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Original Article

Using the Computer Model of a Single-Phase Transformer with a Middle-Point Tap in the Secondary Winding to Study the Current Stabilization System for Excitation Winding of a Commutator Traction Motor

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Abstract - A single-phase transformer with a tap at the middle of the secondary winding is a common element in various electrical circuits, including those onboard electric rolling stock. A typical case is the power supply from such a transformer of a single-phase full-wave mid-point thyristor converter with a freewheeling diode. The article provides a detailed description of the computer model of the said transformer developed by the author, built on the basis of a combination of circuit and operational principles of compilation. The proposed model can also be used to describe processes in a single-phase two-winding transformer without a tap, taking into account possible connection groups I/I-6 or I/I-0. An example of embedding the transformer model in a more complex computer model of the excitation current stabilization system (PI controller of current based) of traction electric motors of a DC electric locomotive is shown.

Keywords - Mainline DC electric locomotive, Commutator traction motor, Mid-point thyristor converter with freewheeling diode, Excitation winding, single-phase transformer, Computer model, Current stabilization.

1. Introduction

A single-phase transformer with an additional terminal (tap) at the middle point of the secondary winding is a special case of a single-phase multi-winding transformer [1], used, for example, to supply single phase full wave mid-point thyristor converter with freewheeling diode [2-5]. The diagram in Figure 1 shows an example of using such a transformer onboard a DC electric locomotive [6, 7] to maintain the current of the excitation windings EWM1 and EWM2 with the feed current from the rectifier when the armature current of the M1 and M2 Commutator Traction electric Motors (CTM) [8, 9] drops. The I_{rectif} current is induced by applying alternating voltage V_1 in the form of a meander with a frequency of 400 Hz to the primary winding of the transformer T1.

The device consists of SCR thyristors VS1 and VS2, and a freewheeling diode VD1 is called An Excitation Control Rectifier (ECR). ISh is an inductive shunt, i.e. a choke with a ferromagnetic core (its computer model is described in [10]). In an electric locomotive with series-excited CTM, an urgent task is to stabilize the current in the

Excitation Winding (EW) of CTM with a decrease in the armature current. For example, the armature current can decrease due to the development of the slippage process of the driven axle of the electric locomotive.

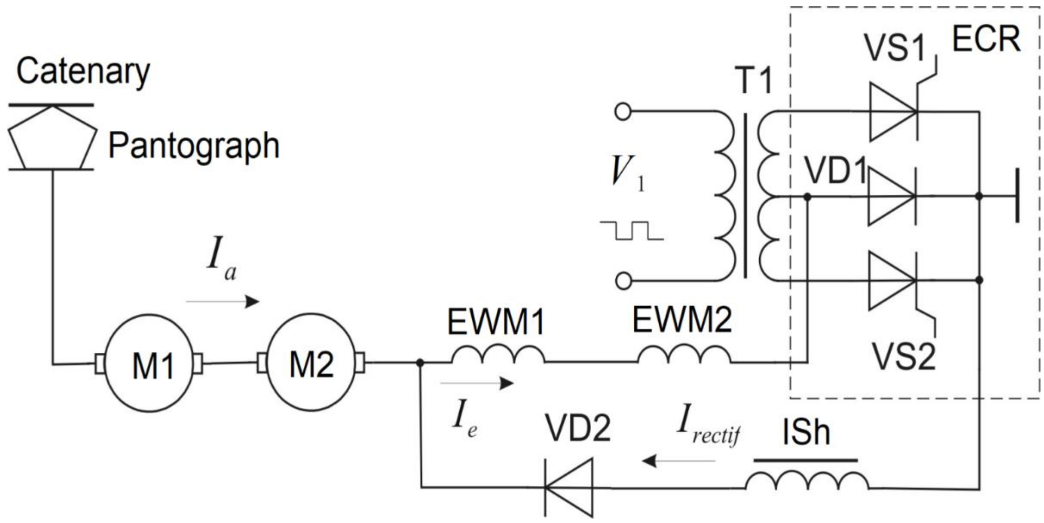

Fig. 1 Schematic illustrating using a single-phase transformer with a secondary center tap to power the excitation control rectifier onboard DC electric locomotive with CTM

