ELECTRIC DRIVE FOR TRAMS EQUIPPED WITH TWO MOTORIZED BOGIES AND A SINGLE DC CHOPPER

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În articol se analizează acţionarea electrică a tramvaiului cu două boghiuri motoare conectate în paralel şi alimentate de la un singur variator de tensiune continuă cu comandă numerică. Se prezintă comanda procesului de pornire cu verificarea stării iniţiale a echipamentului, cu realizarea controlului acceleraţiei şi vitezei şi cu limitarea efectului pierderii aderenţei. Se prezintă rezultate obţinute prin simulare şi pe cale experimentală.

This article contains an study of the electrical driving equipment of the tram with two motorized bogies parallel connected and supplied from a single DC chopper with numeric control. It presents the commands of the starting process with initial state check, performing the acceleration and speed control and the reducing of the effects of adherence failure. Simulation and experimental results are included.

Keywords: tramcar, drive, numerical, control, sliding.

Introduction

The present paper is focused on the operation of an electric drive equipment designated to control a tramcar equipped with two motorized bogies driven by a single DC chopper designated to control both motors, which are parallel connected.

Analyzing the behavior of the driving system, in the most probable cases of failures and, also, in the cases of the failures with the most important consequences, was necessary to develop several solutions to treat those failures.

The approach concerns the technical solutions related to the numerical control, which can improve the performances and the reliability of the whole equipment. One subject is the starting of the motors in open loop and the passing to closed loop after feedback signals of the regulators are validated. After this validation shall be enabled the closed loops for: the regulator of the motor currents, the acceleration control and the speed limiter. Also here is described the solution for downsizing the motor's torque during sliding phenomenon (low adherence between wheels and rail). Simulations and experimental results are included for exemplification purposes.

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1. Starting procedure

As example for the starting procedure of the vehicle we shall refer to the power diagram of the tram equipped with two motorized bogies supplied through a single DC chopper [14], diagram presented in Fig. 1. The type of the traction motors is TN71- with series excitation, 120kW nominal power, 750Vcc nominal voltage and 1450 rpm nominal speed.

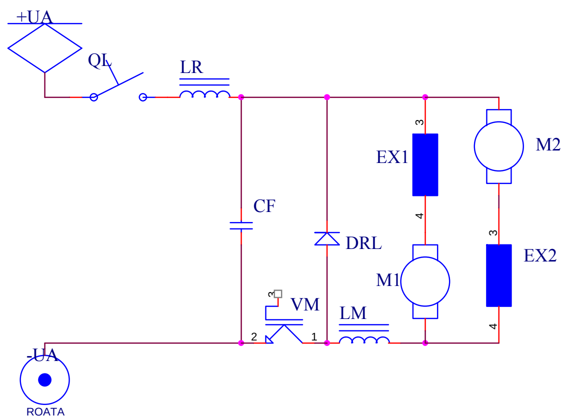

Fig. 1 Electrical diagram of the driving system for tramcar

The model of this circuit is realized based on the Matlab software as described in the Fig. 2.

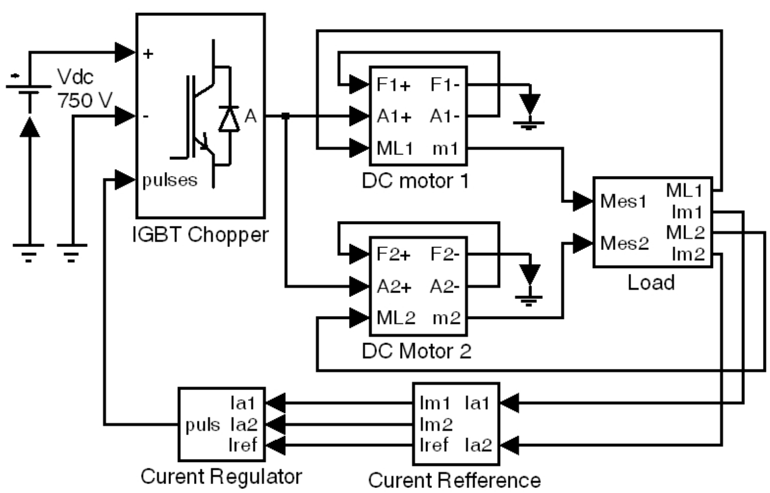

Fig. 2 Simulation model of the DC drive for two motorized tramcar

The model contains: the voltage supply, the DC chopper, the subsystems with the model of the two motors (DC series excited motors), the subsystem with the load torque calculus, the subsystem with the current reference generator and the subsystem of the current regulator. Control principle consists in motor's current control by modulating (adjusting the filling factor) of the voltage pulses applied by the DC chopper (Pulse Width Modulation with fixed frequency) [10]. The subsystems were parameterized as below:

