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THEORETICAL RESEARCH INTO MOTOR BACK EMF INFLUENCE ON EMERGENCY STATE IN THE ELECTROTECHNICAL COMPLEX OF A MINE SECTION

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Abstract

In this paper we developed a mathematical model for a mining electrotechnical complex in case of emergency (current leakage and three-phase fault in the flexible cable). The results of the research confirmed the necessity of motor back EMF forced reduction to ensure electrical safety in a mine section.

Keywords: mathematical model, current leakage, short-circuit, asynchronous motor, back EMF, quantity of electricity, diagrams of current change, electrical safety

Introduction

Electrotechnical complex (ETC) of a coal mine section (MS) consists of high-powered induction motors, long flexible cables, switching devices and protective equipment. The probability of cables damage is high enough. Breakdown of insulation integrity leads to miners' electrical shocks, fires and explosions of mine air. For instance, electricity was the 4^{th} leading cause of death reported in mining in the USA between 1990 and 1999 [1]. In Ukraine 6,2% of industrial fatalities happened in mining industry from 1992 to 2001 [2]. The energy, expended in short−circuit, is capable of igniting loose coal, coal dust and other inflammable substances.

Protective devices used nowadays guarantee safety tripping in case of emergency. But current keeps on flowing through the fault point, after a circuit breaker had been switched off by a protective device. It is caused by exponentially decreasing motor back electromotive force (EMF). Existence of this factor complicates observance of safety requirements [3, p.97−100; 4, p.24−27].

Background

Till now the influence of motor back EMF on the current leakage circuit has been considered to depend upon characteristic times of rotors of the asynchronous motors (AD) [5, p.12−18]. Increase of their values worsens state of the current leakage circuit. But some other factors were not taken into account: braking torque and moment of inertia. Together with characteristic times of rotors, these parameters are supposed to determine the duration of back EMF existence.

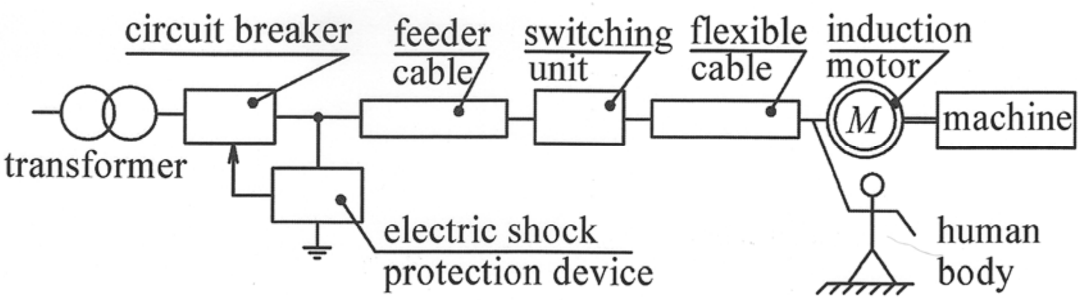

Figure 1. Configuration of an electrotechnical complex of a mine section with one branch (the neutral is insulated)

Hitherto the dependence between the parameters of motor back EMF and short-circuit conditions was not determined.

Goal of the Research

The purpose of this paper is to estimate the influence of motor back EMF on the fault point of the electrotechnical complex in emergency cases under different circumstances.

Results

The safety of ETC operation may be estimated by the probability of fatality (when current flows through a human body in emergency case). If we assume that the variable Q (total quantity of electricity through a human body) obeys the normal distribution law, this probability can be calculated as follows:

$$P(Q > Q_{\max}) = 0{,}5 - \Phi\left(\frac{Q_{\max} - \overline{Q}}{s}\right), \qquad (1)$$

where $Q_{\max}$ is the maximum permissible total quantity of electricity through a human body defined according to normative documents [6, 7]; $\Phi(x) = \frac{1}{\sqrt{2\pi}}\int_0^x e^{-z^2/2}dz$ is a Laplace function; $\overline{Q}$, s are sample values of mean Q and square deviation of Q respectively.

ETC of a mine section is considered to be safe in case of meeting the condition $P(Q > Q_{\max}) \le P_{\lim}$, where $P_{\lim}$ is the maximum permissible probability of electrocution. Death of a person is possible if this condition is false.

