TRACK CIRCUITS - ELECTROMAGNETIC PERTURBATION AND COMMUNICATION CHANNEL MODELING AND SIMULATION WITH QUAD-GATES MODELS

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Track circuits are used to positioning the rolling stock, verify the integrity of the line and to transmit the on-board information to the train. Due to the use of an unspecialized communication channel, the data transmission is affected throughout the communication channel. The article presents a model with quad-gates that can simulate the behavior of a line portion in various constructive configurations, as well as in the presence of electromagnetic disturbances. Some examples of quad-gates are presented which, by connecting them in cascade, allow the simulation of the behavior of the communication channel. The model was used to simulate the communication channel with Multisim software for designing a new type of track circuit.

Keywords: track circuit, modelling, simulation, electromagnetic perturbation model

1. Introduction

The conventional rail signalling system sends the train driver the necessary information to drive the train safely, through mechanical or light signals that are installed on the side of the track. Signage by appearance, colour and number of lights indicates to the mechanic the conditions to be respected. The necessity to increase the speed of the transport system exceeding the human sensory limitations, is binding the need to send the information directly to the on -board equipment. The on-board equipment is doing the automatic information interpretation, and the driver has only the task of supervising the system.

Transmission of data through the channel made up of railway tracks is undergoing severe disturbance, because it is not a dedicated channel for data transmission. The rail tracks attached to wooden or concrete sleepers that are placed on a resilient bed made of ballast. This construction does not provide a very good insulation resistance between the two rails. Modelling and simulation of this transmission channel in the presence of electromagnetic disturbances in the electric traction system has become a necessity to facilitate the design and maintenance of the data transmission system to the train. Using the theory of

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multi-conductor lines, Dommel [1] has developed the technique of differential equations for the analysis of wavelength and the loss of power in transmission networks. The method is based on Bergeron's observations [2] and uses circuit analysis by stresses in nodes, with the behaviour of the concentrated parameter elements represented algebraically by differential equations. Another implementation is offered by the University of Columbia English as EMTP (electromagnetic transient program) and EMTDC (electromagnetic transient including DC) from the Manitoba High Voltage Research Centre. A way to solve the above problem is the technique based on nodal analysis of the discrete components network, through the SPICE software package originally developed by Nagel at the University of California [3] [4]. The method is based on the analysis of time-varying nonlinear circuits by setting a circuit model and solving the conduction matrix-by-matrix factorization assuming linearity. The nonlinearity is then solved by successive and time-dependent linearization by successive solutions of the non-linear circuit. In order to use SPICE, the complete circuit must be represented by passive components, independent or dependent voltage or current sources, semiconductor components (diodes, bipolar or field effect transistors) represented by non-linear models with exponential functions. Thyristor, GTO (gate turn off) thyristor and other switching components used in power circuits are not available in SPICE, they must be created by the user or can be represented by simple switches, acceptable for audio frequencies.

2. Track circuit- models of the communication channel analysis [5] [6]

The analysis of the communication channel, represented by the track circuit, is a complex problem. The electric model usable in both, analysis and design, is the multi-threaded electrical line with losses. This model faithfully reproduces the propagation through the two tracks in the presence of neighbouring lines, the catenary or the third rail and the ground. In practice, three particular cases are used:

Bifilar long line - it accurately simulates normal and shunt propagation; it is used to analyse these regimes and to develop regulatory rules;

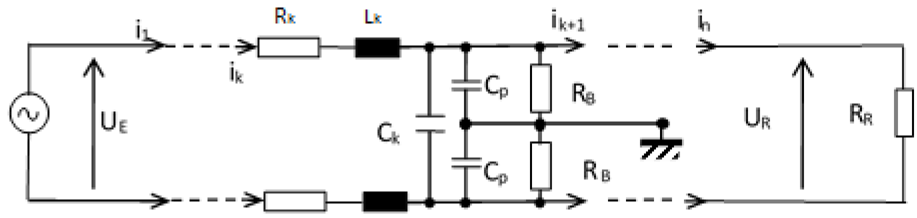

Fig. 1 Equivalent electrical circuit of the track circuit in the presence of the earth

Long line with two active conductors in the presence of ground considered a zero-resistance conductor - this accurately simulates the normal, shunt, control and most of the cases of the disturbance analysis produced by the electric traction current; long line with three active conductors in the presence of the soil (physical, the two rails and the catenary or the third rail) - the model provides the analysis of the electric traction disturbances in some particular cases.

Frequencies used by the track circuits in the Bucharest subway are in the 6100 Hz - 8100 Hz range, so they have a wavelength greater than 30 km, and the length of these circuits is 300 m, the length of the circuit is much smaller than the length of the waveform of the signal passing through this transmission channel. The path seen from T_X (transmitter) and R_X (receiver) is a transmission line shorter than the wavelength of the signal. For modelling the transmission channel, we can use the modelling with distributed elements. A simple transmission line, without connections to external equipment or secondary voltage sources and totally isolated from other neighbouring circuits is considered, consisting of two conductors in the presence of the earth represented by Fig. 1.