Discrete simulation with time constant Ts = 10 μs;

DC Chopper [13]:

- Forward voltages: IGBT Vf(V) =1.8V, Diode Vfd(V) = 1,8V;
- Snubber resistance Rs = 10Ω;
- Snubber capacitance Cs = 3 μF;

DC machine, discrete [8]:

- Armature resistance and inductance: Ra = 0,005 Ω, La=1 mH;
- Field resistance and inductance: Rf = 0,033 Ω, Lf=10 mH;
- Field-armature mutual inductance: Laf = 26.7 mH;
- Total inertia: J = 50 kg*m^2;
- Viscous friction coefficient : Bm= 52,5 N*m*s:
- Coulomb friction torque: Tf = 0,1037 N*m;
- Initial speed : V_0 = 0.

Load subsystem operates according to the equation:

$$M_f = \sqrt{m} * D * g * \left(25 + 0.0325 * v^2\right), \tag{1}$$

Where:

- M_f : the load torque based on the air resistance and the line resistance;
- The tram's mass *m* = 34,5 [tones];
- Wheel diameter *D* = 0.7 [m];
- Vehicle speed *v* [km/h].

Current regulator subsystem has the transfer function:

$$H(s) = \frac{10 * s}{1 + 0{,}01s} \tag{2}$$

PWM generator subsystem's parameters are:

- PWM frequency: f_{PWM} = 1000 Hz;
- Gamma for current error: [0.01…1].

The motor's current measurements (Ia1 and Ia2) are validated inside the subsystem "Current reference" presented in Fig. 3. This subsystem generates a current reference I_{ref}, with a current ramp (slope 143A/100ms) and a superior saturation of 280A, presented in the Fig. 4.

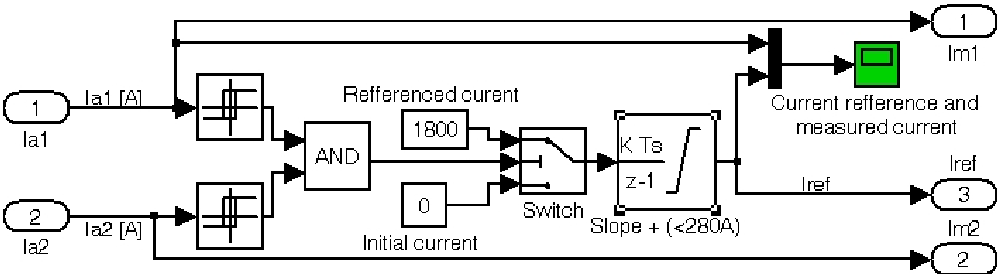

Fig. 3 Reference current subsystem- validates the current measurements (I_{a1} and I_{a2}) and profiles the current reference I_{ref}

At start up the minimum pulse width is initialized (10μs as prescribed by the semiconductor's manufacturer), and the reference current I_{ref} has null value. The motor current measurements I_{a1} and I_{a2} are checked and, after both of them are overtaking the threshold of I_{mmin} (in Fig. 4, the moment 0.015s), the reference generator and the current regulation loop shall be enabled. The feedback of the current loop is provided by the most significant motor current [$\max(I_{a1},I_{a2})$]. In our example the value of the I_{mmin} current is stated at 30Adc, value which corresponds to the minimum coulomb friction torque of each motor [14].

The diagrams of the motor's currents I_{a1} and I_{a2} are presented in Fig. 4 and are placed above the reference current diagrams. Because the two motors are equals for the idealized case, the curves of I_{a1} and I_{a2} are superimposed.