Processes in ETC of a mine section with one branch (fig. 1) after safety tripping of the circuit breaker can be described by differential equations in stator coordinate system [8, p.493–499]:

$$\begin{cases} \overline{u}_1 = L_m \dfrac{d\overline{i}_r}{dt}; \\ \dfrac{d\overline{i}_r}{dt} = j\omega\overline{i}_r - \dfrac{\overline{i}_r}{T_r}; \\ \dfrac{d\omega}{dt} = \dfrac{-M_c}{J}, \end{cases} \qquad (2)$$

where $T_r = L_r / R_r$ is characteristic time of rotor; M_c is braking torque; J is moment of inertia; ω is rotor speed; $\overline{i}_r$ is the space vector of the rotor current; $\overline{u}_1$ is the space vector of voltage caused by back EMF; L_m is the inductance of chief magnetic circuit. Current in stator circuit is equal to zero.

The first equation of system (2) shows, that free rotor current causes motor back EMF. This current depends on characteristic time of rotor T_r and rotor speed ω – the second equation of system (2). The last parameter has been decreasing since safety tripping according to the third equation. It shows that the character of motor stopway is formed by M_c / J relation. Increase of this relation results in more intense fading of motor back EMF, that leads to the reduction of leakage current and electric shock duration. Correspondingly, total quantity of electricity through the human body decreases.

Fading of motor back EMF causes spontaneous tripping of the switching unit. This leads to abrupt changes of insulation parameters, which determine the magnitude of leakage current.

Suppose, ETC in fig. 1 is characterized by the following parameters: line-to-line voltage – 660 V; motor power – 160 kW; feeder cable: length – 250 m, cross-section of a conductor – 120 mm^2; flexible cable: length – 330 m, cross-section of a conductor – 50 mm^2; leakage circuit resistance is assumed to be 1000 ohm. The neutral of the transformer is insulated. Computer modeling allows obtaining the diagrams shown in Figure 2. Leakage through the human body is supposed to happen at the time point t_1. Circuit breaker safety tripping occurs at the time point t_2. Figure

2, *a* shows the curves of motor back EMF (effective values) when the braking torque varies within the range M_c=0,1÷1 relative units (r. un.).

