Simulation of a Return Current System for AC Power Traction Network

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Abstract. The paper deals the problem of the reverse traction current's asymmetry in the rail circuit under heavy haul traffic conditions for AC railways. The consequences and the possible causes of the negative influence of asymmetry of the return current system for AC power traction network are considered. For analyse the degree of influence of various factors on the reverse traction current's asymmetry the return current system model is created in Multisim 12.0 software. The simulation model consists of the reverse traction current block-section. The model allows researching the influence of various factors including environmental conditions such as temperature and humidity, power and type of throttle-transformers, rail track ballast resistance on the conditions of the return current system breakdown. Particular attention is paid to the study of the breakdown voltage critical values on the spark gap in the return current circuit on the example of a railway section located in the Far East of Russia. Simulation results show that in addition to improving electrical characteristics, a positive effect of reducing asymmetry of the return current system for AC power traction network can be achieved by cleaning of the track ballast layer.

1. Introduction
It is well known, that electric traction for almost 140 years of its history has proven its reliability and high efficiency for rail transportation throughout the world. The average volume of freight carried by electric trains is threefold that carried by diesel trains [1, 2]. A major advantage of electric traction is saving of oil fuel, whose world reserves are limited. Electrified rail networks are 23% faster and have less impact on the environment then non-electrified railways. The cost of electric traction is 54% cheaper than diesel traction [1–3]. Because of these benefits, about 25% of world railways are electrified [2]. Alternating current (AC) is used in 55.6% of electrified systems and direct current (DC) - in 41.8%. The AC traction power supply system 25 kV, 50 Hz is used in Russia, China, France, Great Britain, Hungary, Germany, Denmark, Italy, Portugal, Finland, etc. [1–3].

In traction power supply system an important role is played by the return traction current system, which restores the current, consumed by the electric locomotive from the contact network back to the traction substation. The return traction current system is consists of the track circuit (which consist of track rail, intermateable connectors or sockets, isolated tongs, track chokes or impedance bonds and other equipment) and the return wire [2, 4, 5]. The track circuit is both an element of the power supply system, and also the element of the signals and interlocking system. Therefore, the asymmetry of the track circuit (or, in other words, the asymmetry of the return traction current system), caused by the inequality of traction currents flowing in the tracks, leads to problems in the operation of both systems.
up to the failure of the elements of the track circuit, automatic locomotive signaling and train disruptions [4-7].

The return traction current operation for DC power traction network is well described in the works of many authors [5-9], especially the problem of stray currents. However, such specific questions for AC power traction network as influence of spark gaps, power and type of throttle-transformers, etc. are still not considered enough. Moreover, the failures statistics data of technical means located in return traction current circuits [10-12] indicate that the problem of asymmetry is very urgent now, has some significant negative consequences for signals and interlocking system and requires the search for effective measures to elimination. Therefore, the purpose of this work is to reduce the asymmetry of the return traction current. To achieve this goal, it is necessary to evaluate main factors that affect the magnitude of the return traction current’s asymmetry. It can be researching most effectively and conveniently by a simulation of return current system for AC power traction network through modern means of computer modeling software. Nevertheless, the principles of creating simulation model for DC power traction network for stray current and earth modeling [13-17] can be adapted for AC power traction network and can help more efficiently achieve the goal.

2. System description

Traction current is supplied to locomotive through the catenaries from traction substation and returns to traction substation through return current network, forming a complete energy cycle system [4-7] as it shown at figure 1 and figure 2.

As it shown at figure 1, the return traction current \( I_{rc} \) comes from the catenary to the locomotive and leaves it through the wheel pair is divided into two parts: \( I_1 \) and \( I_2 \). These reverse traction currents flow through the first and second rails respectively. Further, in the each rail, current is divided into two components \( I_a \) and \( I_b \), that flows to the right and left from the point of its inflow to traction substations. Thus, the following sums of currents are formed: \( I_1 = I_{1a} + I_{1b} \); \( I_2 = I_{2a} + I_{2b} \). At the first stage, in...
order to simplify the consideration, leakage currents are not accepted. The return traction current will be written as the sum of the above currents as 

\[ I_{tr} = I_1 + I_2 + I_{r_1} + I_{r_2} + I_{2a} + I_{2b} \]

Thus, the return traction circuit for AC power traction network includes electrically in series and/or in parallel connected basic elements, as it shown at figure 3, and they are performed in the simulation model in the form of separate blocks.