During slippage, due to deterioration of the adhesion of the wheel to the rail, which is identical to a decrease in the load torque on the CTM shaft, the rotation frequency of the CTM armature increases. Due to this, the CTM's back-EMF increases, leading to a decrease in the armature current. With a series excitation circuit, a decrease in the current in the armature leads to a decrease in the excitation current, which is equivalent to a weakening of the CTM field. In order to avoid the CTM going into a runaway in the described situation, it is necessary to maintain an unchanged excitation current value, for which an ECR is provided that feeds the CTM's EW with current when the armature current decreases.

The task of the ECR is to respond to a decrease in the current in the EW. While the current through the EW is equal to the rated value, the ECR thyristors are in the OFF state. When the current through the EW decreases, the conduction angle of the ECR's thyristors increases as a function of the actual value of the current through the EW. In the selected rectifier circuit, the firing angle is limiting. A detailed description of the ECR power supply circuit as applied to the 2ES4K mainline DC electric locomotive is contained in [11, 12].

The electric locomotive circuit allows for additional feeding of the EW (field forcing) and the use of field weakening or independent excitation. This article only considers the mode of additional power supply of the EWs of the CTMs from the ECR (field forcing). In the technical literature, there are known studies devoted to the control of the current in the EW of a CTM [13, 14], but these works were carried out in relation to other power converter circuits. On the topic of stabilizing the current in the winding using a PI controller, work [15] is also known, but it relates to another industry. This article fills a gap in research.

2. Materials and Methods

Let us consider the structure of the computer model of a single-phase transformer with a tap at the middle point of the secondary winding. The computer model is based on a combination of the circuit and operational (block diagram [16]) principles of compilation in the OrCAD environment in the form of a hierarchical block [17-19] with the internal content shown in Figure 2 - 4. The use of the circuit principle allows, in the environment of visual programming of electrical and electronic circuits, to obtain the ability to interface models of various devices by simply connecting virtual terminals.

Figure 2 $I_{\mu rated}$ is the RMS value of the magnetization current of the transformer in the rated mode. In Figures 2 and 3, the factor "sign" must be set equal to "1" (to obtain the I/I-6 connection group) or "-1" (to obtain the I/I-0 connection group). The nonlinearity of the magnetization curve in Figure 2 is specified according to [20]. In Figure 2-4, index C denotes belonging to the secondary winding section. r_{serv} - resistances for service purposes: r_{serv4} of the order of 1 μOhm or less, the rest of the order of 1 - 10 MOhm or more. By analogy with that described in previous study, elements of the VSCV, VSCC, and CSCV types are used as sensors and for signal input in the model in Figure 2-4. In these abbreviations: S - source; C - controlled (if third letter); V – voltage; C – current (if first or fourth letter). For example, VSCC is a voltage source controlled by current.

Other designations in Figure 2-4 are generally accepted: v - voltage i - current; w - number of winding turns; r - resistance; L_σ - leakage inductance. Subscripts 1 and 2 indicate belonging to the primary and secondary windings, respectively. A prime in the designation of a variable or parameter with subscript 2 means a reduction in magnitude to the parameters of the primary winding.