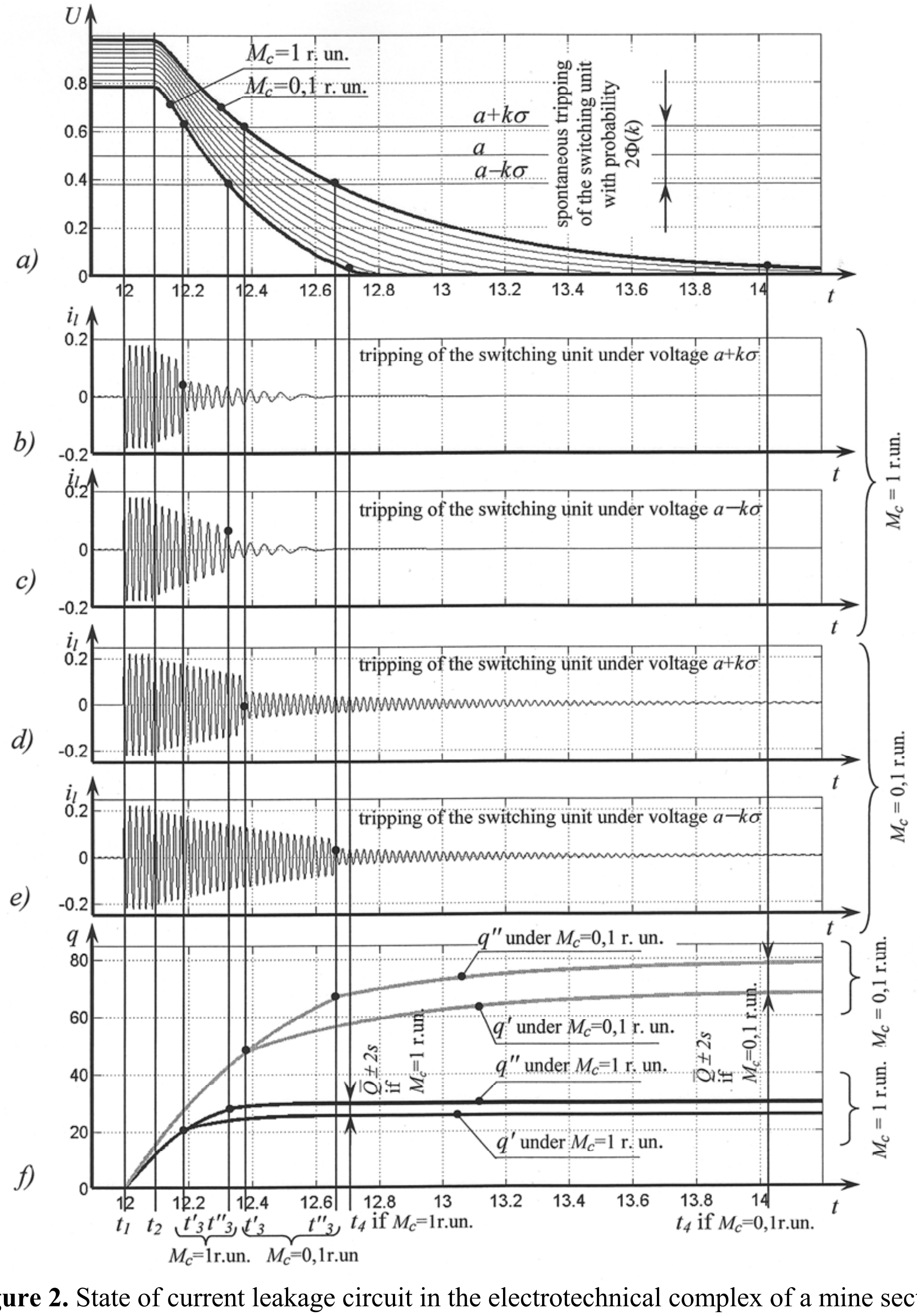

Figure 2. State of current leakage circuit in the electrotechnical complex of a mine section

For M_c=0,1 r. un. and M_c=1 r. un. leakage current i_l curves are plotted in Figure 2, *b*–*e*. The voltage of spontaneous tripping of the switching unit is considered to be a normally distributed variate with mean value *a*=0,5 r. un. and square deviation σ=0,06 r. un. So, its values with probability $2\Phi(k)$ belong to the interval ($a-k\sigma$; $a+k\sigma$). In our case *k*=2. The boundaries of the above mentioned interval are in accordance with time points t_3'' and t_3' for fixed braking torque. Spontaneous tripping of the switching unit occurs with probability $2\Phi(k)$ within the time range (t_3'; t_3''). Diagrams of leakage current (if spontaneous changes of insulation parameters happened at t_3' and t_3'' time points) for M_c=0,1 r. un. and M_c=1 r. un., are shown in Figure 2, *b–e*.

The quantity of electricity through a human body changes according to the curves q' and q'' under the condition of spontaneous tripping of switching unit at t_3' and t_3'' time points respectively. The diagrams in Figure 2, *f* allows comparing the quantity of electricity for M_c=0,1 r. un. and M_c=1 r. un. The effective value of motor back EMF reached 3% of the initial value at time t_4. This moment is considered to be the end of emergency state. The values of q' and q'' at this time point are the limits of range $\overline{Q} \pm ks$, which contains the total quantity of electricity through the human body *Q* with probability $2\Phi(k)$. The following results were received under specified conditions: $\overline{Q}$ = 73,23 mAs, s =2,54 mAs, $t_4 - t_1$=2,03 s if M_c=0,1 r. un.; $\overline{Q}$ = 28,21 mAs, s =1,16 mAs, $t_4 - t_1$=0,7 s if M_c=1 r. un.

Short-circuit processes in ETC after safety tripping can be illustrated by the electrical scheme in Figure 3. In this figure AB is automatic circuit breaker; MC is magnetic starter contactor; M is asynchronous motor.