3. Simulation model description

The simulation model is implemented in Multisim 12.0 software. To create a simulation model based on the real data of the research object, we set the types and models of main using equipment, as it shown at table 1.

| Equipment          | Type / model            |
|--------------------|-------------------------|
| Catenary           | ПБСМ-95+МФ-100          |
| Rail               | Р65                     |
| Block-section rail length | 1.5 km              |
| Throttle-transformer | ДТ-1-150               |
| Isolation transformer | ПРТ-А-1              |
| Spark gap          | ИП-3                   |

For each block, shown at figure 3, it was necessary to determine the resistance values of elements from the reference data and then set them in model. As an example, for track rail block it is well known, that the rail resistance and reactance depend on the current magnitude, flowing through it. According to [21], for flowing current of 625 A and frequency 50 Hz the resistance of P65 rail type is equal \( R_r = 0.11 \text{ Ohm} \text{ / km} \). Thus, for 1.5 km block-section rail length model we get \( R_r = 0.11 \times 1.5 = 0.165 \text{ Ohm} \text{ / km} \). Due to the limited volume of this article, we are forced to hide detailed calculations of each of the model elements. The resulting simulation model of the return traction circuit is shown at figure 4.

Figure 4. Simulation model of the return traction circuit.

Rail circuit is the distributed parameter circuit and it characterized by a multitude of states for normal, emergency and post-emergency modes [4, 5, 8, 13, 18-20]. Thus, in order to take into account the resistances along the entire length of the rail circuits is duplicated the track rail block and the catenary block four times between the track receiver block and signal current source block. At figure 4 it is shown twice, and the rest of it is replaced by the rupture of mentioned circuits.
In model are used the following symbols shown at figure 4: 

- $R_{c}$ - catenary reactance;
- $R_{loc}$ - locomotive reactance;
- $L_{r1}$, $L_{r2}$ - inductive reactance of first (1) and second (2) rails, respectively;
- $R_{sg}$ - spark gap reactance;
- $R_{air}$ - air reactance;
- $R_{tow}$ - tower reactance;
- $R_{bal}$ - track ballast layer reactance;
- $R_{r12}$ - reactance between first and second rails, etc.

Then, the current distribution in each mode of the return current system was analyzed and each mode was modeled in created model. So, for example, the transition to the emergency mode of the system is accompanied by a breakdown of the spark gap. In this case, the current flows from the traction substation through the catenary, through the locomotive and the track rails, and returns to the substation via the return wire. However, some of the current from the grounded rail thread flows through the pierced spark gap into the ground of the tower. Such disruption of the rail circuit operation occurs when the leakage current is 15 A or more, and the asymmetry in the rail lines exceeds 4% of the total traction current [4, 22]. Obtaining exactly these values of the indirect quantities (leakage current is 15 A and the rail lines asymmetry coefficient is 4%) in the simulation of the emergency mode allows to make an inference about the adequacy of the constructed model.

4. Results

The main parameter of the spark gap operability is the breakdown potential (in volts) $\phi_{sg}$, which can be calculated as the traction current $I_t$ (or return traction current $I_{rc}$) multiplied by the transient resistance $R_t$ by equation:

$$\phi_{sg} = I_t \cdot R_t.$$

Next, the measuring instruments were placed in the system control points, as it shown at figure 5, and began to monitor the spark gap breakdown conditions.

Figure 5. Measuring in simulation model of the return traction circuit.

Then, with the aid of the model, we researched the effects of the resistances of every blocks that are included in the transient resistance $R_t$, on the spark gap breakdown conditions and came to the conclusion that the breakdown condition to a greater degree determines the ballast layer resistance $R_{bal}$. 
Transient resistance $R_{\text{bal}}$ mainly depends on the weight of the train, the types of throttle transformers, as well as on the state of the ballast layer of the earth [4, 7-9, 13, 18, 22].

