{21}]\frac{d}{dt}[X_{11}(t)]+[B_{21}|B_{22}].\begin{bmatrix} X_{11}(t) \\ \overline{X_{21}(t)} \end{bmatrix}+[E_{11}(t)], \tag{12}$$

whereby equation (12) is multiplied on the left and right by the opposite matrix $[A_{22}]^{-1}$ and then RK4 method is applied. The obtained solution is substituted in equation (9) so that the next step forward in time be performed, and then again in equations (10), (11) and (12), until the second interval is finished and switch K_3 opens.

The computation procedure operates with nonsingular submatrices $[A_{22}]$, $[A_{11}]$ and $[A_{33}]$ and the obtained solutions do not accumulate error in the time of the second subinterval.

In the third interval, the second transitive process can be observed; here, however, only switch K_4 is closed. The analysis is made in a similar way by the state variables method in the temporal field. The

number of the state variables is now eleven since here the mesh current $i_7^{'}(t)$ is removed from the group of unknowns in the previous interval. The system of equations in third interval has the following form:

$$[A_3]\frac{d}{dt}[x(t)] = [B_3].[x(t)] + [e_3(t)], \tag{13}$$

where the matrices $[A_3]$ and $[B_3]$ have dimensions 11x11 and each of them consists of three submatrices:

$$[A_3] = \left[\begin{array}{c|c|c} a_{11} & a_{12} & a_{13} \\ \hline a_{21} & a_{22} & a_{23} \\ \hline a_{31} & a_{32} & a_{33} \end{array}\right], \quad [B_3] = \left[\begin{array}{c|c|c} b_{11} & b_{12} & b_{13} \\ \hline b_{21} & b_{22} & b_{23} \\ \hline b_{31} & b_{32} & b_{33} \end{array}\right]. \tag{14}$$

The matrices [x(t)] and $[e_3(t)]$ have dimensions 11x1 and each of them consists of three submatrices:

$$[x(t)] = \left[\begin{array}{c} x_{11}(t) \\ \hline x_{21}(t) \\ \hline x_{31}(t) \end{array}\right], \quad [e_3(t)] = \left[\begin{array}{c} e_{11}(t) \\ \hline e_{21}(t) \\ \hline e_{31}(t) \end{array}\right]. \tag{15}$$

The matrix [x(t)] contains the state variables in the order given for the second interval without the current $i_7^{'}(t)$, and the matrix $[e_3(t)]$ contains the input e.m.f.e(t) and the drops u_{t7} and u_{t8} over the thyristor switch K_4 in a saturated state.

The dimensions of the submatrices are as follows:

$[a_{11}]$ и $[b_{11}]$ са 5x5; $[a_{12}]$ и $[b_{12}]$ са 5x2; $[a_{13}]$ и $[b_{13}]$ са 5x4;

$[a_{21}]$ и $[b_{21}]$ са 2x5; $[a_{22}]$ и $[b_{22}]$ са 2x2; $[a_{23}]$ и $[b_{23}]$ са 2x4;

$[a_{31}]$ и $[b_{31}]$ са 4x5; $[a_{32}]$ и $[b_{32}]$ са 4x2; $[a_{33}]$ и $[b_{33}]$ са 4x4;

$[x_{11}(t)]$ и $[e_{11}(t)]$ са 5x1; $[x_{21}(t)]$ и $[e_{21}(t)]$ са 2x1; $[x_{31}(t)]$ и $[e_{31}(t)]$ са 4x1.