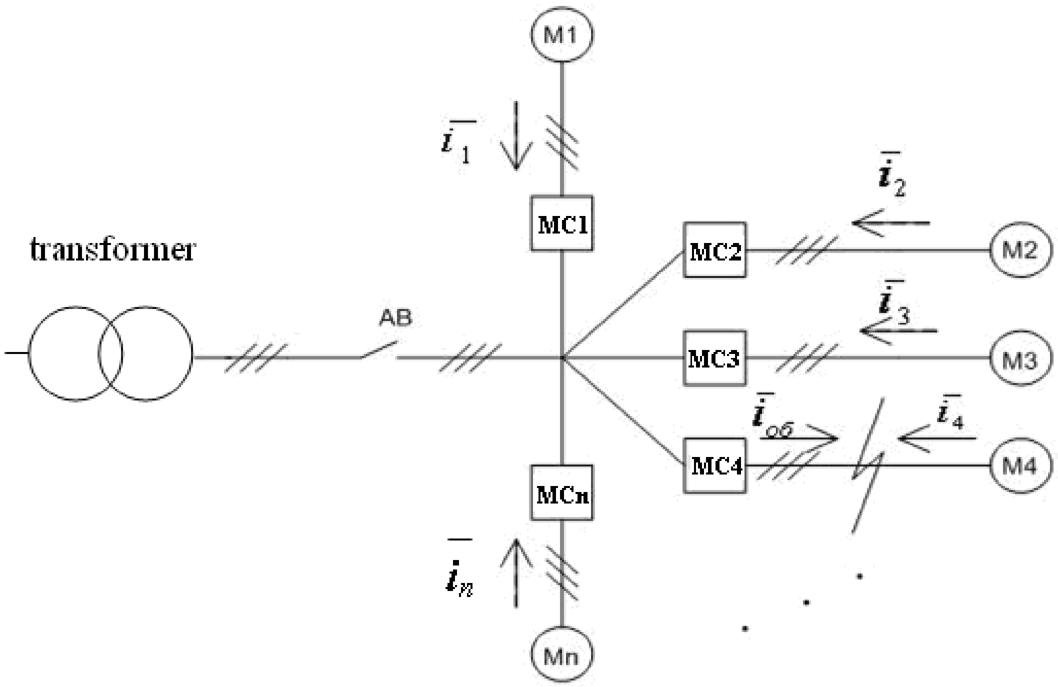

Figure 3. Electrical scheme of ETC of a mine section in case of three-phase fault after safety tripping

Short-circuit process is represented by a number of successive states [9]:

- short-circuit occurs; current flows to the fault point from the transformer;
- fault point is fed from transformer and current flows to the fault point from the stator of asynchronous motor that belongs to the emergency branch (process continues up to the safety tripping);

- equalizing currents are caused by back electromotive force of the AM after power supply is switched off by protective device;
- fault point is fed only from AM of the emergency branch (after contactors of the other connections are switched off).

The process of the AM current change in case of a short-circuit in a flexible cable of this motor has gained practical importance.

The electric diagram in Figure 4 shows an equivalent circuit of AM with tree-phase fault between the in-feed source and the asynchronous motor.

Here R_s is the stator resistance; R_r is the resistance of the rotor reduced to the stator; L_{sl} is the leakage inductance of the stator; L_{rl} is the leakage inductance of the rotor reduced to the stator; L_m is the inductance of the main magnetic flux; $\overline{\psi}_s$, $\overline{\psi}_r$ are space vectors of the linkage of stator and rotor; ω_k is the rotation speed of the coordinate system; ω is the speed of AM rotor; i_s, i_r are the stator and rotor currents.

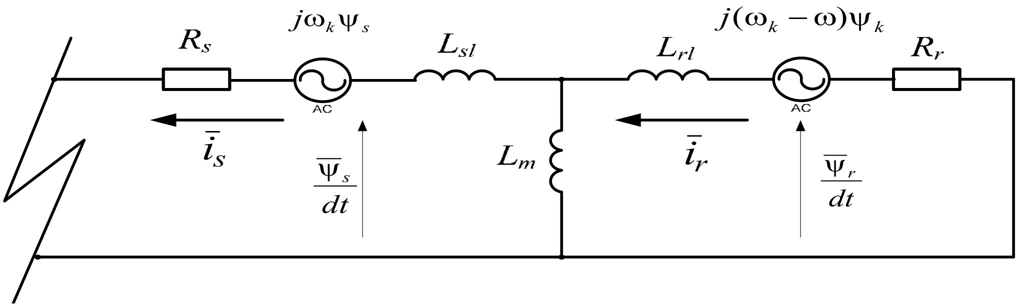

Figure 4. Equivalent circuit of AM with a three-phase fault between the in-feed source and the asynchronous motor

