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PREVENTING THE FORMATION OF ICE ON THE CATENARY LINES

ZAPOBIEGANIE POWSTAWANIU OBLODZENIA NA PRZEWODACH SIECI TRAKCYJNEJ

A b s t r a c t

Atmospheric icing on traction lines is very important problem because it causes difficulties of using electric vehicles by people and can result to breaking of traction lines. Heating the wire can preventing atmospheric icing.

Keywords: traction lines, icing, wire

S t r e s z c z e n i e

Powstawanie oblodzenia na przewodach sieci trakcyjnej jest bardzo ważnym problemem, ponieważ wprowadza utrudnienia w korzystaniu z pojazdów elektrycznych przez ludzi i może prowadzić do zerwania przewodów trakcyjnych. Podgrzewanie przewodu może zapobiegać powstawaniu oblodzenia.

Słowa kluczowe: linie trakcyjne, oblodzenie, przewód

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1. Introduction

In most countries, combustion-powered traction vehicles have been replaced with electric vehicles. In order to deliver power to their engines, a traction lines is needed. The line is located in an environment whose parameters change depending on the season. The winter is the most difficult season for traction lines, as with the environmental temperature at around –5°C and precipitation in the form of wet snow or sleet, a layer of icing forms on traction lines. Depending on the duration of the precipitation and the decrease in the temperature, the thickness of the ice changes and a situation in which the entire line will be covered with ice can occur. In such a case, the electric locomotive can not receive electricity via a pantograph which is separated from the line with a layer of ice. That is why the issue of preventing the formation of icing on traction lines is crucial [9].

The lines can be covered in grease that prevents icing from forming on the line. However, it is troublesome, expensive and requires the line to be disconnected from the source of energy. The carrying out of this idea is not economical and is technically difficult to implement.

A method that can be implemented relatively easily id to heat up the traction line to a positive temperature at which icing can not form. The best way to do it is to heat it using electrical current [1, 3, 4, 7].

The main purpose of this article is to analyze different variants and suggest a system of carry out the aforementioned concepts of heating.

2. Theoretical part of atmospheric icing on traction lines

The first task is to define the dependency of the temperature of the wire on the current density and heating time. In this case, it is possible to use rectifying units which already exist in rail applications in order to carry out this task, which will lower the cost compared to an the installation of additional sources.

It is extremely important to determine the duration of electricity transit in the wires in order to heat them. The current will be tied to active power looses in the network. The time needed to heat the wire to a given temperature and the length of the wire at a given current density are crucial factors. For that purpose, theoretical principles of heating a wire with direct current need to be taken into consideration. This case will be analyzed for a wire free of atmospheric icing.

As practice of overhead lines usage shows, three types of residues exist: wet snow, crystalline residue and atmospheric icing. Wet snow coats the lines when wind occurs with the air temperature of 0°C. Residues on lines occur together with fog or mild wind at temperature from –3°C to –10°C. Atmospheric icing occurs with the negative temperature of approximately –5°C, rain precipitation and wet snow precipitation and with the presence of wind at the speed of $12\frac{\mathrm{m}}{\mathrm{s}}$, which causes rapid icing of the lines. Obviously, at the same time, car routes are covered with similar residues. That is why, most people take advantage of passenger trains and, for that reason, the role of such trains becomes very important. The coating of the traction lines with ice significantly decreases the contact surface between the line and the pantograph of an electric locomotive. Apart from that, there exists the risk of line tearing and network damage during locomotive's movement, which is the result of mechanical influence on the line.

Experiments point that in order to melt the ice with a current in overheat lines made of steel-aluminum wires, the current density is selected within the range of $4-4.5\frac{\text{A}}{\text{mm}^2}$. The current will allow for the ice to melt within 20 min, whereas for steel wires the current density is selected between $2\frac{\text{A}}{\text{mm}^2}$ to $3\frac{\text{A}}{\text{mm}^2}$. If the time of melting is acceptable to be at 60 min, the current density for wires of such a construction ranges between $3.5\frac{\text{A}}{\text{mm}^2}$ and $4\frac{\text{A}}{\text{mm}^2}$. In such case, the mechanical characteristics of materials the overhead line is manufactured of are taken into account. Current density in traction line wires can be higher because copper wires of the traction line will have their bay length much shorter than the bays of an overhead line of high and very high voltage [6–9].