The matrices $[A_3]$ and $[B_3]$ are sparse, while matrix $[A_3]$ is almost singular. The following submatrices are also zero ones: $[a_{13}]$; $[a_{23}]$; $[a_{31}]$; $[a_{32}]$; $[b_{23}]$; $[b_{32}]$; $[b_{33}]$; $[e_{31}(t)]$. In addition, submatrices $[a_{33}]$, $[b_{13}]$, $[b_{31}]$ are diagonal. The submatrices of the state variables have the following form:

$$[x_{11}(t)] = \begin{bmatrix} i_1^{'}(t) \\ i_2^{'}(t) \\ ..... \\ i_5^{'}(t) \end{bmatrix}; \quad [x_{21}(t)] = \begin{bmatrix} i_6^{'}(t) \\ i_8^{'}(t) \end{bmatrix}; \quad [x_{31}(t)] = \begin{bmatrix} u_{cs1}(t) \\ u_{cs2}(t) \\ u_{cs3}(t) \\ u_{cs4}(t) \end{bmatrix}. \tag{16}$$

The algorithm, used in order to avoid the fact that matrix $[A_3]$ is almost singular, consists in breaking down equation (13) into three matrix equations containing the submatrices listed above, and at each step forward in time, the following matrix equations are solve:

$$1)\quad [a_{22}]\frac{d}{dt}[x_{21}(t)] = [b_{22}].[x_{21}(t)] + [e_{21}(t)], \tag{17}$$

whereby equation (17) is multiplied on the left and right by the opposite matrix $[a_{22}]^{-1}$ and then the obtained approximate values for the first derivatives $\frac{d}{dt}[x_{21}(t)]$ are substituted in the next matrix equation:

$$2)\ [a_{11}]\frac{d}{dt}[x_{11}(t)] = [b_{11}|b_{12}|b_{13}].[x(t)] - [a_{12}]\frac{d}{dt}[x_{21}(t)] + [e_{11}(t)], \qquad (18)$$

whereby equation (18) is multiplied on the left and right by the opposite matrix $[a_{11}]^{-1}$ and then RK4 method is applied. The obtained solution is substituted in the next matrix equation:

$$3)\ [a_{33}]\frac{d}{dt}[x_{31}(t)] = [b_{31}].[x_{11}(t)], \qquad (19)$$

whereby equation (19) is multiplied on the left and right with the opposite matrix $[a_{33}]^{-1}$ and then RK4 method is applied to the normalized equation. The obtained solution is substituted in the last matrix equation:

$$4)\ [a_{22}]\frac{d}{dt}[x_{21}(t)] = -[a_{21}]\frac{d}{dt}[x_{11}(t)] + [b_{21}|b_{22}].\begin{bmatrix} x_{11}(t) \\ x_{21}(t) \end{bmatrix} + [e_{21}(t)], \qquad (20)$$

whereby equation (20) is multiplied on the left and right with the opposite matrix $[a_{22}]^{-1}$ and then RK4 method is applied.

The procedure can be repeated for the next step forward by using equations (17), (18), (19) and (20) again in the same sequence.

In the third interval, the computation procedure operates with nonsingular matrices $[a_{22}]$, $[a_{11}]$ and $[a_{33}]$, and the obtained solutions do not accumulate computation error in time.

The algorithm in the second and third interval is identical per se. It starts with approximate computation of a group of the first derivatives of the state variables (equations (9) and (17)) and then the accurate solutions are obtained by soling three subgroups of equations one after another (equations (10), (8), (11) and (185), (19), (20) respectively), which were obtained through breaking down parts of the general system and of ADAVR (equations (5) and (13)), which should not be solved directly since the matrices of systems ($[A_2]$ and $[A_3]$) are almost singular. The stability of the solutions, obtained via this algorithm, does not depend on the commutation phase of switches K_3 and K_4.

The automated computer program AVTO was developed for simulation of processes in ADAVR with SCE in the environment of the computer program MATLAB in view of its suitability to perform complex mathematical computations in a matrix form and its features allowing spatial visualization in graphic form of the obtained numerical results from the studied parameters. Fig.5 shows a flow-chart of the program AVTO.

