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DETERMINATION OF BASIC DATA FOR THE SIX-POLAR MODEL OF ELECTRICAL TONAL RAIL CIRCUIT

Introduction

In modern operating railway automation devices to protect equipment and staff used ground. Due to this safety performance and reducing the negative impact are increased within violation electrical insulation resistance conductive elements. In the electric rail circuit grounding influence is the most important because each rail line in rail track is used as grounding elements and has little transition resistance to it [1]. Individual elements of the rail circles, such as oscillators, filters, receivers, etc. [2] have insulation resistance values that are limited to values given in technical documentation tools and operating instructions [3]. In the technology operating methods of the periodic determination of insulation resistance designed to control individual components of complex systems. Because important is the determination of the mutual influence of insulation resistance elements on the performance of the whole system. This makes it possible to determine the minimum insulation resistance values at which the possible exploitation systems and insulation resistance values during formation of the diagnosing system that includes prognosis states before malfunction [4].

Purpose

The purpose is to determine baseline data for calculation of electrical rail circuit (ERC) considering insulation resistance of all its elements, that are the base for further analysis of boundary values of insulation in the current exploiting system. During the determining of baseline data is necessary to perform the following:

- determine the type and structure of the research object;
- make a structure scheme considering "ground";
- form or upgrade principal scheme of an individual element considering the replacement of insulation resistance (IR);
- determine the future direction of planning calculation of required dependency of electrical signals in ERC from IR; type and composition of baseline data for further calculations considering distracted elements parameters; analysis of changes in electrical signals by changing the IR in electric rail circuit.

Forming the structure of research object

With further analysis of the type and structure of the research object as electrical rail circuit will guide by electrical tonal frequencies rail circuit (TRC) [5]. This choice is caused by that the overall structure of phase recognized, coded and other electrical rail circuits is the same – power source and relay end of rail line (RL) [6]. In addition, as the electric tonal frequencies rail circuit selected electrical rail circle with centralized placement of the equipment with available cable line (CL) [5, 6]. In the mentioned example structured scheme is shown in fig. 1.

At fig. 1 adjusted such shorts and definitions:

- Ug – power source voltage;
- UTF – universal track filter (original Russian abbreviation – ФПУ) or similar;
- Cals, Rcab – capacitance of automotive locomotive signalization (ALS)

and cable line resistor (listed separately for power source and relay end of electrical rail circuit);

- CL PSE and CL RE – cable lines of power source and relay end of ERC respectively;
- CB PSE and CB RE – cable boxes of power source and relay end of ERC respectively;
- RL – rail line;
- Ztr – resistor of track receiver of TRC.

First four 4-polar modules included inside power source end equipment, last three is a part of relay end TRC [5-7]. In account with “Ground” as electrical scheme conductor (fig. 1), two poles added with next conditions:

1) ground resistance is connected for all similar scheme element (power source end, rail line and relay scheme end) [8];
2) ground resistance (specific resistance) as current conductor is accounted in case of low resistance at current scheme node [9].

So, structure scheme of ERC with accounted ground is following:

At fig. 2 used: PLE – power line end equipment; RLE – rail line end equipment; TR – tonal rail circuit track receiver of “TR” type (originally Russian abbreviation is ПП) or similar; 1 and 2 – current lead conductor of ERC; 3 – ground connector of electrical rail circuit as electrical current conductor.

For next development of primary data of 6-polar tonal rail circuit is needed to consider principal scheme of separate structure scheme elements (fig. 1 and 2).

Development of principal scheme of 6-polar element for rail circuit model

Classical calculation at electrical rail circuit is operated within multi-polar model [10]. That’s why simplest calculation to form base parameters of principal scheme from structure scheme is realized at formula (1).