Figure 1 presents the scheme of powering of one segment of the traction network from the rectifier of a two-rail substation of a DC voltage U_d.

In case of a traction network, catenary wire which supports the traction wires and cross-connectors all transmit electricity. The catenary wire and the connectors are made of copper and together with the traction lines make a parallel connection. A reference drawing is included below.

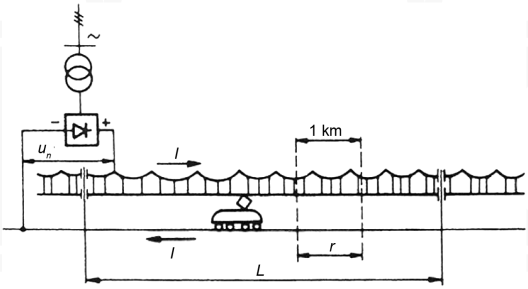

Fig. 1. A reference scheme of a segment of traction line powering

A segment *l* between railway substations is on average 15–25 km, and the resistance of this segment equals around 1.6 Ω. In such a case from a DC voltage of a traction network in the value of 3300 V, the electrical value on that segment can reach over 2000 A. In case of insufficient power of one of the rectifiers, two rectifiers connected in parallel or a higher power rectifier should be used.

A wire of a cross-section of 100 mm² has the long term electrical ampacity within range of 400 A. It has to be taken into consideration that a traction line is dual (2 lines connected in parallel) and that, additionally, it – as a whole – is hanging on a copper catenary wire of a cross-section of about 95 mm². That is why rope will transmit about 30% of the current and the remaining 70% will be more or less equally distributed between both lines, which will give maxim working current within the range of 800 A. It is sufficient and the value of several additional amperes stemming from the need to heat up a traction line can be disregarded. The speed of heating up of such a wire will depend mostly on the temperature of the surroundings and the density of the current [2, 5].

It has to be specified how quickly a copper wire will heat up in various atmospheric conditions in order the prevent the formation of ice on the traction line; that is why relevant examinations or calculations need to be carried out.

An experimental examination requires a significant amount of time, equipment and the access to statistical data over the period of several years. That is why, this method is expensive. The required result can be achieved by analyzing a system model, most conveniently in the form of dependence of the temperature of the line on the time of heating and the density of the current being transmitted through this line. For this purpose, a mathematical model which takes into consideration the parameters of the material of which the line is made and the construction of such lines [1, 3, 4, 7].

A mathematical model will be created using basic equation for electrical circuits and processes of heating based on the laws of electrical engineering and thermodynamics. From the formula of energy balance in the following form:

$$RI^2 = KS\left(\theta - \theta_0\right) \tag{1}$$

we can determine the value of current depending on the temperature which is expressed by the following formula:

$$I\left(\theta - \theta_0\right) = \sqrt{\frac{KS\left(\theta - \theta_0\right)}{R}} \tag{2}$$

where:

- K – heat coefficient through convection and radiation $\left[\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{C}}\right]$,
- S – the surface of the wire [m^2],
- θ, θ_0 – temperature of wire and environment [°C],
- R – resistance of the wires segments [Ω].

It has to be noted that the resistance of wires is expressed by the following formula:

$$R = \rho \frac{4l}{\pi d^2} \tag{3}$$

where:

- ρ – proper resistance of the wire's material,
- l – the length of the wire,
- d – the diameter of the traction wires.

After taking into consideration the parameters of the wires' resistance, the value of current is expressed using following formula:

$$I\left(\theta - \theta_0\right) = \sqrt{\frac{K_0 d^2\left(\theta - \theta_0\right)}{\rho}} \tag{4}$$

where:

K_o – factor of proportionality.

Formula (4) allows us to determine the value of current, which raises the wires's temperature to θ. For practical applications, however, the formula (4) will not allow us to obtain the relationship between the time of heating a wire to a given temperature and the different values of heating current. In order to obtain the heating a wire with electrical current based on Newton-Richman law in the following form:

$$RI^2 dt = mCd\theta + \alpha\left(\theta - \theta_0\right) Adt \tag{5}$$

where:

A – wire's circumference,
l – the wire's length,
α – heat transfer coefficient onto the borderline between the wire and air,
m – the wire's mass,
C – heat absorption coefficient by the material the wire is made of,
θ_0 – the temperature of the surrounding air,
θ – the wire's temperature after certain heating time.