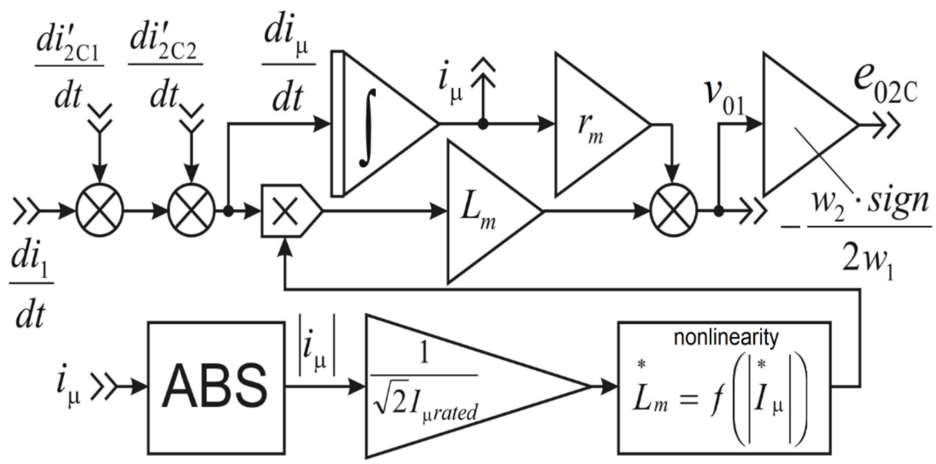

Fig. 2 Block diagram for modeling the EMF e_{02C} and voltage v_{01} of the magnetization branch with a series connection of resistance r_m and inductance L_m in it.

For example, $1'_{2c1}$ the current of the 1st section of the secondary winding is reduced to the parameters of the primary winding of the transformer. e_{02c} - EMF of the magnetization branch for the section of the secondary winding; v_{01} - voltage at the terminals of the magnetization branch on the primary side; L_m - main inductance of the transformer with a series connection of the resistance of iron losses r_m. The computer model in Figures 2-4 has the property of universality in the sense that it can be used to model a single-phase two-winding transformer if the load is connected between terminals A2 and X2 without using the secondary winding tap for connections. The equality is satisfied

$$v_2 = v_{2C1} + v_{2C2}\,. \tag{1}$$

The above-considered computer model of a single-phase transformer with an additional terminal (tap) at the middle point of the secondary winding is built in as an element into the computer model of the current stabilization system in the EW of CTM. Another element - a computer model of the power section of the thyristor rectifier - is shown in Figure 5. The thyristors are modeled simplified as idealized voltage-controlled switches with diodes connected in series. The ISh (type ISh 84) and EW of CTM of type DTK800A (6 poles, 800 kW, 1500 V DC, 945 rpm [21]) models are implemented as computer models of the choke [10], taking into account the nonlinearities of the magnetization curves [20].