The computer program AVTO contains an input block for the parameters of the computation process and the parameters of the studied ADAVR. This block is for setting the duration of the first and the third interval of the commutation process, the size of the computation step, the effective value of input voltage, as well as the parameters of the windings, ferromagnetic core, commuting elements, switch-off assemblies and the load. The phase of the desired commutation is set and the inherent parameters of the commutation process are computed.

The block for determining the processes in the first interval of the commutation process is used to make analysis by the mesh current method in a complex form, whereby the Gauss-Jordan method is applied. After that the effective values of the studied parameters are determined and they are visualized in the temporal field.

The block for determining the initial conditions of the second interval of the commutation process is used to set a correct assignment of the problem for the first transitive process in ADAVR.

Next is the block for determining the processes in the second interval of the commutation process or the so-called first transitive process. Here the analysis is made by help of the state variables method in the temporal field by applying a specialized algorithm to avoid the fact that the matrix of the system control of ADAVR is almost singular. In the computation procedures, RK4 method is used. At the same time, the general control system is broken down into three subsystems which are solved one after another [7].

Next is the block for visualization of the studied parameters in the second interval and the block for determining the initial conditions in the third interval of the commutation process.

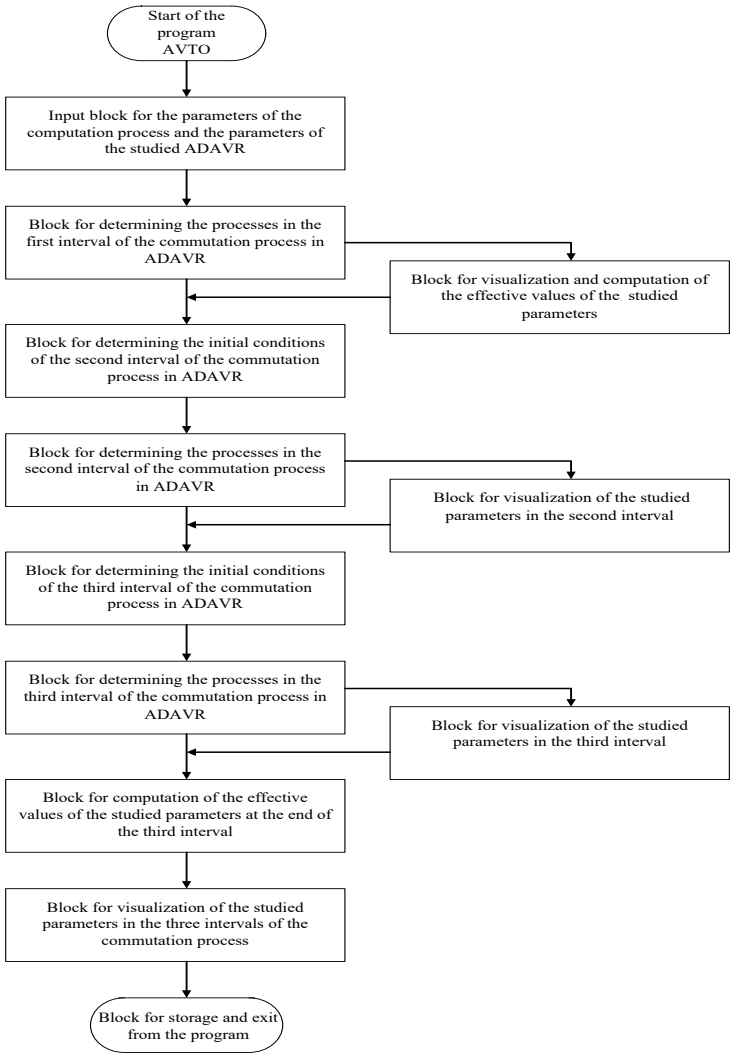
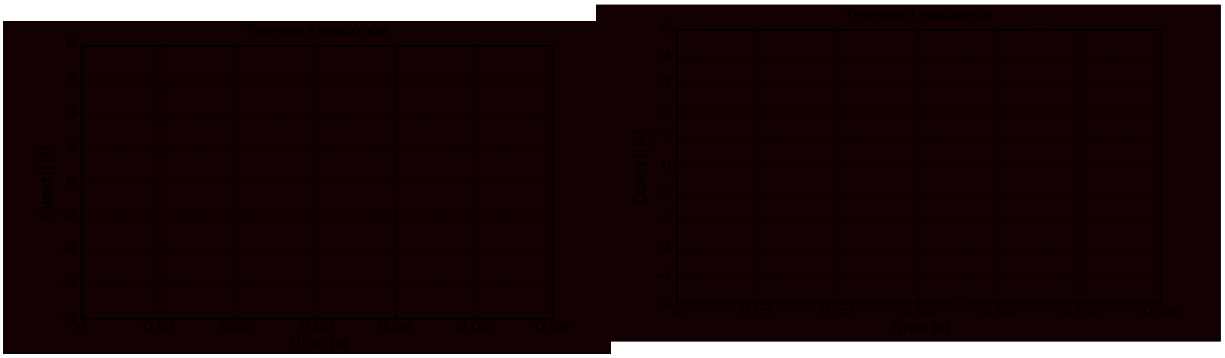