If we observe that $R = \rho \frac{l}{S}$, $m = \gamma \cdot l \cdot S$, and $A = 2\pi rl$ and insert into equation (5) we will get:

$$\rho \frac{l}{S} \cdot J^2 \cdot S^2 dt = \gamma \cdot l \cdot S \cdot Cd\theta + \alpha\left(\theta - \theta_0\right) \cdot 2\pi rldt \tag{6}$$

where:

r – the wire's radius.

Having taken into consideration that $S = \pi r^2$ we receive:

$$\rho \cdot l \cdot J^2 \cdot \pi r^2 dt = \gamma \cdot l \cdot \pi r^2 \cdot Cd\theta + \alpha\left(\theta - \theta_0\right) \cdot 2\pi rldt \tag{7}$$

After reducing identical values we obtain:

$$\rho \cdot J^2 \cdot rdt = \gamma \cdot r \cdot Cd\theta + 2\alpha\left(\theta - \theta_0\right) dt \tag{8}$$

After rewritings, we can write down the final differential equation:

$$\frac{d\left(\theta - \theta_0\right)}{dt} + \frac{2\alpha}{\gamma rC}\left(\theta - \theta_0\right) = \frac{\rho J^2}{\gamma C} \tag{9}$$

An equation characteristic for differential equation:

$$p + \frac{2\alpha}{\gamma rC} = 0 \tag{10}$$

from where we receive the equation's root:

$$p = -\frac{2\alpha}{\gamma r C} \tag{11}$$

The solution of the homogenous equation (9), that means with the right-hand side equal to zero, can be expressed as:

$$\theta - \theta_0 = Be^{-\frac{2\cdot\alpha}{\gamma\cdot r\cdot C}\cdot t} \tag{12}$$

where:

B – is a constant of integration, which is being determined.

The coerced component is determined by the condition which, for the time $t = \infty$ the derivative equals zero, and $\theta - \theta_0 = \frac{\rho\cdot r\cdot J^2}{2\cdot\alpha}$.

The complete solution to the equation (5) can be written in the following form:

$$\theta - \theta_0 = \frac{\rho\cdot r\cdot J^2}{2\cdot\alpha} + Be^{-\frac{2\cdot\alpha}{\gamma\cdot r\cdot C}}. \tag{13}$$

from where, we can finally write down the relationship between the temperature and time in the following form:

$$\theta(t) = \frac{\rho\cdot r\cdot J^2}{2\cdot\alpha} + \theta_0 + Be^{-\frac{2\cdot\alpha}{\gamma\cdot r\cdot C}\cdot t} \tag{14}$$

To specify the constant of integration, we can apply the boundary conditions for $t = 0$:

$$\theta_{t=0} - \theta_0 = \frac{\rho\cdot r\cdot J^2}{2\cdot\alpha} + B \tag{15}$$

from where:

$$B = \theta_{t=0} - \theta_0 - \frac{\rho\cdot r\cdot J^2}{2\cdot\alpha} \tag{16}$$

After inserting into the formula (14) we get:

$$\theta(t) = \frac{\rho\cdot r\cdot J^2}{2\cdot\alpha} + \theta_0 + \left(\theta_{t=0} - \theta_0 - \frac{\rho\cdot r\cdot J^2}{2\cdot\alpha}\right)e^{-\frac{2\cdot\alpha}{\gamma\cdot r\cdot C}\cdot t} \tag{17}$$

The final equation allows us to calculate the temperature of heating of an item with the radius r and proper resistance of the wire's material ρ with the specific weight of $\gamma\left[\frac{\mathrm{N}}{\mathrm{m}^3}\right]$, current density of $J\left[\frac{\text{A}}{\text{mm}^2}\right]$, in time of t in the case when the temperature of the wire, from the moment the current is switched on, until the moment of heating up is different than the temperature of the surrounding air.

3. Experimental part

The wire's temperature, when switching on the current until the heating of the wire aimed towards melting the glazed ice usually equals the temperature of the surrounding air. That is why the equation (17) will be expressed as:

$$\theta(t) = \frac{\rho \cdot r \cdot J^2}{2 \cdot \alpha} + \theta_0 - \frac{\rho \cdot r \cdot J^2}{2 \cdot \alpha} e^{-\frac{2 \cdot \alpha}{\gamma \cdot r \cdot C} \cdot t} \tag{18}$$

The diagram in Fig. 2 depicts a graphic presentation of the equation (18) for the selected values of current density.