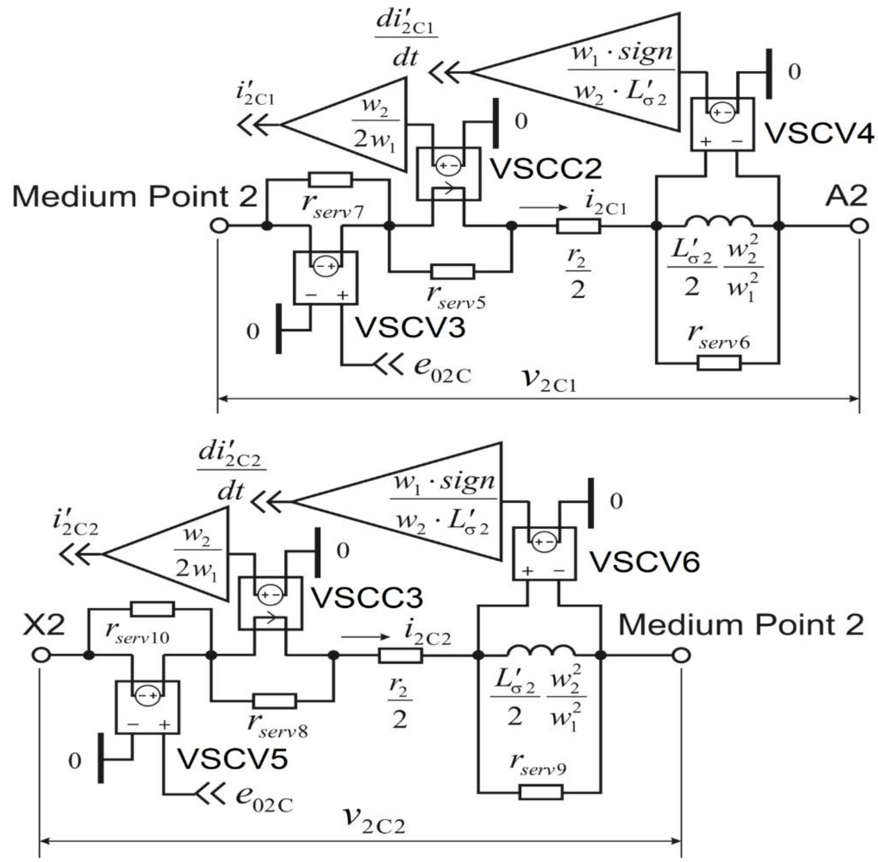

Fig. 3 Model of secondary winding with a tap at midpoint

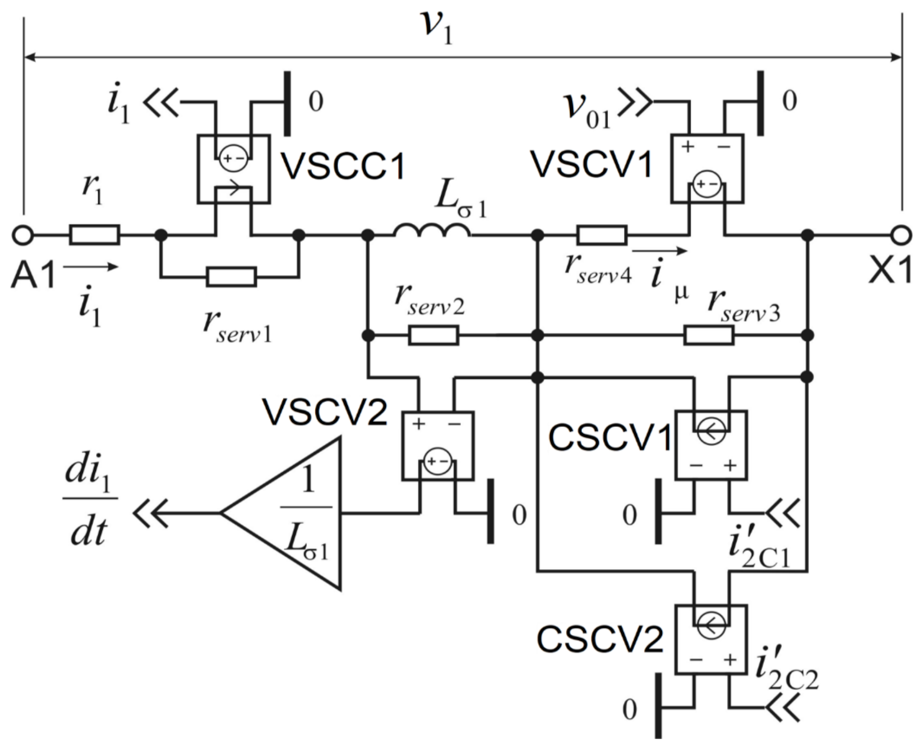

Fig. 4 Primary winding model

Since the author knew that, according to the results of the experiments, the current through the EW decreases from 570 A to 0 A in 7.125 s, but the exact nature of the current decrease curve was not known. Also, in order to simplify the model, reduce the calculation time, and check the current stabilization system under obviously more severe conditions, it was decided that it was sufficient to model the decrease in the armature current according to a linear law with a significantly accelerated current decrease (in 71.25 ms).