In expression (1) used next designations:

- $U1$ and $U3$ – voltage between conductors 1 and 3 respectively at input and output pins;
- $I1$ and $I3$ – input and output current at line 1;
- $I2$ and $I4$ – input and output current at line 2;
- $U2$ and $U4$ – voltage between conductors 2 and 4 respectively at input and output pins;
- $a11 \ldots a44$ – constant parameters, that fully characterize element properties of structure scheme in limits of the given task.

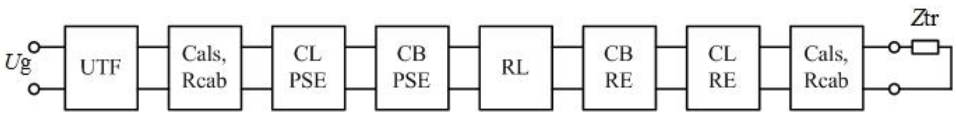

Fig. 1. Structured scheme of electrical rail circuit

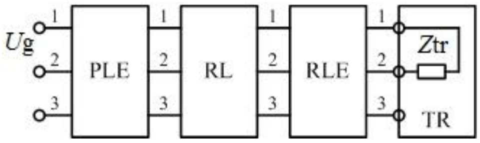

Fig. 2. Electrical rail circuit scheme with ground resistance

$$\begin{cases} U1 = a11 \cdot U3 + a12 \cdot I3 + a13 \cdot I4 + a14 \cdot U4, \\ I1 = a21 \cdot U3 + a22 \cdot I3 + a23 \cdot I4 + a24 \cdot U4, \\ I2 = a31 \cdot U3 + a32 \cdot I3 + a33 \cdot I4 + a34 \cdot U4, \\ U2 = a41 \cdot U3 + a42 \cdot I3 + a43 \cdot I4 + a44 \cdot U4. \end{cases} \quad (1)$$

Chosen expression form, that given at expression (1), afford the advantages by using of simple math operations within next calculations [10, 11]. No doubt, for tonal rail circuit the track filter is most complicated object with concentrated parameters that is located at power source end of ERC. Because next calculation of concentrated parameters, node is showed in example of track filter [5, 7].

Filter parameters calculations (node UTF at fig. 1) is considered improving of principal scheme of ERC [12] that finally looks like a fig. 3.

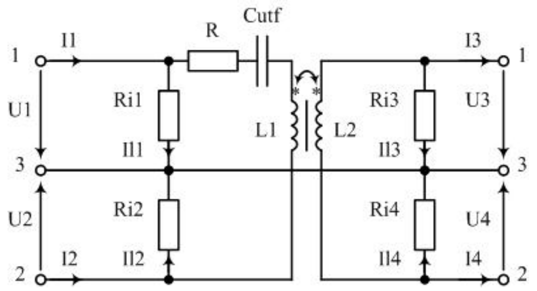

Fig. 3. Principal scheme of universal track filter

At fig. 3 classical view shows input pins at left side and output pins in the right side.

Filter elements: R – limiting resistance, Cutf – resonance capacity; L1 and L2 – throttle resistance of filter transformer (resistance less than reactors at filter transformer because they do not account in scheme and calculations); Ri1 – Ri4 – insulation resistors of lead conductors 1 and 2 comparatively ground line (line 3); Il1 – Il4 – leak current throw insulation resistance.

To form math model of 6-polar parameters model likely showed at expression (1) or similar, needs at least four equations [11, 13]. So that detailed calculations step next at this work.

For every leak current its value finds from general formula (2):

$$Iyi = \frac{Ui}{Rui}. \qquad (2)$$

To each voltages is actually Kirchhoff's low using that gives such equations at respectively circuit as set of formulas (3–6).

Expressions (3–6) includes value w – basic frequency of signal current; $M12$ and $M21$ – mutual inductance of 1 and 2 transformer winding. Following transformations is leaded with simplifications that $Ri1 = Ri2 = Ri3 = Ri4 = Ri$ and adding of (3)–(4) expressions gets (7) and (8).