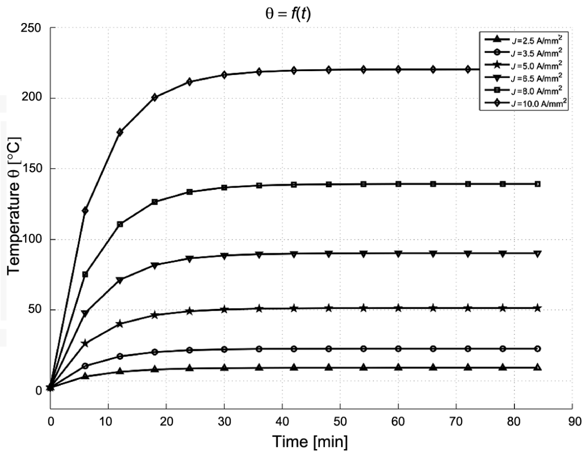

Fig. 2. The dependence of the wire's temperature on the heating time

For the above diagram, it was assumed that the initial temperature value is –5°C. The maximum temperature value, however, remains limited by current density.

For the same equation, a diagram of dependence of the wire's heating temperature on current density, while assuming different heating duration, was created. The results are presented in Fig. 3.

Analogously to the diagram from Fig. 2 – the initial value of temperature also equals –5°C, and the maximum value is limited only by the time of heating.

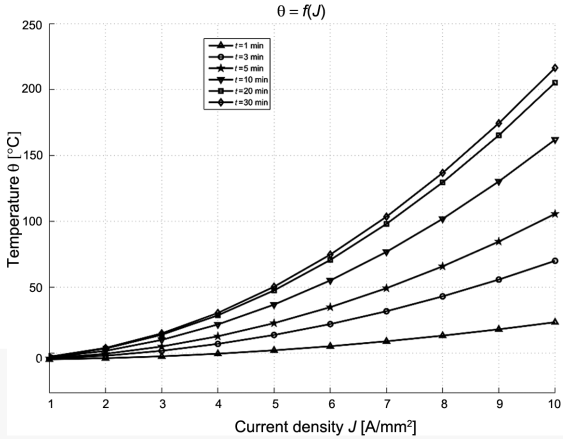

Fig. 3. The dependence of the wire's temperature on current density

From the equation (18) we can write:

$$e^{-\frac{2\cdot\alpha}{\gamma\cdot r\cdot C}\cdot t} = \frac{\frac{\rho\cdot r\cdot J^2}{2\cdot\alpha}+\theta_0-\theta(t)}{\frac{\rho\cdot r\cdot J^2}{2\cdot\alpha}} \tag{19}$$

Equation (19) is re-written into the following form:

$$\frac{1}{e^{\frac{2\cdot\alpha}{\gamma\cdot r\cdot C}\cdot t}} = \frac{\frac{\rho\cdot r\cdot J^2}{2\cdot\alpha}+\theta_0-\theta(t)}{\frac{\rho\cdot r\cdot J^2}{2\cdot\alpha}} \tag{20}$$

where:

$$e^{\frac{2\cdot\alpha}{\gamma\cdot r\cdot C}\cdot t} = \frac{\frac{\rho\cdot r\cdot J^2}{2\cdot\alpha}}{\frac{\rho\cdot r\cdot J^2}{2\cdot\alpha}+\theta_0-\theta(t)} \tag{21}$$

After applying the logarithm to the formula (21), we get the following equation:

$$\frac{2\cdot\alpha}{\gamma\cdot r\cdot C}\cdot t = \ln\left(\frac{\frac{\rho\cdot r\cdot J^2}{2\cdot\alpha}}{\frac{\rho\cdot r\cdot J^2}{2\cdot\alpha}+\theta_0-\theta(t)}\right) = \ln\left(\frac{\rho\cdot r\cdot J^2}{2\cdot\alpha}\right) - \ln\left(\frac{\rho\cdot r\cdot J^2}{2\cdot\alpha}+\theta_0-\theta(t)\right) \tag{22}$$

From this equation (22), we can obtain the formula to determine the time of transmission of a given value of DC current density, depending on the temperature of the surrounding air and the temperature necessary to melt the ice. The formula has the following form:

$$t = \frac{\gamma \cdot r \cdot C\left[\ln\left(\frac{\rho \cdot r \cdot J^2}{2 \cdot \alpha}\right) - \ln\left(\frac{\rho \cdot r \cdot J^2}{2 \cdot \alpha} + \theta_0 - \theta(t)\right)\right]}{2 \cdot \alpha} \tag{23}$$

Figure 4 presents the block diagram for the connection of a rectifier in order to melt the ice on the line of a monorail railway.