Due to soil freezing, the surface resistance and resistance of the lower ballast layer are significantly increased. Sleepers and ballast largely change their electrical conductivity, depending on the presence of moisture in them, changes in ambient temperature and other factors. Therefore, the ballast resistance is low or high and very unstable (varies from 0.25 to 100 Ohm·km) [2, 4, 13, 19, 21, 22].

Further, the traction current $I$ values at the considered gradient for different train weights and two critical (maximum and minimum) values of the ballast layer resistance $R_{\text{bal}1} = 60 \text{ Ohm} \cdot \text{km}$ and $R_{\text{bal}2} = 1 \text{ Ohm} \cdot \text{km}$ were taken. The calculated spark gap breakdown voltages are showed at table 2.

| Train weight, tons | Traction current, ampere | Spark gap breakdown voltage, volt, at $R_{\text{bal}1} = 60 \text{ Ohm} \cdot \text{km}$ | Spark gap breakdown voltage, volt, at $R_{\text{bal}2} = 1 \text{ Ohm} \cdot \text{km}$ |
|-------------------|--------------------------|---------------------------------|---------------------------------|
| 12000             | 1020                     | 823                             | 473                             |
| 10000             | 980                      | 691                             | 435                             |
| 9000              | 970                      | 685                             | 428                             |
| 6000              | 850                      | 590                             | 372                             |
| 3000              | 520                      | 376                             | 233                             |

It is statistically proved [10] that, with the same values of train weights and the current consumed by them, faults and breakdowns of spark gaps occur at the research object mainly during the cold season. That again proves that the main influencing factor for the spark gap voltage is the resistance $R_{\text{bal}}$. Also, in accordance with the passport characteristics of spark gaps at the research object, the lower limit of their breakdown is the value of 800 volts [2, 22]. The calculation results show that there are no conditions for spark gap breakdown with the train weight up to 12000 tons in the warm season at $R_{\text{bal}2} = 1 \text{ Ohm} \cdot \text{km}$. Opposite, the spark gap breakdown conditions are created in the cold season, when $R_{\text{bal}1} = 60 \text{ Ohm} \cdot \text{km}$ at the train weight 11000÷12000 tons and over.

5. Discussion

The model allows to take into account the features of heavy haul traffic, to calculate and predict the status before return current circuit failure of the preceding the spark gap breakdown for any railway area. The model parameters can be adapted for any section of the railway where there is a problem of the spark gaps mass failure. Consequently, the pre-failure area of spark gaps, located at research object at the Far Eastern Railway of Russia can be calculated and determined, as shown in figure 6.

As we can see from figure 6, in order to avoid spark gaps breakdown during heavy haul traffic at research object where the locomotive traction current reaches 1000 A and higher, the ballast layer resistance should not exceed 60 Ohm·km. Also, in areas with traction currents from 900 to 1000 A it should not exceed 70 Ohm·km.
Thus, for each railway zone it is possible to determine the ballast layer resistance’s optimal value depending on the range of locomotive currents. In case for the considered zone fall in the spark gap failure area abandoned, it is necessary to reduce the ballast layer resistance by cleaning the ballast layer, change the sleepers, etc. Thus, it is necessary to control the value of the ballast layer resistance and not to exceed the values recommended by the calculation results in those zones, where there are increased locomotive currents.

6. Conclusion
1. Created simulation model allows analyze influence of many various factors for AC power traction network such as temperature and humidity, power and type of throttle-transformers, rail track ballast resistance, type of spark gap on the asymmetry of the return current system.
2. The model allows to take into account the features of heavy haul traffic, to calculate and predict the status before return current circuit failure of the preceding the breakdown conditions of the spark gap.
3. Positive effect on reducing asymmetry of the return current system for AC power traction network can be achieved by cleaning of the track ballast layer and increasing the upper limit of the spark gaps breakdown voltage.

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