With this assumption, the armature circuits of the CTM are implemented in the model as a pulse current source with programmable pulse and front durations (see Figure 5). The rectifier's Pulse-Phase Control System (PPCS) is designed to form and distribute pulses for the turning-on of the thyristors of the ECR. The PPCS model includes an excitation current reference value setter of the EW; feedback on the current of the EW of the CTM, nonlinearity, forcing the time moment of turning-on of the thyristors already at minor deviations of the excitation current downwards from the rated value, and thereby increasing the speed of the current stabilization system in the EW; PI controller of current (selected based on the condition of adjusting the excitation current circuit to the modulus optimum according to the recommendations [22-24]), a unit for forming the firing angle α for the thyristors.

This unit distributes signals to the thyristors. Figure 6 shows a computer model of the PPCS, built on the principle of a block diagram. In the computer model of the PPCS, the excitation current feedback signal arriving at the PI controller input cannot exceed the value of 3.141593. For this purpose, the signal is previously limited within the range of (0 … 8) V. The voltage value in the excitation current feedback equal to 8 V occurs when the excitation current reaches the rated value.

To accelerate the response time of the EW current stabilization system, the signal arriving from the excitation current sensor is passed through a specific nonlinearity, which allows forcing the time moment of thyristor turn-on already at small deviations of the excitation current downwards from the rated value. The configuration of the forcing nonlinearity used in the modeling is given in Table 1. The signal at the PI controller output is normalized within the range of –3.141593 … +3.141593. The modulus of this signal is supplied as the value of the rectifier thyristor firing angle for processing in accordance with the trigonometric expression

$$\sin(\alpha+\beta)=\sin\alpha\cdot\cos\beta+\cos\alpha\cdot\sin\beta, \qquad (2)$$

The phase angle of the voltage source Vsin1 is used as the angle β. For the correct adjustment of the PPCS operation, it is necessary that the phase of the reference sinusoidal voltage source Vsin1, in comparison with the output signal of which the thyristor triggering moment is shifted, coincides with the phase of the first harmonic of the voltage at the input of the ECR. In this model, this coincidence is ensured by selection. The sinusoidal signal obtained as a result of processing according to expression (2) is inverted, amplified and limited, forming a meander, which is used to control the idealized switches included in the simplified thyristor models.

Table 1. Forcing nonlinearity for processing the signal from the excitation current sensor in order to increase the speed of the EW current stabilization system

Nonlinearity input voltage, V	Nonlinearity output voltage, V
0.0	0.0
7.5	0.0
7.7	3.0
7.9	5.0
8.0	8.0