The differential equations in $\alpha-\beta$ ($\omega_k=0$) coordinates for the equivalent circuit of an asynchronous motor, which describe the processes in AM are placed below [8]:

$$\begin{cases} \overline{u}_{s\alpha}=\dfrac{d\overline{\psi}_{s\alpha}}{dt}+\dfrac{R_s}{L'_s}\overline{\psi}_{s\alpha}-k_r\dfrac{R_s}{L'_s}\overline{\psi}_{r\alpha}\ ; \\ \overline{u}_{s\beta}=\dfrac{d\overline{\psi}_{s\beta}}{dt}+\dfrac{R_s}{L'_s}\overline{\psi}_{s\beta}-k_r\dfrac{R_s}{L'_s}\overline{\psi}_{r\beta}\ ; \\ \overline{u}_{r\alpha}=0=\dfrac{d\overline{\psi}_{r\alpha}}{dt}-k_s\dfrac{R_r}{L'_r}\overline{\psi}_{s\alpha}-\dfrac{R_r}{L'_r}\overline{\psi}_{r\alpha}-j\omega\psi_{r\beta}\ ; \\ \overline{u}_{r\beta}=0=\dfrac{d\overline{\psi}_{r\beta}}{dt}-k_s\dfrac{R_r}{L'_r}\overline{\psi}_{s\beta}-\dfrac{R_r}{L'_r}\overline{\psi}_{r\beta}+j\omega\psi_{r\alpha}\ ; \\ M=1{,}5\dfrac{L_m}{L_s L'_r}\overline{\psi}_r\times\overline{\psi}_s\ ; \\ J\dfrac{d\omega}{dt}=M-M_{мех}\ ; \end{cases}$$

where $\overline{u}_s$ is the voltage of short-circuit section ($\overline{u}_s=0$); $k_r=L_m/L_r$ is the coupling factor of the rotor; $k_s=L_m/L_s$ is the coupling factor of the stator; $L'_s=L_{sl}+L_{rl}\cdot L_m/(L_{rl}+L_m)$ is the coupling inductance of the stator; $L'_r = L_{rl} + L_{sl} \cdot L_m / (L_{sl} + L_m)$ is the coupling inductance of the rotor; M is the motor torque; $M_{мех}$ is the load moment ; J is the moment of inertia.

According to the received mathematical model the computer model has been developed for asynchronous motors of various capacities (55-220 kW). Computer modeling resulted in the diagrams of stator current change in case of a short-circuit (Figure 5).

Table 1. AM parameters

№	Motor	Pн, kilowatt	J, kg*m^2	Mп/Mн
1	ЭКВ3-55	55	0,296	3,2
2	2ЭКВ3,5-90	90	0,331	1,2
3	ЭКВ4-140	140	1,17	1,8
4	ЭКВ3,5-180	180	0,691	1,5
5	2ЭКВ4УС2	220	1,6	1,8

The study of the model showed that the short-circuit process is accompanied by the increase of current and its further intensive reduction in magnitude and frequency (Figure 5). However at the moment of short-circuit occurrence there is a dead time (i. e. there is no current). See Figure 6, Figure 5, point A.