Expression (8) is the first formula that connects current and voltage according fig. 2. Using subtraction (3)–(4) formula gets next transformations to formula (9) and (10).

Second equation from set was find as formula (10), where Ntr – transformation coefficient of internal transformer with resonance inductor inside first circuit. Similarly, find the third formula from the set of equation like a subtraction of formula (5) and (6), finally showed at formula (11).

Last equation got according with minimum loss at primary and secondary circuit inside transformer with assumption about primary and secondary power equality like expression (11).

Finally got dependencies for forming connections between input and output electrical signal inside principal scheme. They combine the set of equations within formula (8), (10), (11) and (14). Analyzing got equations let the possibility of making such preliminary conclusions about coefficients $a11 \ldots a44$ definition:

- formulas (11) and (14) combined from dependencies that includes $U1$ and $I1$ values, because they accepted as base for definitions at set;
- predicted final result will give much inform dependencies between input and output parameters of voltages and currents an account their standing in expressions (10), (11) and (14);
- next development is possible and do not create considerable changes between input and output voltages and currents, and make possible further improvement of math UTR model for 6-polars.

$$U1=\left(I1-\frac{U1}{Ru1}\right)\cdot\left[R+j\cdot w\cdot L1+\frac{1}{j\cdot w\cdot C\text{фпу}}\right]-\left(I3+\frac{U3}{Ru3}\right)\cdot j\cdot w\cdot M21+U2, \tag{3}$$

$$U2=\left(I2-\frac{U2}{Ru2}\right)\cdot\left[R+j\cdot w\cdot L1+\frac{1}{j\cdot w\cdot C\text{фпу}}\right]+\left(I3+\frac{U3}{Ru3}\right)\cdot j\cdot w\cdot M21+U1, \tag{4}$$

$$U3=-\left(I3+\frac{U3}{Ru3}\right)\cdot j\cdot w\cdot L2-\left(I1-\frac{U1}{Ru1}\right)\cdot j\cdot w\cdot M12+U4, \tag{5}$$

$$U4=-\left(I4+\frac{U4}{Ru4}\right)\cdot j\cdot w\cdot L2+\left(I1-\frac{U1}{Ru1}\right)\cdot j\cdot w\cdot M12+U3, \tag{6}$$

$$U1+U2=\left(I1+I2-\frac{U1+U2}{Ru}\right)\cdot\left[R+j\cdot w\cdot L1+\frac{1}{j\cdot w\cdot C\text{фпу}}\right]-$$

$$-\left(I3+\frac{U3}{Ru}\right)\cdot j\cdot w\cdot M21+U2+U1, \tag{7}$$

$$I1+I2=\frac{U1+U2}{Ru}, \tag{8}$$

$$U1-U2=\left[R+j\cdot w\cdot L1+\frac{1}{j\cdot w\cdot C\text{фпу}}\right]\cdot\left(I1-I2-\frac{U1-U2}{Ru}\right)-$$

$$-2\cdot\left(I3+\frac{U3}{Ru}\right)\cdot j\cdot w\cdot M21+U2-U1, \tag{9}$$

$$U1-U2=\frac{1}{2}\cdot\left[R+j\cdot w\cdot L1+\frac{1}{j\cdot w\cdot C\text{фпу}}\right]\cdot\left(I1-I2-\frac{U1-U2}{Ru}\right)-$$

$$-\left(I3+\frac{U3}{Ru}\right)\cdot j\cdot w\cdot\frac{L1}{Nmp}, \tag{10}$$

$$U3-U4=\frac{1}{2}\cdot\left(I4-I3+\frac{U4-U3}{Ru}\right)\cdot j\cdot w\cdot L2-\left(I1-\frac{U1}{Ru1}\right)\cdot j\cdot w\cdot\frac{L1}{Nmp}, \tag{11}$$

$$(I1-Iy1)^2\cdot j\cdot w\cdot L1=(I4+Iy4)^2\cdot j\cdot w\cdot L2, \tag{12}$$

$$\left(I1-\frac{U1}{Ru}\right)^2\cdot L1=\left(I4+\frac{U4}{Ru}\right)^2\cdot L2, \tag{13}$$

$$\frac{I1\cdot Ru-U1}{I4\cdot Ru+U4}=\sqrt{\frac{L2}{L1}}. \tag{14}$$

Final values definitions is connected with partial multi polar models. Within math model salvation, filter parameters $a11\ldots a44$ finds out during four steps:

- parameters $a11$, $a12$, $a21$, $a22$ definition upon partial forming of 6-polar model (according to fig. 3) with input electrical values $U1$ and $I1$, and output – $U3$ and $I3$;
- parameters $a13$, $a14$, $a23$, $a24$ finding from partial 4-poles with input and output parameters $U1$, $I1$ and $U4$, $I4$ respectively;
- finding $a31$, $a32$, $a41$, $a42$ parameters from 4-polar model and input-output electrical voltages and currents $U2$, $I2$, $U3$, $I3$ respectively;
- transforming model at 4-polar expression of input-output $U2$, $I2$, $U4$, $I4$ for $a33$, $a34$, $a43$, $a44$ finding.

On the assumption of 6-pole math model according the formula (1) and basic scheme (fig. 3), principle filter scheme was formed at fig. 4.

Equation, that connect input and output electrical voltages and currents at algebraic and matrix view, is following at expressions (15) and (16).

$$\begin{cases} U1 = a11 \cdot U3 + a12 \cdot I3, \\ I1 = a21 \cdot U3 + a22 \cdot I3. \end{cases} \quad (15)$$

$$\begin{pmatrix} U1 \\ I1 \end{pmatrix} = \begin{pmatrix} a11 & a12 \\ a21 & a22 \end{pmatrix} \times \begin{pmatrix} U3 \\ I3 \end{pmatrix}, \quad (16)$$

$$\begin{pmatrix} a11 & a12 \\ a21 & a22 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \dfrac{1}{Ru1} & 1 \end{pmatrix} \times$$
$$\times \begin{pmatrix} 1 & R + Xc + Ru2 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} Amp & Bmp \\ Cmp & Dmp \end{pmatrix} \times$$
$$\times \begin{pmatrix} 1 & Ru4 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 \\ \dfrac{1}{Ru3} & 1 \end{pmatrix}. \quad (17)$$

Constant coefficients parameters of math model of 4-poles (according formulas 15, 16 and fig.4) find likely multiplication of 4-polars components of electrical parameters (see at formula (17), where $Amp \ldots Dmp$ – transformer coefficients that entire to filter composition and include characteristics from principal scheme (fig. 3) and math expressions (3)–(14).

The second 4-polar model for coefficients $a13$, $a14$, $a23$, $a24$ present following principal scheme (fig. 5).

Math model according fig. 5 accounts voltage and current vector from input and output data of principal scheme finds at expressions (18) and (19):

$$\begin{cases} U1 = a14 \cdot U4 + a13 \cdot I4, \\ I1 = a24 \cdot U4 + a23 \cdot I4. \end{cases} \quad (18)$$

$$\begin{pmatrix} U1 \\ I1 \end{pmatrix} = \begin{pmatrix} -a14 & -a13 \\ -a24 & -a23 \end{pmatrix} \times \begin{pmatrix} -U4 \\ -I4 \end{pmatrix}. \quad (19)$$

Constant coefficients from formula (19) define by multiplication (20).

