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RISK OF SWITCHING AND ATMOSPHERIC OVERVOLTAGES TO RAILWAY ELECTRO TRACTION VEHICLES

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Abstract: *- The paper presents the results of theoretical investigations of risk of switching and atmospheric overvoltages to railway electro traction vehicles. Besides, the paper also presents adequate protection measures for limiting these overvoltages.*

Key words: *electrotraction vehicle, switching overvoltage, atmospheric overvoltages*

INTRODUCTION

Based on the recommendations of the International Electrotechnical Commission (IEC 71 – 1), the overvoltages on electro traction vehicles are divided in the following way:

Temporary overvoltage. That is the overvoltage of propulsion frequency of a relatively long duration. It can be unweakened or slightly weakened. In some cases its frequency can be several times smaller or bigger than the propulsion frequency.

Transient overvoltage. That is a short-duration overvoltage lasting a few µs or even less. Transient overvoltages are divided into:

- Overvoltages with a **slowly increasing front (switching).** These are the overvoltages with usually one polarity and the front lasting from 20 µs<T_1<5000 µs, and the back lasting from T_2<20 ms.
- Overvoltages with a **fast increasing front (atmospheric).** These are the overvoltages with usually one polarity and the front lasting from 0.1 µs<T_1<20 µs, and the back lasting from T_2<300 ms.
- Overvoltages with a **very fast increasing front.** These are the overvoltages with usually one polarity and the front lasting T_1<0.1 µs, total duration being <3 ms. They are usually superponed by oscillations with 30kHz<f<100MHz frequencies.

Transient overvoltages can be with:

- a slowly increasing front (switching overvoltages)
- a fast increasing front (atmospheric overvoltages)
- a very fast increasing front (VFT – very fast transient)

Figure 1 shows the classification of overvoltages according to the duration of time and the k_p overvoltage factor which, for the single-phase electro traction system, is defined as follows:

$$k_p = \frac{U_{max}}{\sqrt{2}U} \qquad (1)$$

in which: U_{max} - overvoltage amplitude, and U - effective value of phase voltage.

In electro traction vehicle exploitation, taking the length of duration and the k_p overvoltage factor into consideration, it is of special significance to investigate the operation of electrotraction vehicles at the occurrence of atmospheric and switching overvoltages

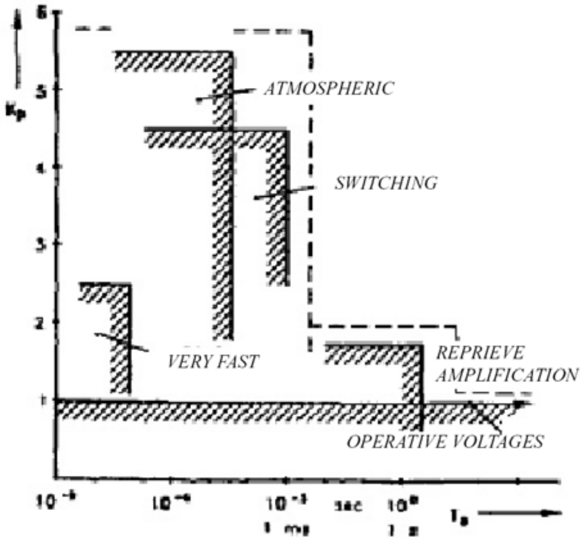

Figure 1. Overvoltages classification according to duration and overvoltage factor

SWITCHING OVERVOLTAGES

The 25kV 50 Hz electro traction system represents a certain oscillatory circuit in which there is induction, capacity and ohm resistance. Due to this fact, cutting operations (turning a high-voltage switch on and off) in electro traction sub-stations and electro traction vehicles can cause overvoltages in the electro traction system.

As for the high-voltage switches in electro traction vehicles of the 25 kV 50 Hz single-phase system, they are vacuum or pneumatic and designed for fast and safely cutting strong predominantly inductive currents, without absorbing too much energy in breaker chambers. However, at the moment of cutting small inductive currents which exist when the pneumatic switch is turned off by the locomotive driver, an electric arc may be created in the power switch before the current normally passes through the zero. Namely, when the switch is normally turned off by the driver, the locomotive transformer is at the idling speed, and the cutting-off currents are equal to the current magnetizing this transformer. At the moment of cutting small inductive currents magnetizing the locomotive transformer, when they are approaching their natural zero, the resistance of an electric arc between the switch contacts is suddenly beginning to change its value and becoming an important element of the electric current contour consisting of the induction resistance of the transformer's primary coil and the capacity resistance between the transformer coils and between the transformer coils and the ground. After the current has been cut off, the accumulated magnetic energy in the locomotive transformer, which existed at the moment of its being magnetized, is transformed into an electric current at the capacity resistance between the coils and between the coils and the ground. This transformation implies [1]:

$$\frac{1}{2}C_t u^2 = \frac{1}{2}L_t i^2 \qquad (2)$$

$$u = \sqrt{\frac{L_t}{C_t}} \cdot i \qquad (3)$$

At the moment of being cut off, the current may be smaller or equal to the maximum value of the current magnetizing the locomotive transformer (I_μ). This current depends on the value of induction resistance of the perceived electric current contour (L_t), the voltage of the overhead contact line (U) and its frequency (f_t):

$$i \le \sqrt{2} I_\mu = \frac{\sqrt{2}}{2 \cdot \pi \cdot f_t \cdot L_t} \cdot U \qquad (4)$$

After opening the high-voltage switch in an electro traction vehicle, two separate electric circuits may be formed (one in the vehicle itself, and the other through the overhead contact line and the electro traction sub-station). In such conditions, the return voltage of the high-voltage switch of the observed vehicle may have two frequencies. If L_g and C_g indicate the induction and capacity resistance of the overhead contact line, and L_t and C_t indicate the induction and capacity resistance of the locomotive transformer, the corresponding oscillation frequencies of the return voltage on the switch are:

$$f_g = \frac{1}{2\pi\sqrt{L_g C_g}} \qquad (5)$$

$$f_t = \frac{1}{2\pi\sqrt{L_t C_t}} \qquad (6)$$

As the induction of L_t is small, the resonant frequency f_t may be very big (100 kHz). When the current "i" in the energy switch, while approaching the natural zero (moment t_o), falls under a certain level I_g, unstable frequency oscillations f_t occur (Figure 2). The oscillations are suddenly increased so that there is cutting very soon after their occurrence at the value I_s of alternative current of propulsion frequency (moment t_s).

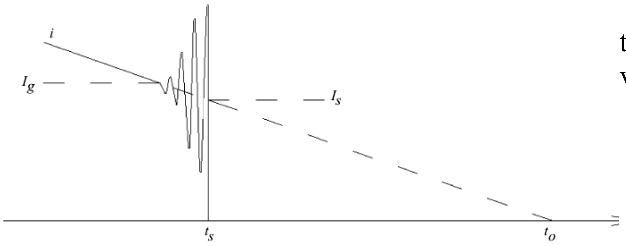

Figure 2. Process of electric current cutting before it passes the zero

Typical electric current values, for pneumatic switches, at which cutting occurs, are in the range from 4 A to 20 A, when the capacity is $C_t=10\ nF$ [2,3].

Electric current cutting causes the occurrence of an intensive transient process in the locomotive transformer which may be manifested by high overvoltages. The maximum overvoltage which then occurs in the single-phase locomotive transformer may be presented as follows [2,3]:

$$U_{max} = \sqrt{U_s^2 + \frac{L_t}{C_t} \cdot I_s^2 \cdot \eta} \qquad (7)$$

in which: U_{max} - momentary value of the voltage of capacity resistance C_t at the moment of cutting, I_s - value of the cut-off current, L_t - induction resistance of the locomotive transformer, η - coefficient of losses which, for unloaded locomotive transformers, is in the interval from 0.3 to 0.5.

Between the switch contacts a transient return frequency voltage is established (f_t), of considerable maximum value, and it may again cause the establishing of an electric arc between the switch contacts by breaking through the space between the contacts.

A characteristic occurrence at the moment of cutting small inductive currents is a multiple repeated ignition of electric arc between the switch contacts. This occurrence is characteristic for the switches which can cut electric current during its high-frequency component caused by the previous repeated ignition of an electric arc. As the switch contacts are moving apart, each next repeated ignition of electric arc is possible only if a high transient return voltage occurs, because the dielectric durability of the space between the contacts also increases. Thus, the voltage in the locomotive transformer may be higher and higher at the moment of each next repeated ignition of an electric arc. This phenomenon is called the voltage escalation and it may cause a very big strain on the locomotive transformer isolation.

A typical appearance of overvoltage in a transformer at the moment of turning off a high-voltage locomotive switch is shown in Figure 3 [2,3].