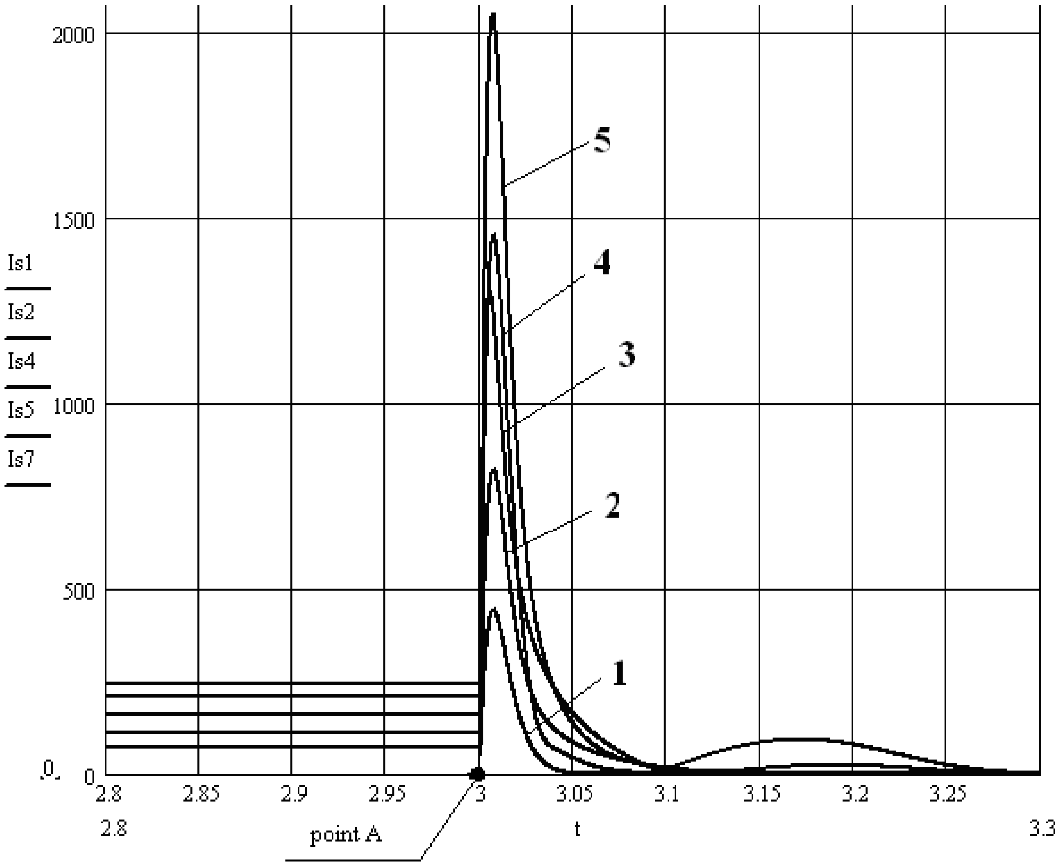

Figure 5. Diagrams of AM stator current changing

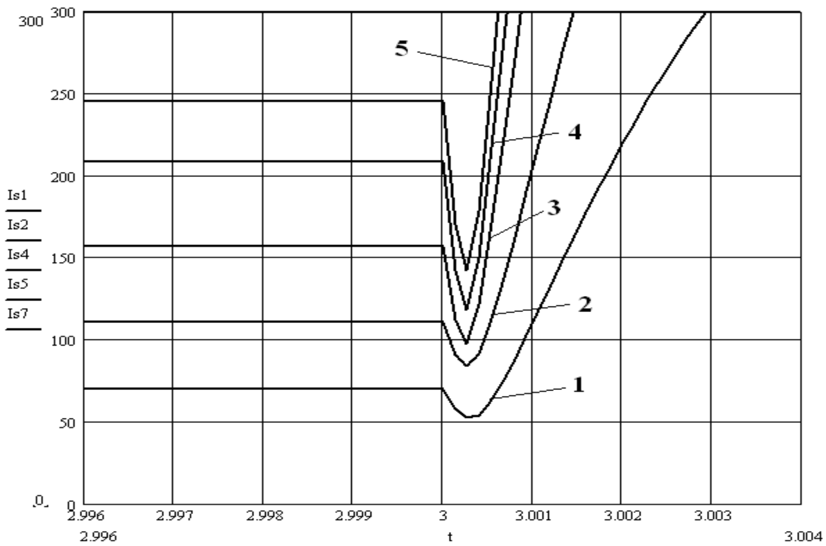

Figure 6. Diagrams of dead time in stator circuits of AM in fault cases

Conclusion. The influence of motor back EMF on the leakage circuit is noticeable. Distributed parameters of the total quantity of electricity through a human body in emergency cases in ETC depend on the mechanical loading of induction motors. The increase of braking torque reduces the magnitude of leakage current and electric shock duration (nearly by three times under the specified conditions). It proves the urgency of the forced neutralization of motor back electromotive force.

Computer modeling confirmed the negative influence of motor back EMF on the fault point. The parameters of ETC were estimated for various capacities of asynchronous motors.

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