The line as consisting of a chain of quad-poles connected in cascade between the transmitting and the receiving end and at the two ends with the di-port, terminal impedances connected according to Fig. 2 can be considered:

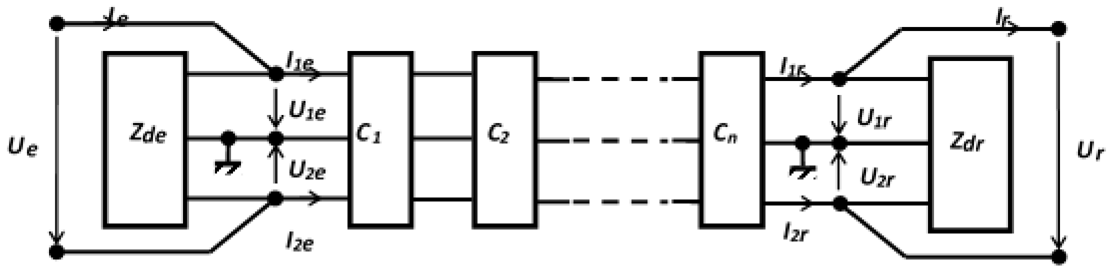

Fig.2. Electrical modelling of the path through a quad-gates chain

Quad-gates components C_k represent linear portions with evenly distributed parameters or concentrated elements connected at the rail. Each component quad-gates is defined by the hybrid transfer matrix $[C_k]$ which establishes the link between the input values U_{1k}, U_{2k}, I_{1k}, I_{2k}, and the output matrices $[U'_{1k}]$, $[U'_{2k}]$, $[I'_{1k}]$ $[I'_{2k}]$:

$$\begin{bmatrix} U_{1k} \\ U_{2k} \\ I_{1k} \\ I_{2k} \end{bmatrix} = [C_k] \begin{bmatrix} U'_{1k} \\ U'_{2k} \\ I'_{1k} \\ I'_{2k} \end{bmatrix} \tag{1}$$

The quad-gates of the path C_k formed by the cascade connection of the quad-gates C_1, C_2, ... C_k is defined by the matrix:

$$[C] = [C_1] * [C_2] * ... * [C_k] \tag{2}$$

Parameters defining matrix [C_k]:

$$[C_k] = \begin{bmatrix} C_{k11} & C_{k12} & C_{k13} & C_{k14} \\ C_{k21} & C_{k22} & C_{k23} & C_{k24} \\ C_{k31} & C_{k32} & C_{k33} & C_{k34} \\ C_{k41} & C_{k42} & C_{k43} & C_{k44} \end{bmatrix} \quad (3)$$

The C_k parameters are to be defined in relationships with the quad-gates structure and the primary parameters of the rail and of the concentrated elements introduced. For a line of length „l" with two active conductors in the presence of earth, the values of voltages and currents at a point situated at the distance x from the output end are defined by relationships 4, 5, 6, 7, where P1, P2, P3 and P4 are integration constants that are determined from the boundary conditions.

$$U_{1x} = P_1 \mathrm{ch}\gamma_1 x + P_2 \mathrm{sh}\gamma_1 x + P_3 \mathrm{ch}\gamma_2 x + P_4 \mathrm{sh}\gamma_2 x\,; \quad (4)$$

$$U_{2x} = M\,(P_1 \mathrm{ch}\gamma_1 x + P_2 \mathrm{sh}\gamma_1 x) + N\,(P_3 \mathrm{ch}\gamma_2 x + P_4 \mathrm{sh}\gamma_2 x)\,; \quad (5)$$

$$I_{1x} = e_{11}(P_1 \mathrm{sh}\gamma_1 x + P_2 \mathrm{ch}\gamma_1 x) + e_{12}(P_3 \mathrm{sh}\gamma_2 x + P_4 \mathrm{ch}\gamma_2 x); \quad (6)$$

$$I_{2x} = e_{21}(P_1 \mathrm{sh}\gamma_1 x + P_2 \mathrm{ch}\gamma_1 x) + e_{22}(P_3 \mathrm{sh}\gamma_2 x + P_4 \mathrm{ch}\gamma_2 x)\,, \quad (7)$$

By determining the values at the end of the line of length "l" (x = 1), the relations of dependence of the input quantities according to the output ones is obtained, which have the form:

$$U_{k1} = C_{k11} \cdot U'_{k1} + C_{k12} \cdot U'_{k2} + C_{k13} \cdot I'_{k1} + C_{k14} \cdot I'_{k2}\,; \quad (8)$$
$$U_{k2} = C_{k21} \cdot U'_{k1} + C_{k22} \cdot U'_{k2} + C_{k23} \cdot I'_{k1} + C_{k24} \cdot I'_{k2}\,;$$
$$I_{k1} = C_{k31} \cdot U'_{k1} + C_{k32} \cdot U'_{k2} + C_{k33} \cdot I'_{k1} + C_{k34} \cdot I'_{k2}\,;$$
$$I_{k2} = C_{k41} \cdot U'_{k1} + C_{k42} \cdot U'_{k2} + C_{k43} \cdot I'_{k1} + C_{k44} \cdot I'_{k2}\,,$$

Where Ck i j (i, j = 1, 2, 3, 4) are the parameters of the quad-gates that define the line of length "l".

