

Computer Simulation of Processes in the Traction Drive of a DC Electric Locomotive Based on Induction Motors at an External Short Circuit

MIKHAIL PUSTOVETOV

Department of Electrical and Electronics Engineering,
Don State Technical University,
344000, Rostov region, Rostov-on-Don, Gagarin sq., 1,
RUSSIA

Abstract: - This article examines the results of a simulation of transient electromechanical processes in the traction drive of a DC electric locomotive that occurs during an external short circuit (a short circuit in the catenary). A hypothesis regarding the feasibility of controlled electrical braking of a traction induction motor in this situation is analyzed. It has been shown that controlled electrical braking of a motor is possible in the case of significantly reducing the opening time of a high-speed circuit breaker's contacts compared to what actually occurs. However, this significantly increases the potential difference between the circuit breaker's contacts during opening.

Key-Words: - DC electric locomotive, 3-phase induction motor, variable-frequency traction drive, high-speed circuit breaker, L-shaped LC filter, external short circuit, catenary, torque, current, simulation

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1 Introduction

When operating DC electric locomotives with traction drives based on 3-phase induction motors (IM), the processes that occur in the event of an external short circuit (SC), i.e., an SC in the catenary, are of interest. Let's examine the behavior of the traction drive using the example of the NPM-2 industrial electric locomotive (Figure 1) [1], [2], [3], [4], [5]. It uses a variable-frequency traction drive with an IM of type DTA-350M, each powered by an individual two-level autonomous voltage source inverter (AVSI) based on high-voltage IGBTs (HVIGBT). A pair of AVSI (using a sinusoidal PWM with 3rd harmonic pre-modulation and IR-compensation up to 30 Hz), supplying the pair of IM of a single two-axle bogie, are connected in parallel and contain a common L-shaped LC filter at the input, which is connected to the 1.5 kV DC catenary via a high-speed circuit breaker (HSCB) (Figure 2).

2 Description of Processes during an External Short Circuit. Computer Model

When an external SC occurs, the catenary voltage drops to zero. The DC link voltage V_d begins to fall,

and the capacitance of the L-shaped filter $C1$ discharges into the SC circuit through the reactor $L1$ and the HSCB (the current through it increases).



Fig. 1: NPM-2 industrial electric locomotive.

Source: [1]

The control system detects the SC, removes control pulses from the AVSI transistors, and sends a signal to the HSCB coil to disconnect the HSCB contacts. The phase currents of the IMs drop to zero. V_d drops to zero. The HSCB contacts begin to open, an arc forming between them. The IMs switch to generator mode, and V_d increases as $C1$ charges. At the same time, the phase currents of the IMs reach significant values - more than 2 kA in amplitude (according to experimental data). The results of computer simulation of the above process are shown in Figure 3.

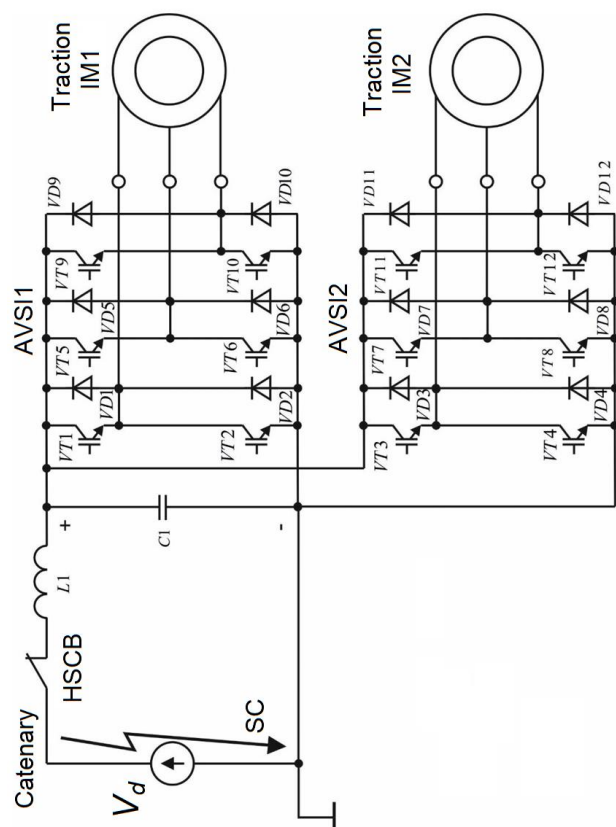


Fig. 2: Electrical schematic diagram of the traction drive of the NPM-2 electric locomotive with an external SC.