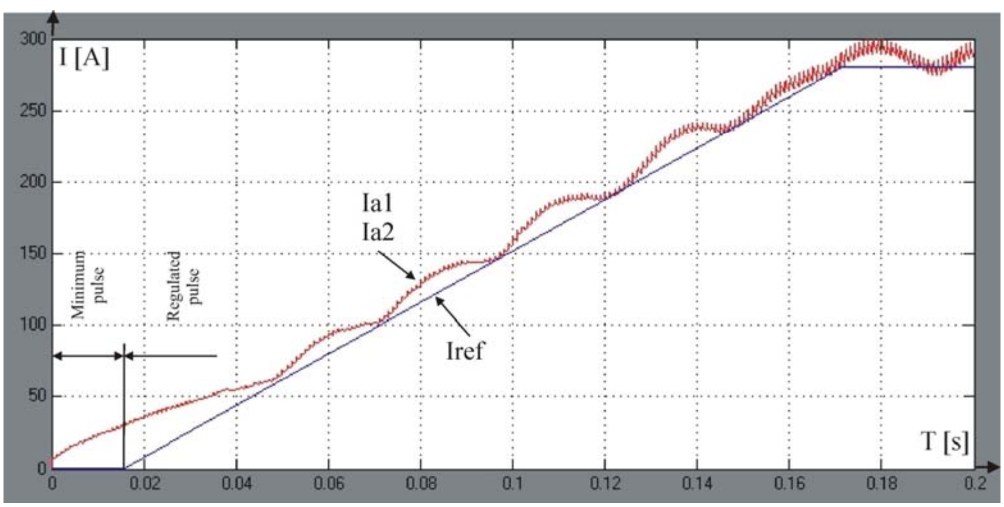

Fig. 4 The diagrams of the current reference (I_{ref}) and the motors currents ($I_{a1,2}$) at start up

In the case that, during the minimum pulse period, one of the motor's currents is much smaller than the other one or is missing, the control unit shall disconnect the power circuit of the defective motor and shall signalize this decision, and the traction will continue, in such case, only with the valid motor unit, with lower speed limit (eg. V < 20 km/h).

2. Vehicle's acceleration control

The maximum prescribed current is calculated that maximum acceleration limit for the vehicle can be reached with full load. Additionally, when the vehicle is not loaded or the vehicle goes downhill, the acceleration limiter loop shall decrease the current reference in such manner that the acceleration will not exceeds the maximum limit, parameter imposed usual by the traffic regulations (1.2…1.4 m/s^2). In order to increase the comfort and to reduce the mechanical stress, the current reference is integrated in such manner that, for any variation of the traction reference (from the driver), the pass from the old value to the new value shall be completed in a fixed period of time (fixed parameter between 2…4s).

In the Fig. 5 are presented the experimental diagrams of the motor's currents in the case of a start without acceleration control, for a sand-loaded vehicle at maximum payload. Please notice that the current reference is rising linear from the minimum value of 30 Adc up to the maximum value of 320 Adc in 3 seconds, and the currents I_{m1} and I_{m2} are following up the reference.

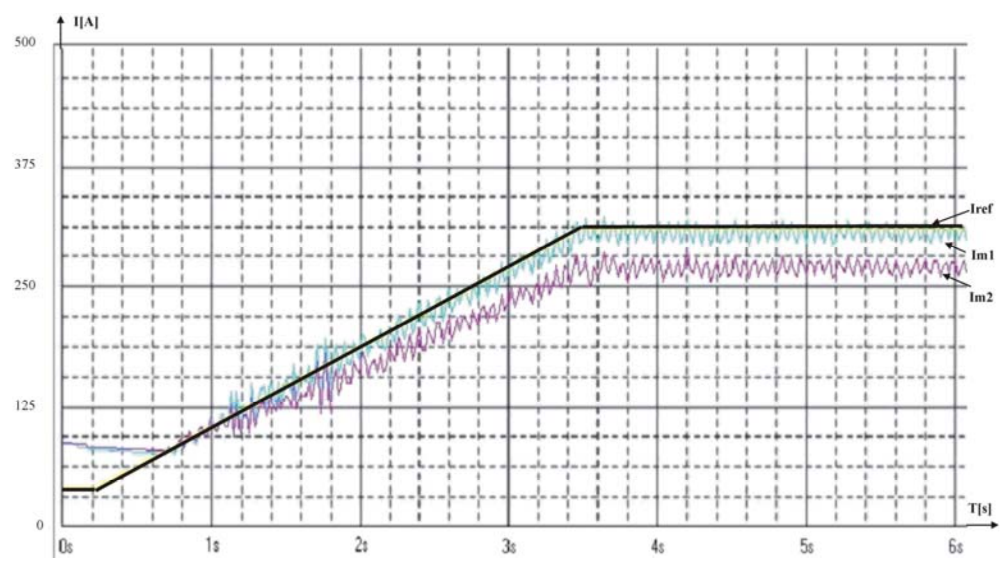

Fig. 5 The experimental diagrams of the current reference (I_{ref}) and the motor's currents (I_{m1}, I_{m2}) at start up without acceleration control

Because the experiment was performed on a new rail, with good adherence, nor the acceleration limiter or the anti slip protection were not modify the current reference.