Considering a very good ballast resistance $R_B = \infty$ and a ideal neighbour frequency rejection circuit, ideal C_A, C_B and ideal L_A and L_B inductors, and identical rail coupons. The receiver di-ports with the simplified diagrams and transmitter di-port shown in Fig. 3 are obtained. After making the calculations and applying the assumption listed above, the value of the Z zone impedance is obtained as being:

$$Z = Z_{21} + Z_1 Z_2 \quad (9)$$

Where the Z_1 notation was used for the characteristic impedance of a 5-meter long rail coupon in the tuning area and with the Z_2 the characteristic impedance of the tuning area, they are:

$$Z_1 = j\omega L_s + R_s$$
$$Z_2 = j\omega L_Z + R_Z \qquad (10)$$

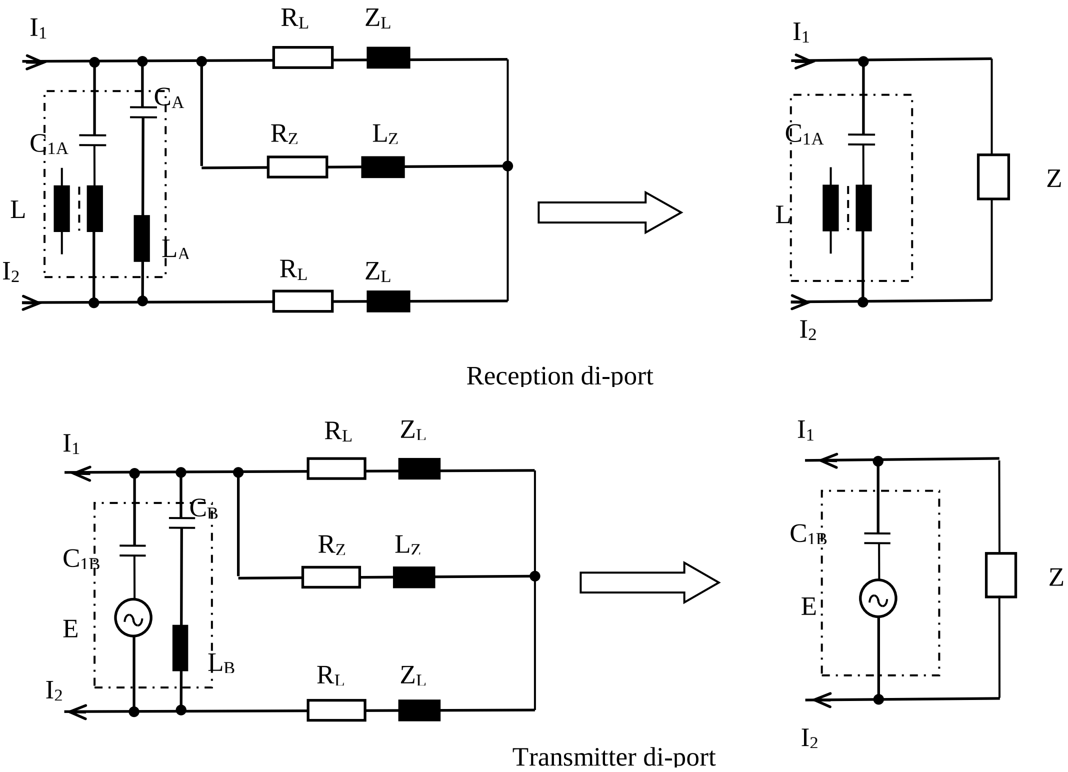

Fig. 3. TI21M equivalent di-poles transmitter-receiver

Having the description of the main quad-gates and the transmission and reception di-poles, the communication channel, used by the track circuit, can be modelled. Using the model shown in Fig. 2 and relationships 11, is obtained a model, that can be used to estimate the losses and restrictions imposed by the communication channel, used by the TI21M track circuits, which are also used in the Bucharest subway.

$$\begin{bmatrix} U_1 \\ U_2 \\ I_1 \\ I_2 \end{bmatrix} = [C_k] * \begin{bmatrix} U_1' \\ U_2' \\ I_1' \\ I_2' \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \\ C_{41} & C_{42} & C_{43} & C_{44} \end{bmatrix} * \begin{bmatrix} U_1' \\ U_2' \\ I_1' \\ I_2' \end{bmatrix} \qquad (11)$$

3. Perturbations in metro electrical transport

The Electromagnetic interferences in electrical railroad systems cause unwanted currents and voltages occurring in communications systems as well as in signalling and control systems. The presence of interference for different types of circuits causes disturbance by conductive, magnetic, electrical or radiant coupling due to noise of the useful signals of track circuits.

3.1 Disturbances introduced by the traction electrical substation

The electric traction substation provides the required power through three-phase low voltage transformers and through hexagonal rectifier bridges feed the third rail, at the output of the electric traction substation it is a pulsating voltage U_0 that shall provide power to the electric motors on the electrical metro trains.

$$U_0 = \frac{2}{2\pi/m} \int_0^{\pi/m} U_{max} \cos(\omega t)\, d(\omega t) = U_{max} \frac{\sin \pi/m}{\pi/m} \quad (12)$$

Output voltage is a pulse-rectified voltage with m = 6 pulses in a period, so the first significant harmonic is the sixth harmonic at 300 Hz. The di-poles of the hexagonal rectifier traction substation may be as shown in Fig. 4

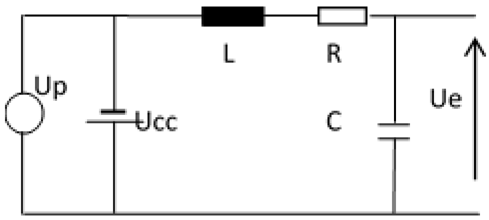

Fig.4. the electrical substation di-port model

For the modelling of the electrical substation's the Up [7] pulse signal source having the main frequency on the 300 Hz harmonic, the Ucc continuous voltage source with a voltage of 825 Vcc, the internal inductance of the substation L, the internal resistance R and parasitic capacity of substation C were used.