Math model of 4-pole that connects voltages and currents $U2$, $I2$ with $U3$, $I3$, respectively principal scheme is follow (see fig. 6).

$$\begin{pmatrix} -a14 & -a13 \\ -a24 & -a23 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \dfrac{1}{Ru1} & 1 \end{pmatrix} \times$$
$$\times \begin{pmatrix} 1 & R + Xc + Ru2 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} Amp & Bmp \\ Cmp & Dmp \end{pmatrix} \times$$
$$\times \begin{pmatrix} 1 & Ru3 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 \\ \dfrac{1}{Ru4} & 1 \end{pmatrix}. \quad (20)$$

Formed math model of scheme (fig. 6) is the part of 6-polar model with coefficients $a33$, $a34$, $a43$, $a44$ at the next view:

$$\begin{cases} U2 = a41 \cdot U3 + a42 \cdot I3, \\ I2 = a31 \cdot U3 + a32 \cdot I3. \end{cases} \quad (21)$$

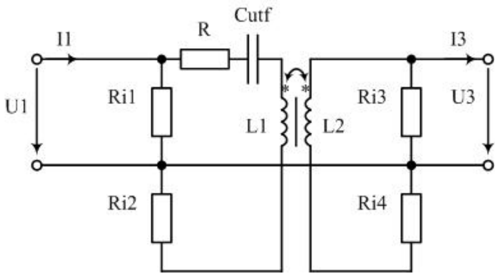

Fig. 4. Principle scheme of the first partial 4-polar model

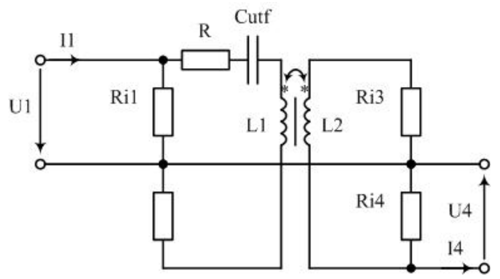

Fig. 5. Principal scheme of the second 4-polar partial model

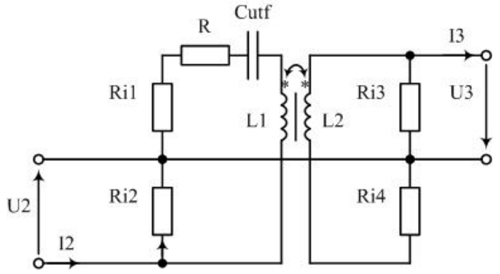

Fig. 6. Principal scheme of third partial 4-polar model

Expression (21) gives vector multiplying that includes opposite direction of voltages $U2$, $U3$ and currents $I2$, $I3$, and has next view:

$$\begin{pmatrix} U2 \\ I2 \end{pmatrix} = \begin{pmatrix} -a41 & -a42 \\ -a31 & -a32 \end{pmatrix} \times \begin{pmatrix} -U3 \\ -I3 \end{pmatrix}. \quad (22)$$

Coefficients $a33$, $a34$, $a43$, $a44$, that connects said voltages and currents, defined from following multiplying of 4-poles (formula (24).

Analogous parameters $a33$, $a34$, $a43$, $a44$ definitions includes created math model at algebraic and vector view, and includes principal scheme of four partial 4-pole (fig. 7, formulas (23).

$$\begin{cases} U2 = a44 \cdot U4 + a43 \cdot I4, \\ I2 = a34 \cdot U4 + a33 \cdot I4. \end{cases}$$

$$\begin{pmatrix} U1 \\ I1 \end{pmatrix} = \begin{pmatrix} a11 & a12 \\ a21 & a22 \end{pmatrix} \times \begin{pmatrix} U3 \\ I3 \end{pmatrix}. \quad (23)$$

In help with last multiplying determined parameters of four partial 4-pole (see fig. 7).

In result, multiplying of coefficients of partial 4-poles determined parameters $a11 \ldots a44$ that is needed for calculation of ERC 6-polar model and showed at formulas (26).

Listed below value $a11 \ldots a44$ gives possibility to find the parameters of UTF-filter at some signal current frequency. Besides within simplification filter scheme and accordance to similar principal scheme CB PSE and CB RE (see fig. 1), formulas (26) is possible to use only parameters $a11 \ldots a44$ is exist at that schemes.