In the Fig. 6 one can see the diagrams of the current reference, the motor currents, the vehicle speed and the line voltage for an experiment of start with acceleration control, performed with an unloaded tramcar.

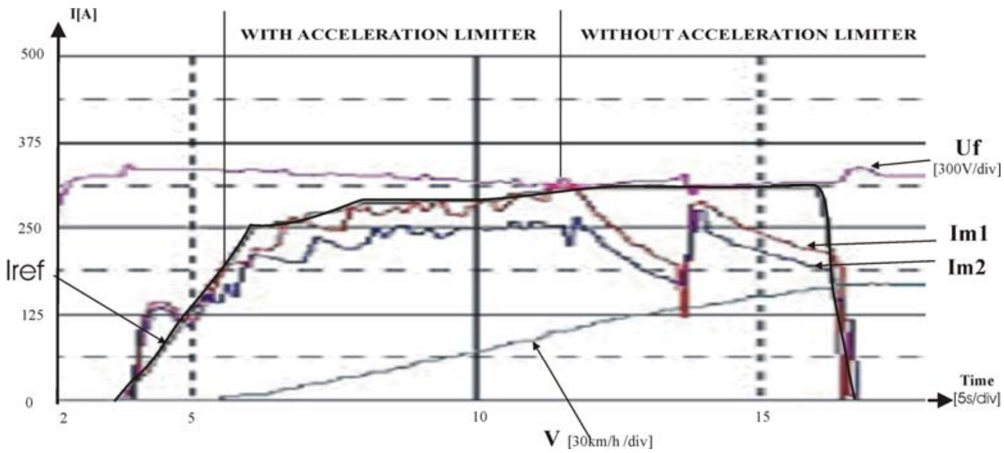

Fig. 6 The experimental diagrams of the current reference (I_{ref}) and the motor's currents (I_{m1}, I_{m2}) at start up with acceleration control

The acceleration limiter action, as seen in Fig. 6, acts through the current reference I_{ref} , which shall be decrease when the measured acceleration exceeds the imposed limit. Form the 6-th second (when the measured current reached 250Adc) when the speed is highly increasing, the slope of the current reference diagram is slowing down in that manner that the acceleration can be kept under the imposed limit, as can be seen in the time interval of 6…12 seconds, where de speed slope is constant. As the vehicle's speed is increased the reference limiter is no longer needed, because the increasing of the air resistance and the line friction reduces the vehicle's acceleration.

3. Vehicle's speed limiter

The international standards regarding the road traffic are stating that the maximum speed of the vehicles shall be limited, and the value of the speed limit for tramcars without separate line is stated at 50 km/h. In order to achieve this objective, the current reference shall be decrease nearby the maximum speed V_{lim} in that manner that the speed shall be maintained constant, with a tolerance of ± 5%. With the intention of discouragement of the over speed, when the speed limit is over passed with more than 5%, the traction diagram shall be disconnected, and a new traction command sill be enabled only if the speed decreases the $0.95*V_{lim}$.

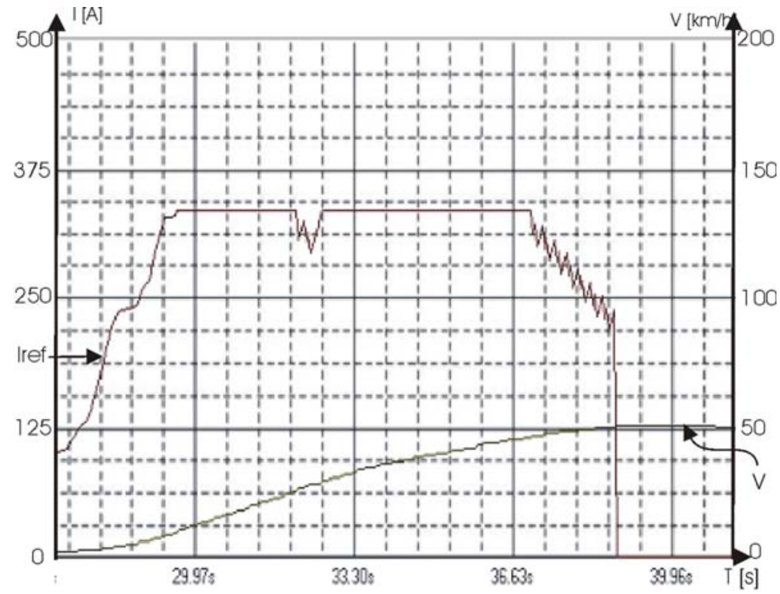

Fig. 7 The experimental diagrams of the current reference (I_{ref}) and vehicle's speed (V) durring the speed limit test

As described in Fig. 7, the current reference is decreased gradually in order to maintain the speed near the V_{lim} = 50 km/h [9].