3.2 Disturbances introduced in track circuits by the third rail

The feeding of subway electric trains, using electric traction motors to provide the necessary driving forces for the movement of the rail vehicle, is accomplished while passing through a tunnel from a rail located in the vicinity of the railway and called the third rail [8]. The subway trains are connected to this track by a slippery sliding contact called collector. The electrical substation feeds the third rail with the hexagonal pulse voltage given by the traction power rectifiers. This pulsating voltage passes through the third feed rail located in the constructive architecture shown in Fig. 4.1 and produces a magnetic field having concentric circular field lines around this feed rail. To model this disturbance in the communication channel, model used by track circuits, the following scheme can be used as a model:

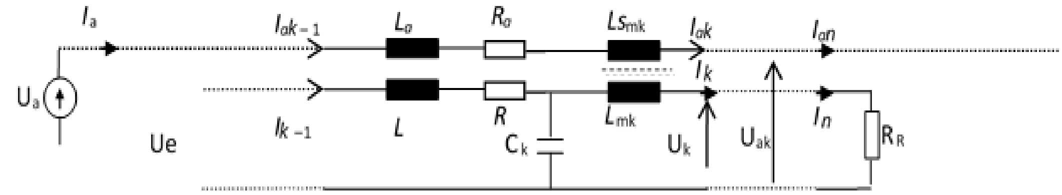

Fig. 5. Modelling circuit for inductive disturbance

Where the third rail feed voltage is denoted by U_a, I_{ak} is the current through the third rail in the cell k and the U_{ak} is feed rail voltage for the same cell. For the track circuit we have L and R the inductance and the resistances of the track rails for the k cell respectively R_{ak} and L_{ak} are the resistivity and the inductance of the third rail in cell k.

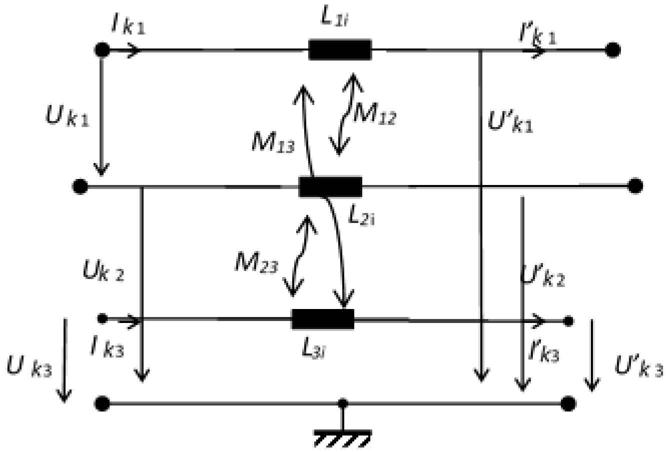

Fig. 6. Equivalent di-port for Inductive Disturbance

The element that shapes the inductive disturbance introduced by the third track into the track circuit is represented by the mutual impedances L_{mk} and L_{smk} that are coupled to each other and having a coupling ratio for the subway configuration of about 5 to 1 for harmonics of the same order [9]. The equivalent di-port for the inductive disturbances introduced by the third rail current in the track circuit is shown in Fig. 6.

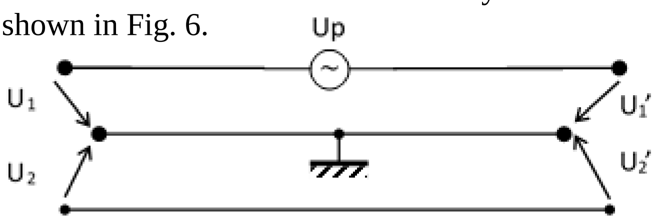

Fig.7. Equivalent di-port for inductive disturbance in the track circuit

For the case investigated, regarding the inductive disturbances affecting the track circuit, can be considered the simplified equivalent di-pole like in Fig. 7. The useful signal of the track circuit is superimposed on a disturbing signal induced by the third rail adjacent to the track circuit, the disturbing signal contains besides the 300Hz harmonic due to the electrical substation and the disturbances introduced by the train motors.

3.3 Disturbances introduced by the subway train motors

The third rail provide power to the subway electric train motors. These motors must ensure the movement of the railway vehicle. The railway vehicle is considered to be a rigid body, which is subjected to forces occurring in the rectilinear motion of this vehicle. These forces are divided into forces controllable by the driver and forces independent of the driver's will. Controllable forces are the braking forces and speed-up forces of the metro train and are commanded by the train control system at the command of the driver or on-board computers. There are also forces independent of the driver's will, namely the opposition forces of the train advance, these forces in the case of the subway are amplified due to the piston effect when the train enters into the tunnel. Modern trains are using electronic control of the traction motors, with chopper at frequencies above 400 Hz. The choppers of motors, of the same train, are discontinued to prevent the occurrence of traction current peak edges of the train motors at the same time, and usually they are offset each to the others by the traction management computer of the train. For the metro train used in Bucharest, consisting of 6 wagons from which four have four-axle tractors, produces disturbances, due to the electronics of sixteen motors of varying frequency, with a maximum effective frequency of 6400 Hz. The electric quad-gates model of the traction circuit is shown in Fig. 8