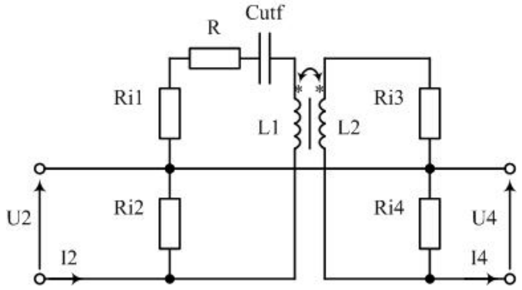

Fig. 7. Principal scheme of four partial 4-pole

During the calculation of 6-polar elements of ERC with extended parameters (cable and rail line) is needed to correct existing replacement scheme, to form math model and decide it. At final parameters $a11 \ldots a44$ determining, accounting of primary parameters is required. Finally sought-for changes at 6-polar replacement scheme gives possibility to evaluate potential dependencies of electrical parameters in electrical rail circuit on IR changes at some element, and, as an option of practical using, diagnose place of refusal.

$$\begin{pmatrix} -a41 & -a42 \\ -a31 & -a32 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \frac{1}{Ru2} & 1 \end{pmatrix} \times \begin{pmatrix} 1 & R + Xc + Ru1 \\ 0 & 1 \end{pmatrix} \times$$

$$\times \begin{pmatrix} Amp & Bmp \\ Cmp & Dmp \end{pmatrix} \times \begin{pmatrix} 1 & Ru4 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 \\ \frac{1}{Ru3} & 1 \end{pmatrix}, \quad (24)$$

$$\begin{pmatrix} a44 & a43 \\ a34 & a33 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \frac{1}{Ru2} & 1 \end{pmatrix} \times \begin{pmatrix} 1 & R + Xc + Ru1 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} Amp & Bmp \\ Cmp & Dmp \end{pmatrix} \times \begin{pmatrix} 1 & Ru3 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 \\ \frac{1}{Ru4} & 1 \end{pmatrix}, \quad (25)$$

$$a11 = Amp + (R + Xc + Ru2) \times Cmp +$$

$$+ \frac{(Amp + (R + Xc + Ru2) \times Cmp) \times Ru4 + Bmp + (R + Xc + Ru2) \times Dmp}{Ru3},$$

$$a12 = (Amp + (R + Xc + Ru2) \cdot Cmp) \cdot Ru4 + Bmp + (R + Xc + Ru2) \cdot Dmp,$$

$$a13 = -(Amp + (R + Xc + Ru2) \cdot Cmp) \cdot Ru3 - Bmp - (R + Xc + Ru2) \cdot Dmp,$$

$$a14 = -Amp - \left(R + Xc + Ru2\right)\cdot Cmp - \frac{\left(Amp + \left(R + Xc + Ru2\right)\cdot Cmp\right)\cdot Ru3 + Bmp + \left(R + Xc + Ru2\right)\cdot Dmp}{Ru4},$$

$$a21 = \frac{Amp}{Ru1} + \frac{R + Xc + Ru2 + Ru1}{Ru1}\cdot Cmp +$$
$$+\frac{\left(Amp + \left(R + Xc + Ru2 + Ru1\right)\cdot Cmp\right)\cdot Ru4 + Bmp + \left(R + Xc + Ru2 + Ru1\right)\cdot Dmp}{Ru1\cdot Ru3},$$

$$a22 = \left(Amp + \left(R + Xc + Ru2 + Ru1\right)\cdot Cmp\right)\cdot\frac{Ru4}{Ru1} + \frac{Bmp}{Ru1} + \left(R + Xc + Ru2 + Ru1\right)\cdot\frac{Dmp}{Ru1},$$