4. The behavior of the tram at low adherence with the rail

The phenomenon of low adherence between the wheel and the rail during the traction is weakening the acceleration control, generates mechanical stress and amplifies the wheel wearing out. There are two methods used to detect the apparition of the slip between the wheel and the rail:

- The comparison between the motorized axle speed and a free axle speed;
- The comparison between two motor currents.

First method is using the speed measurements based on the inductive speed transducers, characterized by a low resolution [1], (no more than 40 pulses for each wheel revolution). For low speed, the number of the pulses is very small and the accuracy of the measurement is not satisfactory, and also the adjustment for slip protection can't be efficient.

The second method, which uses the comparison of the motor currents, is much faster in providing information about low adherence. The motor current used to be determinate twice in a period of the current loop (T_{PWM} = 1ms). The motor from the slipped bogie will have higher speed than the other one, and, supplied with the same voltage, will have smaller current. For this case, of single chopper for two paralleled motors, the method consisting in supervising the percent of difference between the two motor currents provides a fast and reliable detection of slipping bogies [4]. In the same time one must consider that the difference between the two motor currents can have various causes: the electrical parameters of the motors can have 3…5% differences, and the cable length can add more unbalances for the system with two parallel motors. Practically, the method works if the overall unbalance is below 5%.

By experiments we perform anti slid protection for two motors with 4% unbalance by setting the threshold of 8% for the slip detector function of the control unit. In Fig. 8 is presented the diagram of the motor currents I_{m1} and I_{m2}, the current reference I_{ref}, the prescribed reference from controller I_r and the speed of the vehicle.

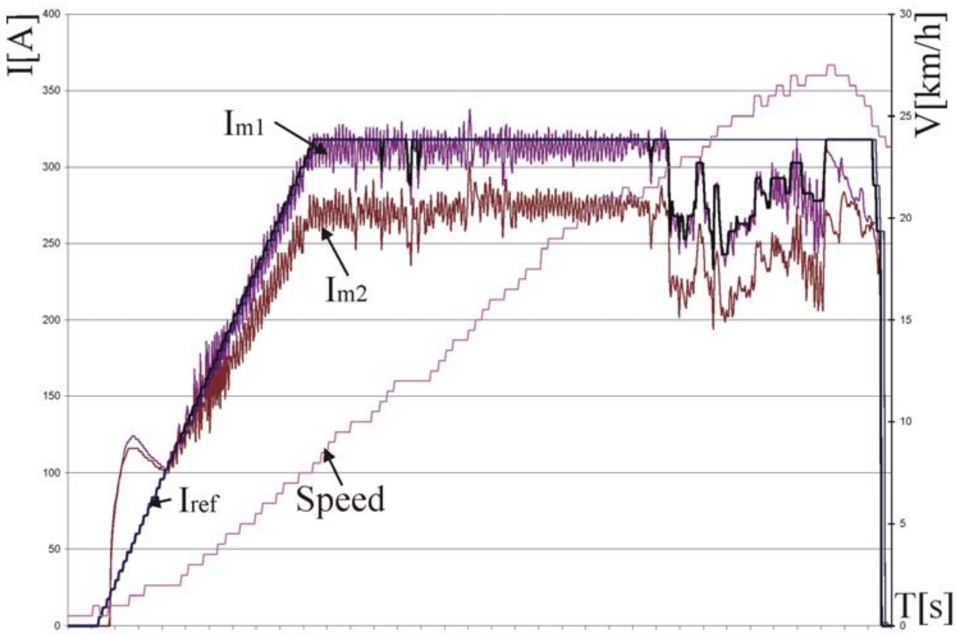

Fig. 8 The experimental diagrams of the current reference (I_{ref}), motor currents (I_{m1} and I_{m2}) and vehicle's speed (V) during the slip protection tests

The diagrams from Fig. 8 presents the current reference, motor currents and vehicle's speed measurement for a test performed with unloaded tramcar. We can notice that the speed is still increasing during the slip protection, the reference is decreased as the current I_{m2} through the motor 2 decreased due to slip phenomena.