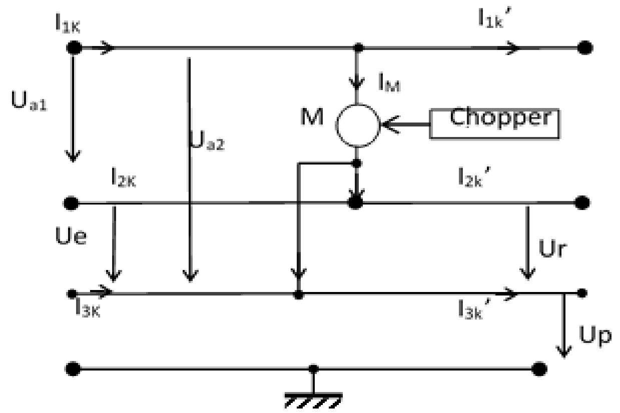

Fig.8. electric pattern of the traction circuit of a subway trains

In the third rail, we have a pulsed six-phase wave with the main harmonics at 300Hz. This voltage is used to power a metro train, on a line section. The metro motors, fed with this pulse voltage, chopper the voltage with variable frequencies up to 6400 Hz. The return current goes, into the way to the electric substation, through the two rails where the track circuit signal passes. The disturbance introduced by the electric train motors affects the track circuit in two ways, inductive disturbances from the third rail and conductive disturbances through the traction return. To avoid these disturbances, introduced by the electric motors of the train, frequencies used by track circuits are chosen so as not to be affected by disturbances introduced by subway electric motors.

3.4 Disturbances introduced by the electric arc

The underground electric powertrain uses, during the journey, for powering electric motors, a metallic rail mounted close to the running track. For dynamic connection to this rail, electric pickers are used that slide on the bottom of this rails. Shoe contacts are made of a graphite material to prevent welding them from the metallic rail. The third rail cannot be built as a continuous rail from one end to the other on the metro line, as like the catenary is built. Due to the safety measures inside stations the third rail has to be installed on the opposite side of the platforms, in the area of the crossings the third rail is interrupted to allow the rolling stock to change the line. When the traction is changed from a piece of the third rail to another piece there is a sudden interruption of the traction current through the pickers, which leads to the occurrence of the electric arc. When the train reconnects the collectors with the next power rail, the motors are in charge and there are big connection currents. The electric arc produces strong radiant disturbances in neighbouring circuits but also by unsymmetrical disturbance of current and voltage, emerging harmonics, induced falls or overvoltage, strongly disturbs the circuitry through the conductive and inductive path. Due to the suddenly interruption or connection of very high currents, steep fronts appear in the power supply circuits of the respective train, respectively through the third rail and the traction return rails, these suddenly fronts disturb the signal of the track circuit. The electric arc occurs when certain conditions are met, namely the existence of a higher voltage than the arc voltage and the existence of a current higher than the minimum arc current. When these conditions are existing at the approaching or disconnecting the electrical contacts, the air between them is ionized and the electric arc appears on a length l, the electric arc goes out when the critical length is reached, or the electrodes come in contact. The electric arc behaves like a movable conductor with the adjustable section by the current that produces it, behaves practically as a non-linear ohm resistance [10]. The arc voltage can be described by the following mathematical form [11]:

$$V(i) = \begin{cases} V_{at} + C/_{D+i} & \mathrm{di/dt} \geq 0 \\ V_{at}\left(1 - e^{-i/T}\right) & \mathrm{di/dt} < 0 \end{cases} \qquad (13)$$

V_{at} is the threshold voltage for electric arc formation and I_0 is the current required for arc formation and D and C are constants corresponding to the power and energy of the arc. The arc electric parameters used in calculations and modelling are the following: arc voltage drop, arc the current trough the arc, arc energy E_a, arc length l_a, arc diameter d_a and arc resistance R_a [12] To calculate the energy of the electric arc we can use the diagram in Fig. 9:

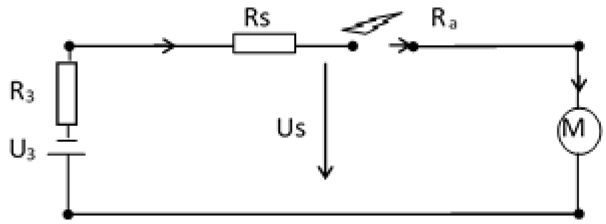

Fig. 9. Scheme for calculation of electric arc energy

Applying Ohm's law for the electric arc formed is obtained

$$I_{arc} = U_S / R_S + R_3 + R_a + R_M \quad (14)$$

Where U_s is the voltage of the electric substation with internal resistance R_s, R_3 is the resistance of the third rail, R_M is the equivalent resistance of the electric train motors, and R_a is the equivalent resistance of the formed arc. Resistance of the electric arc can be described according to [11] [12] with the following equation:

$$R_{arc} = 20+(0{,}534*G) / (Iarc *0{,}88) \quad (15)$$

Where R_{arc} is the resistance of the electric arc in ohms, G is the gap where the electric arc was formed in millimetres and I_{arc} is the current passing through the arc formed. The power and energy of the electric arc are given by the following formulas [6]:

$$P_{arc} = I^2_{arc} * R_{arc}$$
$$E_{arc} = P_{arc} * t_{arc} \quad (16)$$

In the case of a continuous electric arc formed in the open air, the static characteristics can be described using the formulas given by Nottingham according to the arc current “I” and the length of the arc “l” [12] [13]:

$$U(I,l) = a + bl + \frac{c+dl}{I^n} \quad (17)$$

Where a, b, c, d, n are approximation constants, these constants depend on the electrode materials, the geometric location of the electrodes, the type and pressure of the gas in which the arc is formed. [14] In the presented case, the electric arc influences the signal of the track circuit through the abrupt voltage and current fronts that appear in the power supply circuit of the electric train, especially in the return path of the traction current used by the track circuit signal. The electric arc can be modelled to study disturbances in track circuits with the following scheme [15]:

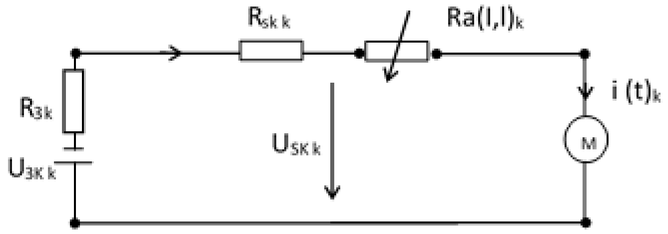

Fig. 10. Modelling scheme for electric arc

The variation of the electric arc resistance Ra (i, t) respects the variation function given by the relations (13) depending on the moment of coupling or decoupling of the motors from the third rail. To modelling the effect of the electric arc in the track circuit, we can use the model shown in Fig. 11. The schematic also contains the motor modelling part that is disconnected or connected to the third rail:

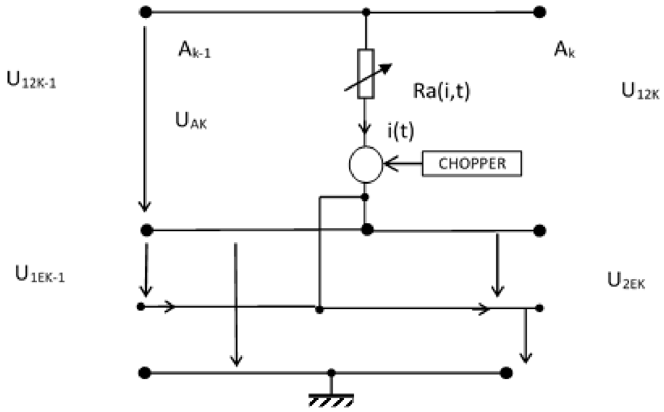

Fig. 11. Model for electric arc on the third rail

As with the electric arc formed on the third rail, the variation characteristic of R_{as} corresponds to the variation function (13). Here the electric arc phenomenon cannot be differentiated exactly as time, in the closing electric contact arc or opening electric arc, this phenomenon is totally random until the contact is welded due to the high return current. The disturbances introduced into the track circuit signal channel are conductive disturbances and directly affect the low power signal, used by track circuits for detection or transmission of information to the on-board train equipment. The electric arc di-poles model for the arch appeared in the rail track is the one shown in Fig. 11, where the following notations are used: Ue and Ur the voltage of the track circuit at transmission and reception, Ic current of the track circuit, I_3 the current absorbed by the electric motors of the metro train.

4. Modeling and simulation of perturbations in the metro electric rail transport

The subway network can be seen as an electrical network to which a number of trains are connected. Trains run on fixed speed-trajectory and absorb power from a distance power supplies. The electrical impedance resulting from the connection of the trains to the electrical substations varies due to system dynamics. A multi-train model should define the spatial relationship between different trains according to the safety conditions imposed by the traffic systems used. The spatial distribution of the subway network can be divided into individual spaces. For each space, we can use a sub-model of disturbance, which must contain traction modules (converters, motors), track circuits, power converters, substations, and signalling equipment installed in the path. [16] [12]. The electromagnetic emission traction modelling allows the effects of these disturbances to be calculated on the different signal receivers such as track circuits and signalling equipment used to train on-board information as well as on different communication systems. The train's movement cycle (acceleration, braking, steady and running) is considered as input for the model through the train equation with motion and trajectory characteristics. The model output is the electromagnetic noise of the train power converters. Interference at the on-board signalling receiver can be deduced through the cab-signal handover function. The traction system is modelled by a multi-input equivalent circuit that contains active and passive elements, power supplies and other time-dependent elements. Another problem that must be contained in the line model is the coupling of the transmission channel between the rail tracks and the ground. This is solved by using a line representation through a network of parameters based on frequency-dependent elements, rail currents, material constants, and line geometry that are used in the matrix of impedances and transfer admissions for the multifilament line. By decomposing these matrices we obtain equations of voltages and currents according to the propagation velocity and the attenuation constant at each frequency. For the subway, was used the circuit diagram for the power conductor shown in Fig. 12. This modelling includes one railcar, a dual two-phase chopper, which produces interference in the alternating current and introduced the ripple into the power supply rail connected to the substation. The noise, which can occur at the reception of track circuits and cab-signal receivers that are coupled to the traction rail, induces an interference voltage. The entire system is connected to the ground through ballast conductance and line capacity. According to Fig. 12, separate sub-modules are combined for subsections of the feed circuit. The sub-model of the line shown in Fig. 12 provides the condition that the own mutual impedance and admittance correctly reflect the behaviour of the electrical circuit.