$$a23 = -\left(Amp + \left(R + Xc + Ru2 + Ru1\right)\cdot Cmp\right)\cdot\frac{Ru3}{Ru1} - \frac{Bmp}{Ru1} - \left(R + Xc + Ru2 + Ru1\right)\cdot\frac{Dmp}{Ru1},$$

$$a24 = -\frac{Amp}{Ru1} - \frac{R + Xc + Ru2 + Ru1}{Ru1}\cdot Cmp -$$
$$-\frac{\left(Amp + \left(R + Xc + Ru2 + Ru1\right)\cdot Cmp\right)\cdot Ru3 + Bmp + \left(R + Xc + Ru2 + Ru1\right)\cdot Dmp}{Ru1\cdot Ru4},$$

$$a31 = -\frac{Amp}{Ru2} - \frac{R + Xc + Ru1 + Ru2}{Ru2}\cdot Cmp -$$
$$-\frac{\left(Amp + \left(R + Xc + Ru1 + Ru2\right)\cdot Cmp\right)\cdot Ru4 + Bmp + \left(R + Xc + Ru1 + Ru2\right)\cdot Dmp}{Ru2\cdot Ru3},$$

$$a32 = -\left(Amp + \left(R + Xc + Ru1 + Ru2\right)\cdot Cmp\right)\cdot\frac{Ru4}{Ru2} - \frac{Bmp}{Ru2} - \left(R + Xc + Ru1 + Ru2\right)\cdot\frac{Dmp}{Ru2},$$

$$a33 = \left(Amp + \left(R + Xc + Ru1 + Ru2\right)\cdot Cmp\right)\cdot\frac{Ru3}{Ru2} + \frac{Bmp}{Ru2} + \left(R + Xc + Ru1 + Ru2\right)\cdot\frac{Dmp}{Ru2},$$

$$a34 = \frac{Amp}{Ru2} + \frac{R + Xc + Ru1 + Ru2}{Ru2}\cdot Cmp +$$
$$+\frac{\left(Amp + \left(R + Xc + Ru1 + Ru2\right)\cdot Cmp\right)\cdot Ru3 + Bmp + \left(R + Xc + Ru1 + Ru2\right)\cdot Dmp}{Ru2\cdot Ru4},$$

$$a41 = -Amp - \left(R + Xc + Ru1\right)\cdot Cmp - \frac{\left(Amp + \left(R + Xc + Ru1\right)\cdot Cmp\right)\cdot Ru4 + Bmp + \left(R + Xc + Ru1\right)\cdot Dmp}{Ru3},$$

$$a42 = -\left(Amp + \left(R + Xc + Ru1\right)\cdot Cmp\right)\cdot Ru4 - Bmp - \left(R + Xc + Ru1\right)\cdot Dmp,$$

$$a43 = \left(Amp + \left(R + Xc + Ru1\right)\cdot Cmp\right)\cdot Ru3 + Bmp + \left(R + Xc + Ru1\right)\cdot Dmp,$$

$$a44 = Amp + \left(R + Xc + Ru1\right)\cdot Cmp +$$
$$+\frac{\left(Amp + \left(R + Xc + Ru1\right)\cdot Cmp\right)\cdot Ru3 + Bmp + \left(R + Xc + Ru1\right)\cdot Dmp}{Ru4}. \qquad (26)$$

Conclusions

In this work analyzed possibilities of dependencies of 6-polar model of ERC, got the evaluation method of 6-polar model of blocks with concentrated parameters of input elements. But for taking the final dependencies is needed to execute common calculates of electrical parameters dependencies at electrical rail circuit on insulation resistance at scheme like the most influence parameters at workability of ERC in all. On the assumption of that, lately is needed to find the whole parameters of 6-polar model of electrical rail circuit elements with extended input electrical elements at replacement scheme.

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Ключові слова: рейкове коло, шостиполюсна модель, опір ізоляції, колійний фільтр.

Ключевые слова: рельсовая цепь, шестиполюсная модель, сопротивление изоляции, путевой фильтр.

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