Fig. 5. Flow-chart of the program AVTO.

The block for determining the processes in third interval is used to study the so-called second transitive process. Here the analysis is made by the state variables method in the temporal field with the help of an algorithm similar to the one used for analysis of the first transitive process. The reason is again the fact that the matrix of the system is almost singular. The system of equations is broken down into subsystems which are solved by RK4 method. After that the solutions are visualized in third interval, followed by computation of the effective values of the studied parameters after the second transitive process has died away and visualization of all studied parameters in the three intervals of the commutation process.

Finally, the obtained numerical and graphic results are stored and the program is exited.

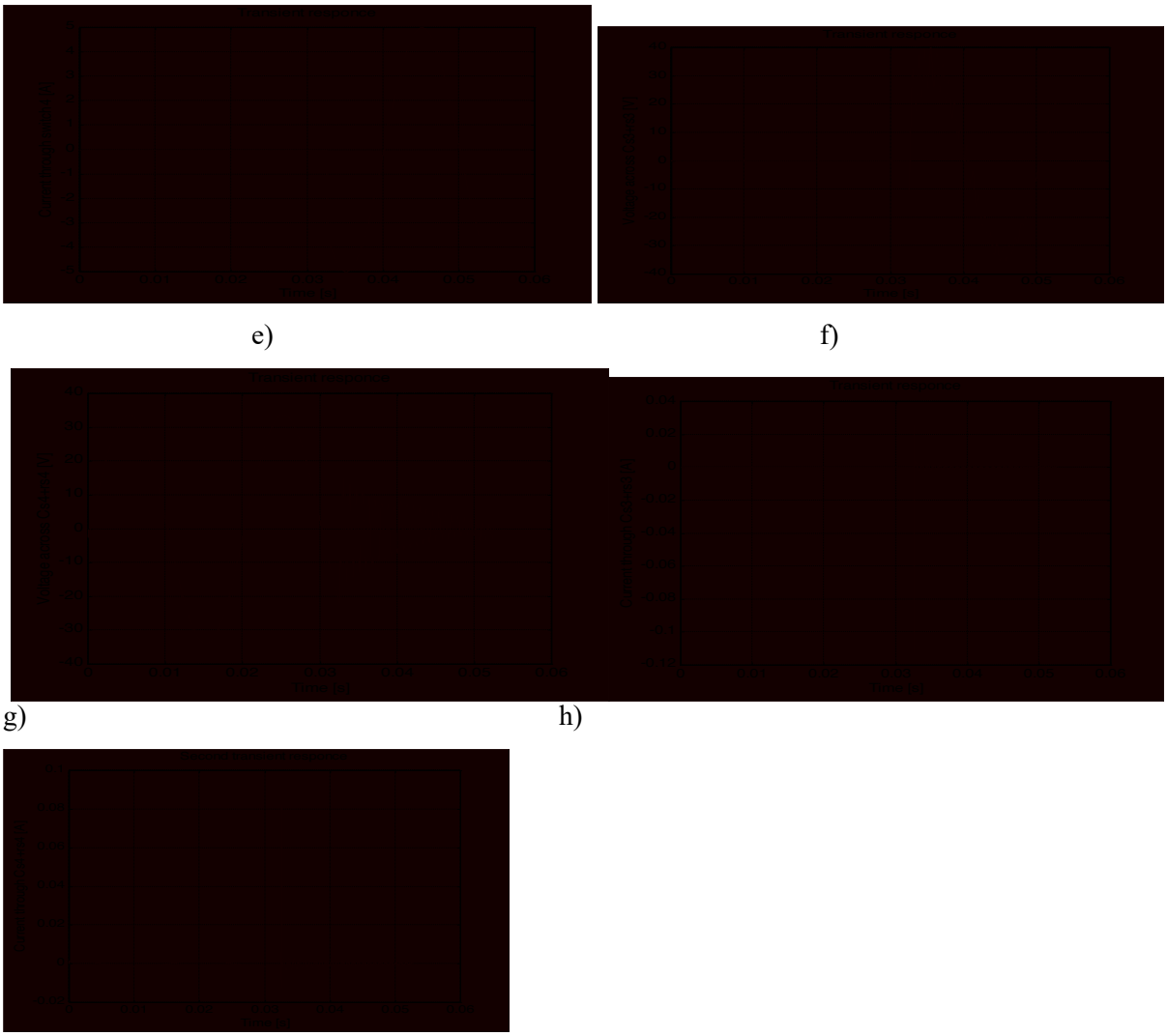
Fig.6 shows the charts of the studied parameters in the three intervals of the commutation process of ADAVR with 0.78 kW of resistive load. The commutation phase of switch K_4 is selected to be $\varphi=225^\circ$. Fig. 6a shows the input current $i_1(t)$ as function of time; fig. 6b shows the output current $i_2(t)$; fig. 6c – current $i_0(t)$ in the main section of ADAVR; fig. 6d – current $i_3(t)$ through switch K_3; fig. 6e – current $i_4(t)$ through switch K_4; fig. 6f – voltage $u_{cs3+rs3}(t)$ over the third switch-off group $C_{S3}+r_{S3}$; fig. 6g – voltage $u_{cs4+rs4}(t)$ over the fourth switch-off group $C_{S4}+r_{S4}$; fig. 6h – current $i_{cs3+rs3}(t)$ through the third switch-off group; fig. 6i – current $i_{cs4+rs4}(t)$ through the fourth switch-off group.



a) b)



c) d)



e) f)

g) h)

i)

Fig. 6. Charts of the studied parameters in ADAVR with resistive load for the three intervals of the commutation process.

Fig. 7 shows the relationship between the first transitive process duration and the commutation phase of switch K_4. The results were obtained for three resistive loads each of respective power as follows: 0.42 kW – marked by asterisk; 0,78 kW – marked by circles; 1,35 kW – marked by crosses.