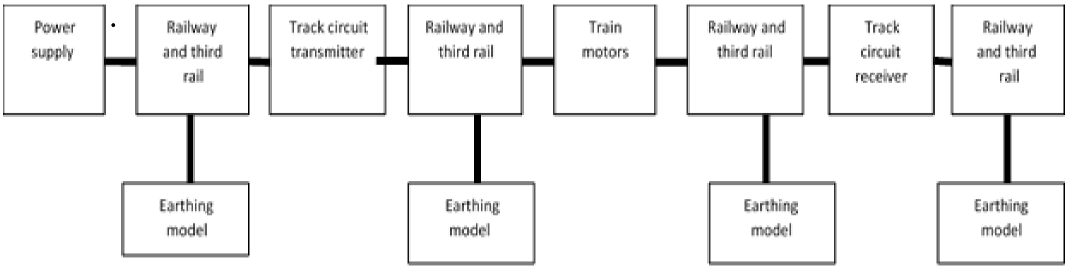

Fig.12. Circuit for perturbation modelling

Thus, variations in the environment change the characteristics of the ballast, affecting the admittance values between the rails and admittance between the rail and the ground. The sub model includes the noise source corresponding to the ripple voltage of the electrical substation and the track circuit receiver impedance. When the power substation is in front of the train the return current is calculated at the train head (the power is collected in front of the first axle) to determine the interference at the cab-signal receiver. The interfering signals in the time domain are in phase with the currents through the motor armature and the current through the rail. The model presented is implemented in the "MULTISIM" utility to process the signals and disturbances that occurred. [16] Results in the frequency domain can be obtained by evaluating Fourier coefficients as a post-processing activity of "MULTISIM" activity. Perturbations are significant if, for example, at the departure train passes directly over the track circuit. The current of the chopper is the charge current of the capacitive filter that is dependent on the instantaneous switching of all four choppers of a motor wagon. Ripple comes from the combination of the effect of the twelve pulses of the substation rectifier, the chopper line filter, and the two-phase chopper operation [18]. Modelling results differ from reality due to introduced simplifications such as engine magnetic field characteristics, uniform acceleration during traction, steady train feed voltage, steady path topography, acceleration without wheel slippage [19]. Using the "MULTISIM" simulator can help determine the interference in track systems at audio frequency, produced by combining conduction effects, magnetic induction and electrical induction. Using this model, the influence of variables such as train position, power supply, service cycle, interferences in track circuits, or any other noise-sensitive on-board receiver can be determined. Variation effects of various parameters, such as path impedance, which strongly influence interference, can be evaluated. The model can be used to evaluate the interference characteristics of the train motor that affect track circuits and cab-signal transmission. For cases where we have the third rail interrupted, in the area of the crossings, the train collectors break electrical contacts with the feed rail in this area. During the start of an electric train that passes over a switch zone, the electric arc appears with high energy and disturbs the communication and the electronic equipment in that area. [19] For a subway train from the Bucharest the rolling stock consists of 4 motor wagons, each wagon with four electric motors, a motor with the power of 147 KW, the approximate power of the electric arc produced is calculated in the following section:

$$I_{arc} = 178 * 2 = 356 \ A \quad (18)$$

According to the relationship 15, considering the distance between the collector and the third rail one millimetre

$$R_{arc} = (20 + 0.534*1)/\ 356*0.88 = 21.534/313.28 = 0.069 \text{ ohms} \quad (19)$$

$$P_{arc} = I^2_{arc} * R_{arc} = 8744 \ VA \quad (20)$$

This result is obtained if only one collector breaks the electrical contact and this collector supplies only two electric motors. For the case where the electric arc occurs on the return circuit we have the approximate arc power for the same 1-millimeter arc distance:

$$I_{arc} = 178*16/2 = 1424 \ A \quad (21)$$

$$R_{arc} = (20+0.534*1)/\ 1424*0.88 = 0.017 \ ohms \quad (22)$$

$$P_{arc} = I^2_{arc} * R_{arc} = 34472.192 \ VA \quad (23)$$

From the results we can see that the electric arc in the path of the return current is much higher than the electric arc formed on the third rail. This energy of the return arc directly affects the track circuit signal that uses the same transmission rail.

5. Conclusions

Electromagnetic disturbances are ubiquitous in rail transport systems. Electromagnetic disturbances are generated by electrically driven motors of locomotives or wagons, electric power installations for rolling stock, on board equipment (converters, choppers, telecommunication, etc.), electrical installations for the railway system and electrical installations in the vicinity of the railway. These disturbances may affect the operation of traffic safety systems such as track circuits and CAB signal transmission [20]. Electrical disturbances that occur in a complex system such as metro transport have been studied. Because the field is very wide, work has been studied in the field of electrical equipment, electric traction, mutual impedances, electric arc protection, modelling and features. The modelling and simulation made it possible to assess the electromagnetic immunity of the equipment to disturbance and the compatibility of the electrical installations. The software "Multisim" was used to simulate the system behaviour in several particular cases, using the quad-gates models for communication channel and for specific electrical railway system perturbations. The simulation was done in two steps: Static model (without perturbations introduced by train and third rail) was used to find the weak points in the track circuits. Were modelled the geographic configurations for more than 100 track circuits and the obtained results were compared with the track circuits measurements. The modelled values were closer to the measured values for the low frequency circuits, for frequency above to 5 KHz could be observed a deviation between the modelled and real values. This model was used to localise the track circuit problems due to ballast or electrical connections. Dynamic model (including the third rail, static train and electric arc) was used to improve the track circuit and power return current. Were funded some configuration which led to the disturbance of the CAB signal. The model was used to change some track circuits borders with the scope to minimize the electric arc perturbation.