The effect of this slip protection function can be estimated in two ways:

- The determination of the displacement between the tramcar's wheels;
- The wear analyze for the motorized wheels.

The test for displacement of the wheels was made on the tram with 4 bogies, two of them with motors and two of them without motors. The low adherence line has dirt, mulch and old grease on it. Results of these tests are placed in Table 1.

Table 1

Relative displacement of the wheel markers during slipping

Acceleration range	Bogie 1 (Motor)	Bogie 2 (Free)	Bogie 3 (Free)	Bogie 4 (Motor)
0-10 km/h	101%	100%	99.5%	101%
0-15 km/h	103%	100%	99.6%	102%
0-20 km/h	102,6%	100%	99.8%	102,2%
0-25 km/h	102%	100%	99.8%	101%

These tests can prove that the motorized bogies (no.1 and no.4) have a small slip, with the remark that the first bogie has additional slip because he trips fists the line impurities and has smaller overall adherence than the other ones.

The wear analyze of the wheels was performed on the prototype, for a 40000 km distance on different quality lines of Bucharest, with measurements at each 5000 km according to the revisions procedure for trams.

Table 2

Medium wear [mm] of the bogie's wheels for a prototype tram

Kilometer counter	Maximum admissible wear 0,48mm/1000km	Medium wear Bogie 1 (Motor)	Medium wear Bogie 2 (Free)	Medium wear Bogie 3 (Free)	Medium wear Bogie 4 (Motor)
10000	4.8	2.10	1.60	1.60	2.00
20000	9.6	5.00	3.50	3.70	5.00
30000	14.4	6.60	5.20	5.40	6.50
40000	19.2	8.50	6.00	7.00	8.20

During the test period the tramcar was 8 times revised, the bogies were inversed and rotated, and the crests of the wheels were lathed. Thanks to the uniform wear of the wheels, was not necessary to lathe the bandage of the wheels.

An important advantage of the numeric control is the goal that one can operate with reported values [2]. For example, the current error can be determined as a percent of the measured current and the efficiency of the regulator will be the same for all range of motor currents. In the case of an analog type control unit, only a absolute error can be considered for current, in this case 8% for the maximum current (320Adc) corresponds to an threshold of 25.6 Adc, and this value represent 12.8% for a 200 Adc measured current, when the method for slip protection can not be efficient.

5. Diagnose capability of the traction motors

The comparison of the two motor currents when the DC chopper is completely open offers the opportunity to perform diagnose of pour contact of the brushes of the motors. When a current error is detected, a signal for driver is engaged and an event is stored in the event memory, joined by a time stamp. If the duration or the amplitude of such error exceeds a critical threshold, the power diagram shall be disconnected in order to protect the motor. This type of failure has major occurrence among the rolling tramcars in Bucharest (about 40% of the trams failures are located at the brush-collector systems) [5].

Fig. 9 The experimental diagrams of the current reference (I_{ref}), motor currents (I_{m1} and I_{m2}) and vehicle's speed (V) during the slip protection tests

In the Fig. 9 the motor current diagrams I_{m1} and I_{m2} currents are presented for a 0 to 50 km/h run, with a defective motor (no. 2). At the moment 9.3s and 9.7s, corresponding to a vehicle speed about 42 km/h, two minor faults happened, and a major fault at the 18.5s (53km/h) followed by a disable command. Those detections are mentioned in the event memory of the control unit and the driver's desk display shows the message "Motor 2 failure" and flushes a red lamp. The comparison of the motor currents is performed with percent values to ensure the same precision for all current range.

Conclusions

Driving two paralleled motors with a single DC chopper, numerically controlled, represents an economical solution for tramcar drive equipment. By using the numerical control can be solved several problems: the initial check of the equipment's status, the acceleration control, the detection of slip phenomena and the limitation of his effects, the continuous speed control [11], [12]. In the meantime, the prevention of the collector flames can be performed by the aid of the detection of pour contact of the brushes, which generates the collector failure.

Experiments performed on the traffic tramcars in Bucharest did confirm the efficiency of the methods proposed herewith and developed by the author within the research and development compartment of the company ICPE-SAERP from Bucharest.

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