Source: created by the author.

In Figure 3 and below, it is assumed that the external SC occurred at $t = 1$ s. Computer models of a 3-phase IM, AVSI, and the reactive type load torque [6], previously developed in the OrCAD environment [7], [8], [9], were used. To simplify the traction electric drive model, the arcing process was not simulated. The HSCB simulation was performed using a switch with programmable opening time and duration and resistance values in the closed and open states. A similar switch, but with a closing function, was used to simulate the SC.

The simulation results in Figure 3 are qualitatively similar to those described in [10], [11], [12].

3 The Idea of Controlling the IM during an External Short Circuit

Due to the danger such high currents pose to circuit elements, the idea arose of not removing control pulses from the AVSI transistors in the event of an external SC. Instead, knowing the rotor speed of the IM, apply voltage from the AVSI to the stator

winding at a frequency synchronous with the rotational speed. In this case, the rotor slip of the IM will be zero.

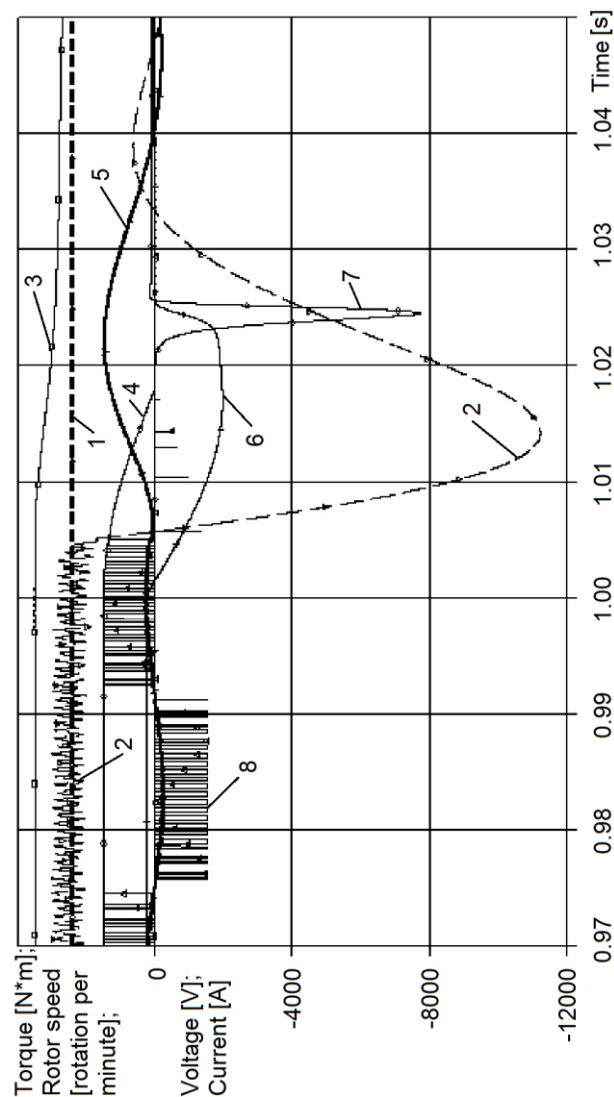


Fig. 3: Computer simulation results of transient processes in a traction drive with an IM of type DTA-350M during an external SC when control pulses are removed from the AVSI transistors.

Graphs: 1 – load torque on the IM's shaft;
2 – air gap torque of the IM;
3 – IM rotor speed multiplied by six;
4 – voltage on DC link capacitor $C1$;
5 – current of the IM phase in which the highest surge value is reached after an SC;
6 – current through the DC link reactor $L1$; 7 – voltage between contacts of the HSCB;
8 – line voltage at the AVSI output.