The simulation using the audio frequency shown the adaptability of the model to provide information close to the real situation in the unwieldy conditions. The simulation was used to identify the sensitive areas to disturbances, the results were confirmed by the measurements done on field. Using this simulation, the following conclusions could be draw. The track circuits are mainly disturbed by the electric current traction current because it uses the same path through the direct electrical coupling between the track circuit signal and the traction return current. The track circuits are severely disturbed when the train starts and passes over the CAB signal of the track circuit, these disturbances are taken into account when designing the CAB signal system embarked on the rolling stock. Pick-up antennas are mounted in front of the first axle on a wagon that is not a motor. The CAB signal is checked, and the messages contained are compared to each other so that the train can take a decision to execute the received order. With all these measures in the event of electrical discontinuities in the return current circuit, these electrical discontinuities produce strong disturbances. The measurements for two types of electric subway trains, namely Bombardier and IVA manufactured in Arad, were done for the appreciation of these disturbances in the operation of the metro in Bucharest. From the measurements made, it has been observed that Bombardier trains introduce more disturbances than IVA trains, due to the use of choppers for powering electric motors on motor wagons. Strong disturbances also occur if the rolling stock motors are not maintained in optimal operating parameters. These disturbances, which occur in certain train positions relative to the electrical substation and the signal CAB signal transmitter, result in the occurrence of very large spikes of current. Current spikes disturb the signal of the track circuits and the train loses the telegram issued for a longer time period than the one in which it can move safely and then for safety reasons the emergency brake is applied to the rolling stock. This situation is rare but results in a sudden braking of the train with major discomfort to the passengers of that train and major delays in passenger trains. These delays are produced due to sudden braking at a high train speed and more often during its start, after this braking the train systems undergo a check that requires a long time to restart. This high value and disturbance of short duration pulses produce amortized impulsions in the track and hence the signal transmission channel CAB signal, the signal being practically covered by this disturbance. The model can be used for improving the track circuits maintenance being a usefully instrument for detect the problematic areas and

R E F E R E N C E S

[1]. *H.W. Dommel*, "EMTP Theory Book", Univerity of British Columbia 1987.
[2]. *Bergeron*, "The Bergeron Method, A Graphic Method for Determining Line Reflections in Transient Phenomena, Texas Instruments", 1996
[3]. *W. Nagel*, EECS Department University of California, Berkeley Technical Report No. UCB/ERL M520 1975
[4]. *W. Nagel*, EECS Department University of California, Berkeley Technical Report No. UCB/ERL M382 April 1973
[5]. *Dumitrescu*, "Metode noi de analiză şi proiectare a circuitelor de cale", PhD thesys "Politehnica" Bucharest
[6]. *E.M. Purcell*, "Electricitate si magnetism", Editura Didactica si Pedagogica București 1982
[7]. *M. Pearsica*, "Electrotehnica,", Editura Academiei Fortelor Aeriene "Henri Coanda" Brasov 2004
[8]. *C.T. Tinsley*, "Modeling of multi-pulse transformer rectifier units in power distribution systems", Blacksburg,Virginia 2003
[9]. *C. Fernando*, „Mutual impedance in parallel lines – protective Relaying and fault location Considerations", Engineering Laboratories revised edition, Mai 2015
[10]. *K. Lippert, M. Donald, W. Clive*,"Understanding arc flash hazards" IEEE Conference in Victoria, 2004
[11]. *H. Andrei, C. Cepisca, S. Grigorescu,* "Power quality and electrical arc furnaces", InTech Open Access Publisher, 2011
[12]. *A. Sawicki*, „Approximation of arc voltage current characteristics in electrotehnological devices" Buletyn Instytutu Spawalnictwa 2003
[13]. *W. B. Nottingham*, "A new equation for the static characteristic of the normal electric arc", Trans. Amer. Inst. Elect. Eng., vol. 42, pp. 302, 1923.
[14]. www.ecmag.com/section/codes-standards/voltage-drop-sizing-equipment-grounding-conductors, accessed July 2016
[15]. *L.Yuan, L. Sun, H. Wu*, „Simulation of Fault Arc Using Conventional Arc Models" Energy and Power Engineering, July 2013
[16]. *O. Popovici, D.Popovici,* "Tracțiune electrică", Edited by Mediamira Cluj Napoca 2009
[17]. *Z. Wang, J. Guo, Y. Zhang, R. Luo* "Fault diagnosis for railway track circuit based on wavelet packet power spectrum and ELM" IEE Conference 2016
[18]. *R.J. Hill, S. L. YU, J. Dunn,* „Rail transit chopper traction interference Modelling Using SPICE circuit" IEEE 1989
[19]. *D.R. Doan*, „Arc flash calculations for exposures to DC systems", IEEE 2010
[20]. Bombardier Transportation "Error Code List"