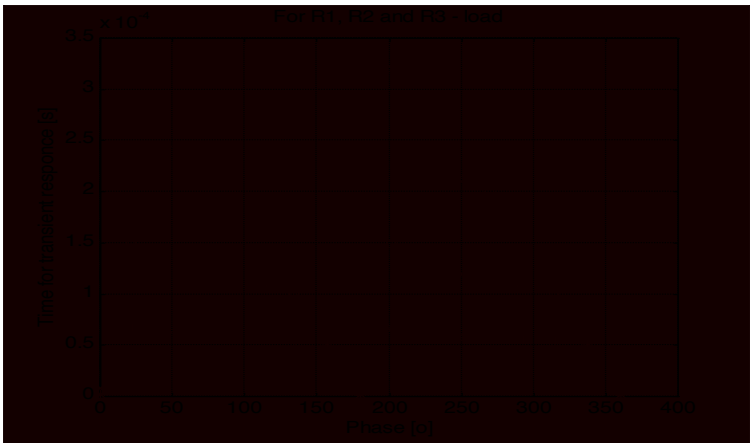
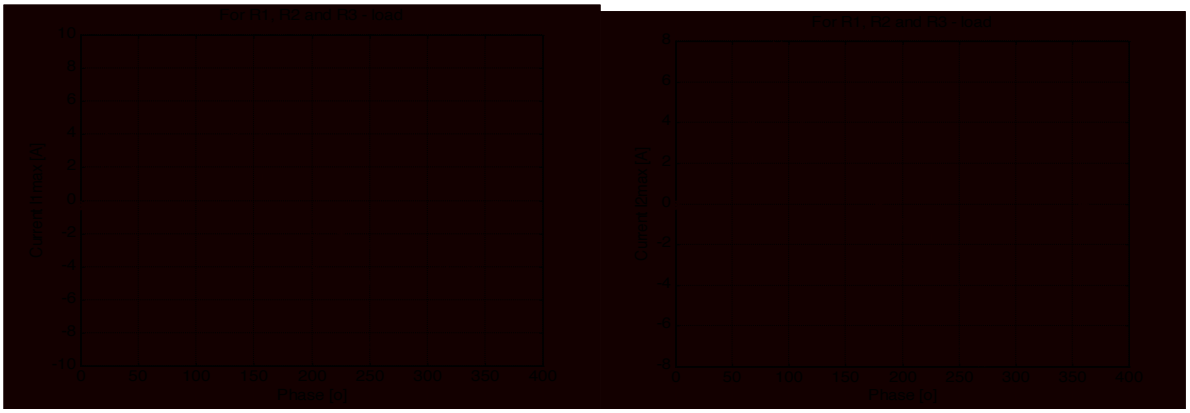


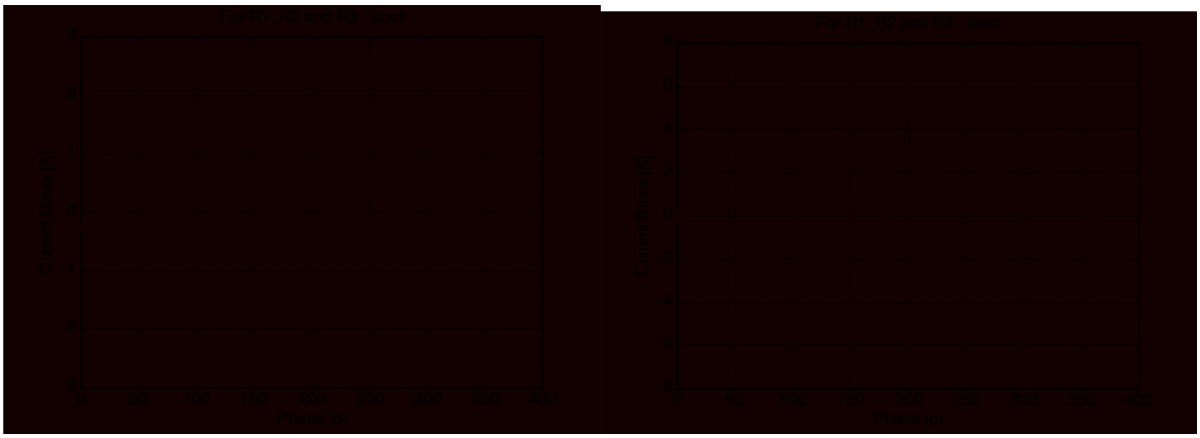
Fig. 7. Diagram of the relationship between the first transitive process duration, the commutation phase of switch K_4 and the power of the load.