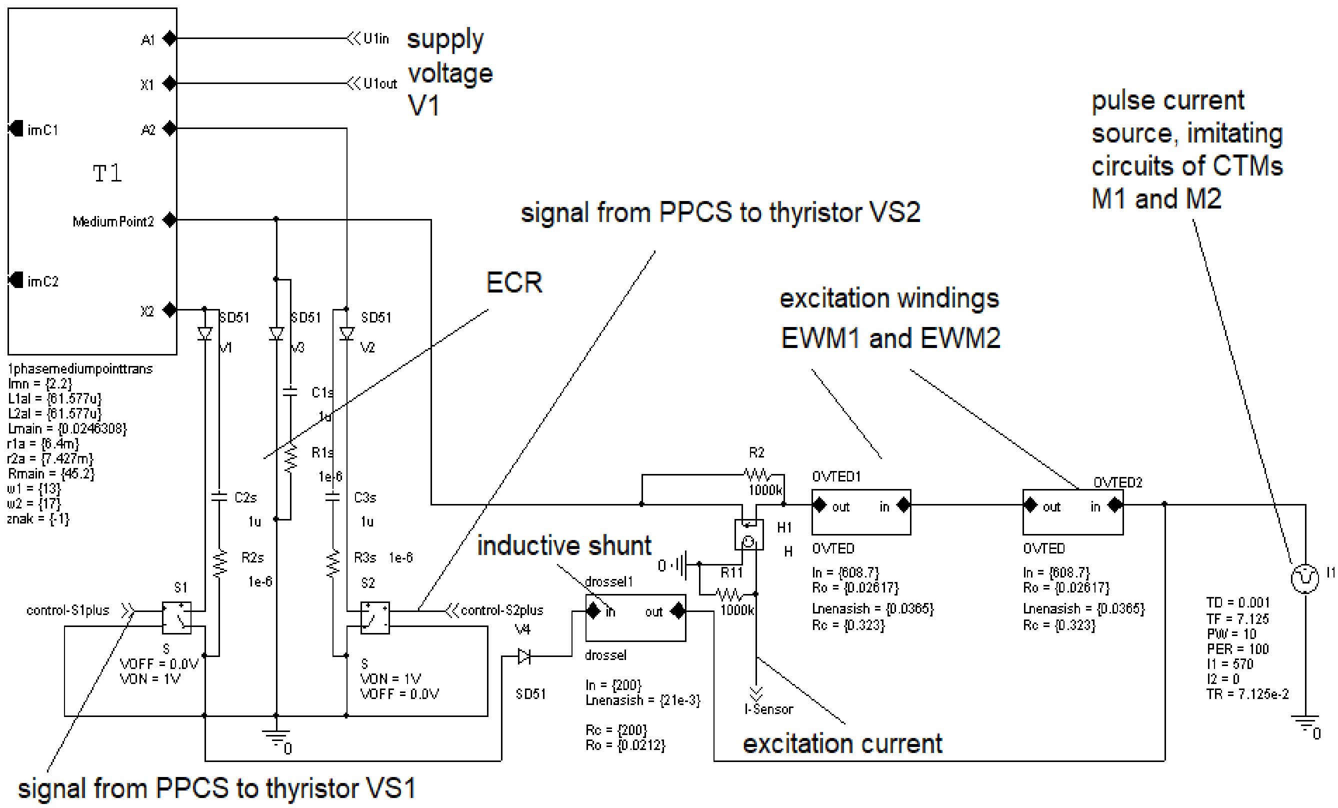

Fig. 5 Computer model of the power section of the current stabilization system in the EW of CTM