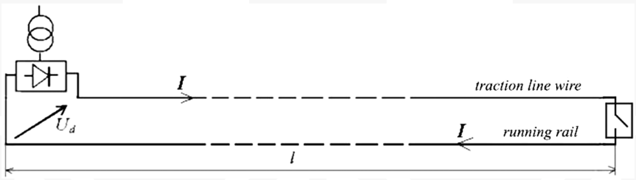

Fig. 4. Block diagram of a ice melting system

The following examination is determining the value of current needed to heat up a wire from the initial temperature –10°C to the following temperatures: 10°C, 35°C and 60°C in time 5 min, 10 min and 20 min. The diagram below presents the results obtained.

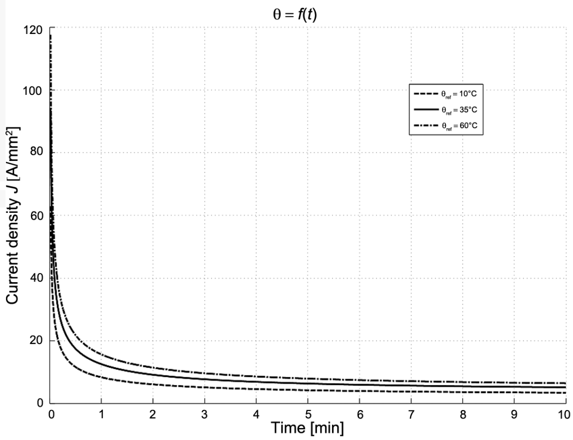

Fig. 5. The dependence of current density on the time of wire's heating

The values of current density for the necessary heating time were extracted from the Fig. 5, a marker tool, displaying the values of *X* and *Y* axes in a given point of diagram was used to that end. The results are presented in Table 1.

Table 1

The current density values extracted from the diagram for the three conditions required in the task

Heating time	Target temperature		
	10°C	35°C	60°C
5 min	4.252 A/mm^2	6.378 A/mm^2	7.954 A/mm^2
10 min	3.461 A/mm^2	5.192 A/mm^2	6.475 A/mm^2
20 min	3.084 A/mm^2	4.626 A/mm^2	5.770 A/mm^2

Analyzing the courses in Fig. 5, we can see that, in the initial temperature range, the value of current decreases rapidly, whereas in the subsequent part of the diagram the changes are smaller.

4. Conclusions

The analyses of the railway situation presented in this article allow us to determine that the occurrence of atmospheric icing on traction lines is a current and important issue which needs to be resolved. The occurrence of icing impacts train schedules by causing problem with supplying electric locomotives with power.

Preventing the formation of icing on traction lines requires the increase of the wire's temperature to the value, in which ice can not deposit on wires. Heating a wire to that temperature in most easily delivered through the transit of electric current through the wire. This, however, requires specifying the dependency of temperature on current density in traction wires, which can be determined experimentally or analytically. Because the antithetical method is the cheapest and does not require interring with the traction network, and as such does not cause obstacles in the functioning of trains during tests, this article formulates a mathematical model based on the laws of electrical engineering and thermodynamics. The obtained model allows us to adequately examine the processes of heating a wire with electricity.

The analysis that was carried out proved that the wire can be heated from temperature of –5°C to the temperature of 6°C, in time 10 min, with the electricity of current density as low as $2.5\frac{\mathrm{A}}{\mathrm{mm}^2}$. Further heating of the wire in the aforementioned conditions can allow it to reach the maximum temperature of 8–9°C. It is obvious that the increase in current density will cause a quicker heating of the wire. If we use the electricity with the current density of $5\frac{\mathrm{A}}{\mathrm{mm}^2}$, then after the time of 10 min, the wire will reach temperature of about 40°C and can reach maximum temperature of 50°C after 30 min. The simulation results presented above are obtained for the case of the wire being cooled with wind and the velocity $12.5\frac{\mathrm{A}}{\mathrm{mm}^2}$ and the temperature of –5°C its surroundings.

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