Fig.8 shows charts of the relationships between the amplitude values of the studied parameters in ADAVR during the first transitive process, the commutation phase of switch K_4 and the same three

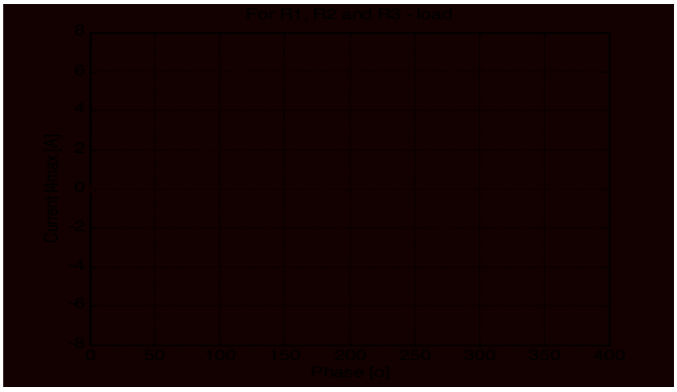


a)

b)



c) d)



e)

Fig.8. Diagrams of the relationships between the amplitude values of the parameters in ADAVR during the first transitive process, the commutation phase of switch K_4 and the power of the load.

resistive loads with identical markings. Fig.8a shows input current i_{1max}; fig.8b shows output current i_{2max}; fig.8c – current i_{0max} in the main section of ADAVR; fig.8d – current i_{3max} through switch K_3; fig.8e – current i_{4max} through switch K_4.

The obtained graphic results very well correspond to the experimental data from a number of tests conducted for ADAVR with four SCE and the same three resistive loads [7].

Table 1 shows data from the experimental testing and computer simulations by help of the proposed algorithm and the program AVTO for a particular ADAVR at input voltage of 160V and three different resistive loads.

Table 1. Results from a number of tests and computer simulations.

	Results from physical experiment					***Results from computer simulations***				
Load	U_1	I_1	I_0	$I_2 \equiv I_T$	$U_2 \equiv U_T$	U_1	I_1	I_0	$I_2 \equiv I_T$	$U_2 \equiv U_T$
№	V	A	A	A	V	V	A	A	A	A
1	160	2,69	0,81	1,9	220	160	2,6674	0,7934	1,8865	218,436
2	160	4,94	1,42	3,56	220	160	4,9232	1,3990	3,5313	218,230
3	160	8,45	2,38	6,16	219	160	8,4757	2,3551	6,1247	217,740

The data indicate very good correspondence with high precision of the computed response of ADAVR related to the results from the physical measurements.

3. CONCLUSIONS

The following conclusions can be drawn from the set forth hereinabove:

1. A mathematical model is proposed for description of the processes of commutation of the terminals of an autotransformer in a discrete alternating voltage regulator as well as a detailed algorithm for

solving the system of equations describing the electrical balance in ADAVR, which allows to overcome the singularity of the matrix of the system in the second and third interval during the action of the voltage regulator.

2. A computer program AVTO has been developed for simulation of the complex processes occurring in ADAVR during the commutation processes, which enables a thorough analysis of the said devices.

3. The developed computer program comprises the specifics of the circuit design, the alteration of the parameters of the autotransformer as a function of the mode, the size and character of the load, the initial phase of commutation and the parameters of the used semiconductor switches. This enables a more comprehensive quantitative analysis of the character and duration of the commutation process, as well as of the electric loading of the individual circuits and semiconductor switches.

4. The data from a number of computer simulations and physical tests have been compared for a large range of loads, indicating very good correspondence between the obtained results.

5. A system version is proposed for virtual design of discrete voltage regulators, whose application would accelerate these processes and economize financial means in the process of development of such devices.

6. The practical implementation of discrete alternating voltage regulators connected before one load or a group of loads is multivalent and could refer to parameter adjustment of the main as well as to improvement of the power and functional indicators of loads connected after a regulator.

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