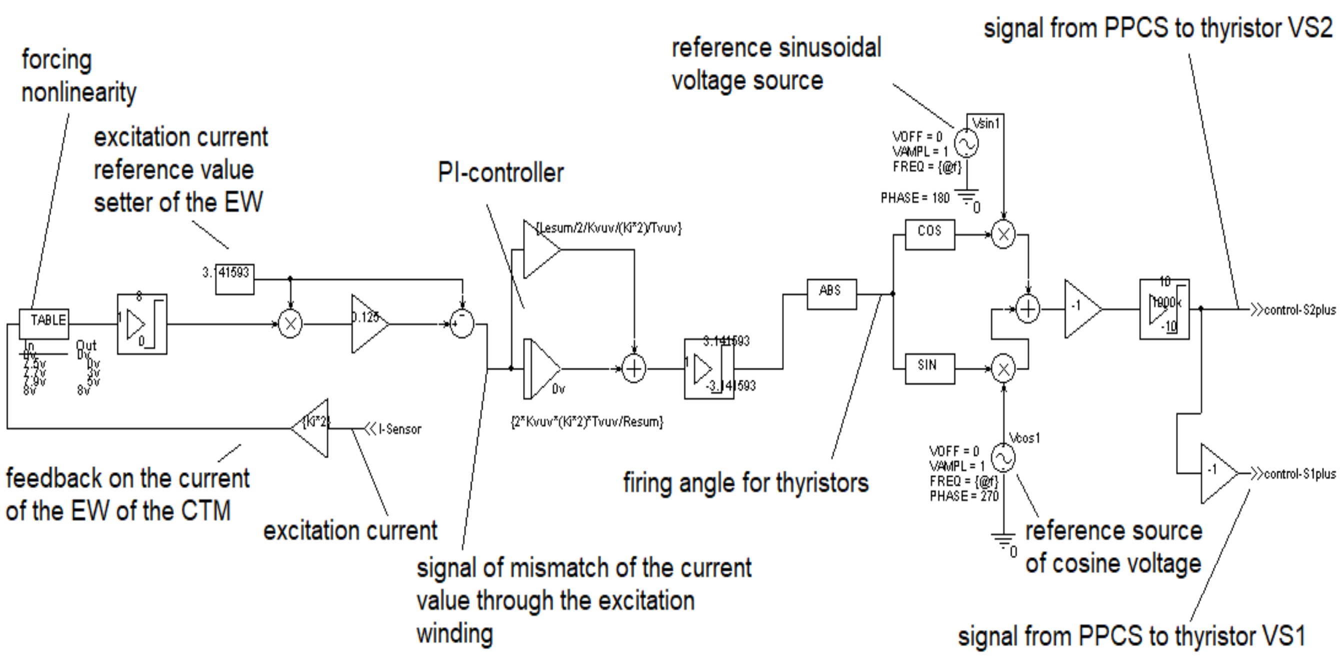

Fig. 6 Computer model of the control part of the current stabilization system in the EW of CTM

3. Simulation Results

The results of computer simulation of the current stabilization process in the EW of CTM are shown in Figure 7. The obtained simulation graphs of the excitation current I_e in the EW of CTM and its reactive component I_{er} show that the considered current stabilization system and its computer model are operational and successfully perform the functions assigned to them: when the armature current I_a drops, the excitation current I_e is maintained due to the growth of the feeder current I_{rectif} from the ECR.

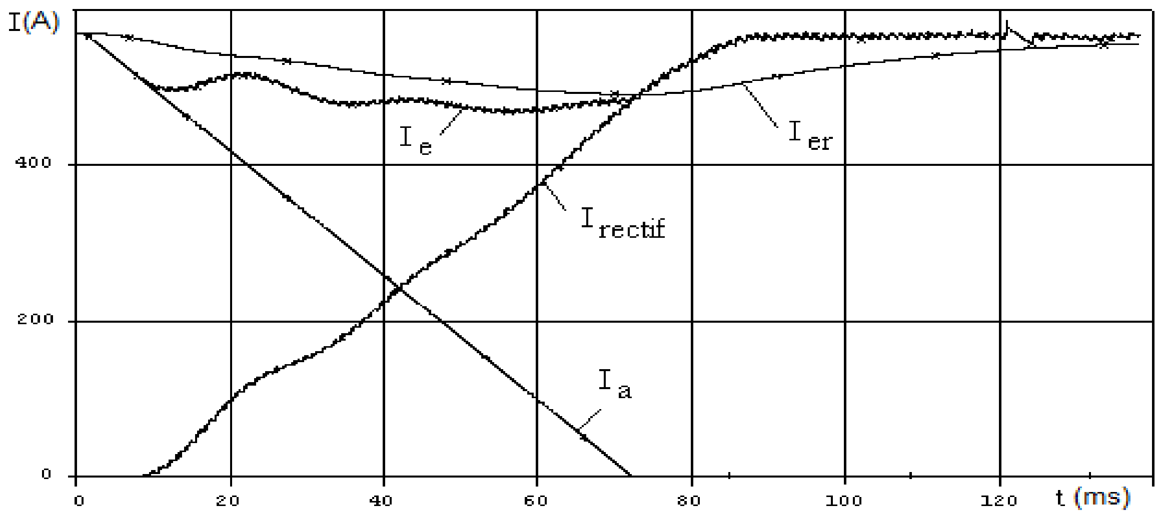

Fig. 7 Results of computer simulation of the current stabilization process in the EW of CTM

4. Conclusion

It should be noted that the computer model of a single-phase transformer with an additional output (tap) at the middle point of the secondary winding, built on the basis of a combination of circuit and operational principles, functions correctly and is easy to use.

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