Source: created by the author.

Thus, by gradually reducing the frequency and voltage at the AVSI output, the rotational speed of the IM can be reduced to a complete stop at zero current. It is also possible to maintain a slight rotor

slip with a positive or negative sign, respectively, bringing the rotor to a complete stop in motor or generator mode.

Maintaining generator mode allows for an increase in V_d due to the kinetic energy of the rotating masses. It should be noted that the frequency converter control method, which interrupts the operating control mode and reduces the output frequency of the AVSI at a limited rate, is used in variable-frequency drives during power supply interruptions, i.e., when the voltage disappears [13], [14], [15]. The rate of change of the output frequency of the inverter is limited to limit the magnitude of the braking current, which is used to maintain or increase V_d . When the power supply is restored, the output frequency of the inverter is increased, and the operating control mode is restored.

The fundamental difference between the modes of power failure in the catenary and during an external SC in the DC catenary is that in the latter case, both buses (positive and negative) of the DC link are shorted to ground before the contacts of the HSCB open.

4 Computer Simulation Results

A series of computational experiments was conducted simulating the process after an external SC for different contact opening times of the HSCB in the range from 0.00229 s to 0.0229 s (the latter value was taken from a test oscillogram, as was the general value for all cases for the time from the moment of the SC occurring to the beginning of the HSCB contact opening – 0.0073 s). The law of change in the output voltage of the AVSI $\frac{V}{f} = \text{const}$ was implemented. The output frequency of the AVSI at each instant of time is calculated as

$$f = \frac{\omega_2 \cdot p}{2 \cdot \pi},$$

where ω_2 - is the rotor speed of the traction IM [rad/s];

p - is the number of pole pairs of the traction IM.

An example of the simulation results of transient processes during an external SC, in the case of maintaining control pulses on the AVSI transistors and monitoring the IM rotation speed in order to obtain the IM deceleration and shutdown process at zero current for a HSCB contact opening duration of 0.00229 s, is shown in Figure 4. It is worth noting in this case a significant increase in the peak voltage

between the HSCB contacts during opening—it exceeds –60 kV.

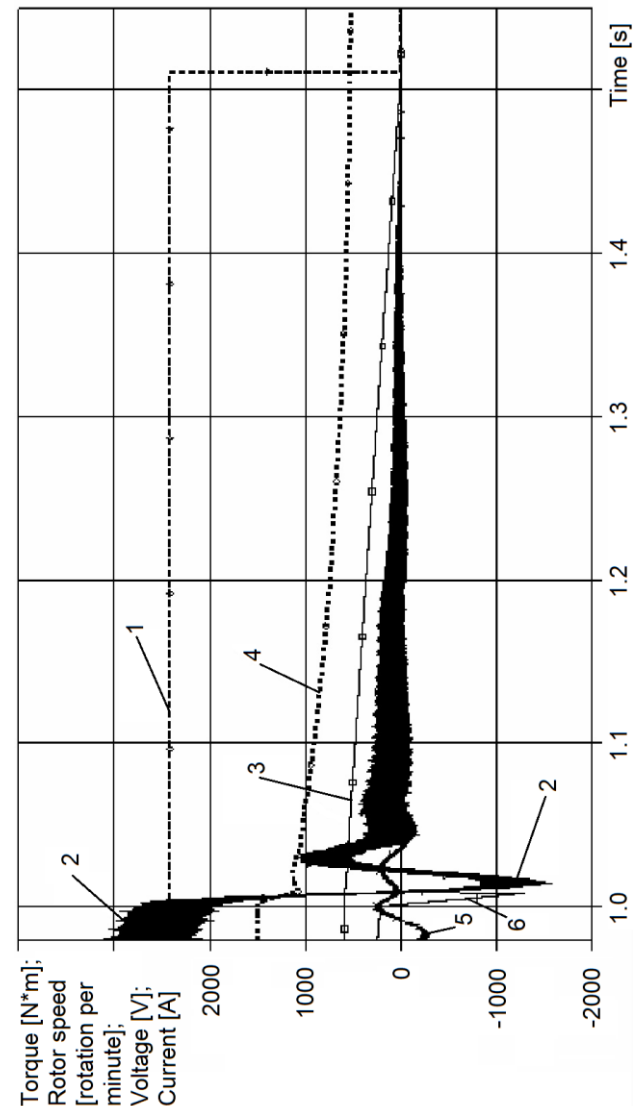


Fig. 4: Simulation results of transient processes during an external SC, in the case of maintaining control pulses on the AVSI transistors and monitoring the IM rotation speed in order to obtain the IM deceleration and shutdown process at zero current.

Graphs: 1 – load torque on the IM shaft;

2 – air gap torque of the IM;

3 – IM rotor speed;

4 – voltage on DC link capacitor $C1$;

5 – current of the IM phase in which the highest surge value is reached after an SC;

6 – current through the DC link reactor $L1$.

Source: created by the author.

The summary results of the simulation for an external SC, with control pulses remaining on the AVSI transistors and the IM rotation speed monitored to obtain the IM deceleration and

stopping process at zero current, are shown in Figure 5, where the values after the SC are given as a percentage of the values before the SC:

- 1 – minimum value of V_d ;
- 2 – absolute value of the peak phase current to the amplitude before the SC;
- 3 – absolute value of the peak braking torque to the load torque.

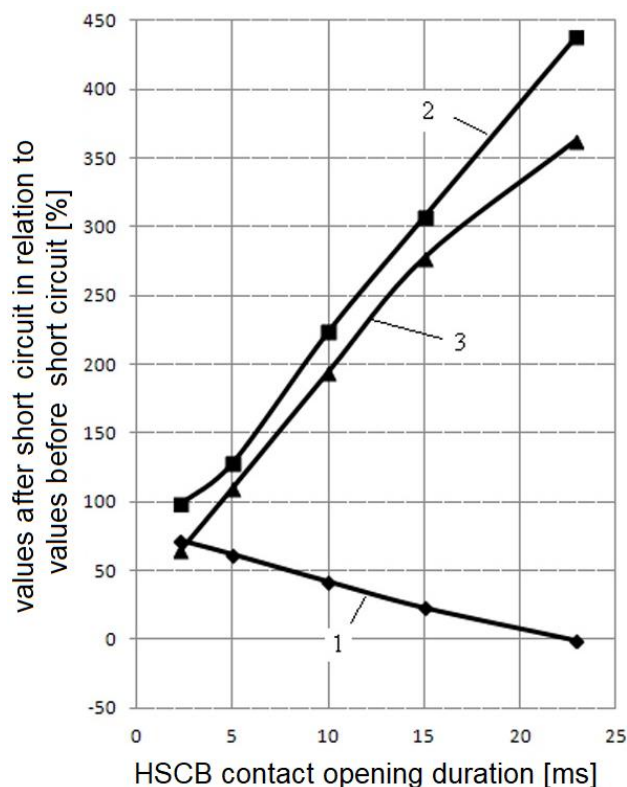


Fig. 5: The summary results of the simulation for an external SC, with control pulses remaining on the AVSI transistors and the IM rotation speed monitored to obtain the IM deceleration and stopping process at zero current.

Source: created by the author.

5 Conclusions

The main conclusions from the simulation results for the behavior of a DC electric locomotive with an IM during an external SC are presented below.

1. If the voltage V_d has dropped to zero by the time the contacts of the HSCB are fully opened, then it makes virtually no difference, from the standpoint of the peak values of the braking current and the air-gap torque of the IM, whether the control pulses on the AVSI transistors are removed or maintained. In this case, the IM braking process cannot be controlled.

2. The smaller the reduction in V_d that will be achieved by the time the contacts of the HSCB are fully opened, the lower the peak values of the braking current and air-gap torque of the IM will be when switching to controlled slip maintenance mode with a decrease in the AVSI output frequency.

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Conflict of Interest

The author have no conflicts of interest to declare that are relevant to the content of this article.

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