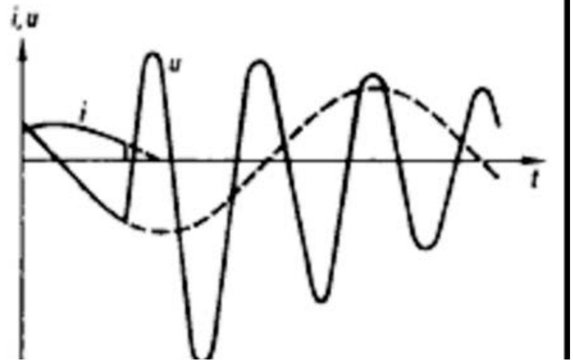

Figure 3. Overvoltages at the moment of turning off small inductive currents

Besides the mentioned case, high-voltage switches in electro traction vehicles also turn off the so-called malfunction currents, i. e. short circuit currents of active parts of a device and the equipment of the main electric circuit of a vehicle with earthing. In such conditions, dangerous return voltages may occur on the contacts of the high-voltage switch of a traction vehicle, because of which switching off malfunctions is of special interest. A return voltage at the moment of switching off a short circuit may be very steep and have a high frequency.

In these conditions, the overhead contact line gives the following voltage:

$$e(t) = E \cdot cos\,\omega_1 t \qquad (8)$$

Before the opening of a high-voltage switch, the malfunction (short circuit) current in an electro traction vehicle is:

$$i(t) = \frac{E}{\omega_1 L} sin(\omega_1 t) \qquad (9)$$

The short circuit current has an inductive character, i. e. $\omega_1 L >> R$. After opening the switch contacts there is:

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int idt = E\,cos\,\omega_1 t \qquad (10)$$

The return voltage on the opened switch is as follows:

$$U_p = E\left[cos\,\omega_1 t - exp(-\frac{R \cdot t}{2 \cdot L})cos\,\omega_2 t\right] \qquad (11)$$

in which ω_1 is a closed-circuit propulsion frequency and ω_2 is the resonant frequency of an electric circuit in the locomotive transformer:

$$f_2 = \frac{1}{2\pi\sqrt{LC}} \qquad (12)$$

A return voltage on the switch might achieve a double value of maximum propulsion voltage; however, due to damping resistance in an electric circuit, this value is somewhat smaller.

Figure 4 shows a substitute scheme of electric circuits at the moment of opening the high-voltage switch on an electro traction vehicle immediately after the occurrence of malfunction current on the vehicle, in which: (I) – Propulsion frequency voltage in the contact line is increased from the value of $i \cdot Z$ (i = short circuit current; Z = impedance of a locomotive transformer) to the value of the contact line voltage; (II) – Transformer switch voltage is decreased from the value of $i \cdot Z$ to 0; (III) – Return voltage on the switch is the difference between the contact line voltage and the transformer switch voltage.

It should be taken into consideration that the analyzed switching overvoltages on the high-voltage switch of electro traction vehicles cannot be avoided, but their height, steepness and frequency can be influenced. The basic measure for their decrease is a choice of good-quality high-voltage locomotive switches, i. e. the ones in which, at the moment of turning off, there is no occurrence of cutting off the electric current before it passes through the natural zero, or the level of cutting off is small.

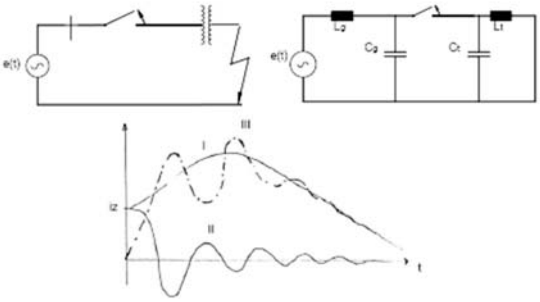

Figure 4. A substitute scheme of an electric circuit and voltages at the occurrence of a return voltage with two frequencies

ATMOSPHERIC OVERVOLTAGES

Due to the lack of protective cords and spark gaps, the contact line in the 25kV 50 Hz single-phase electro traction systems is directly vulnerable to atmospheric overvoltages and discharges. At the moment of a thunderbolt directly striking a contact line, there are two overvoltage traveling waves (direct and inverse) spreading at the speed of light in different directions.

In numerical estimates, the atmospheric overvoltage which is induced in the contact line is changed by an electric current or voltage source, depending on the distance from the place where a thunderbolt struck to an electro traction vehicle. Taking into consideration the distance between the site struck by a thunderbolt and the observed electro traction vehicle, it is possible to differentiate between three basic cases (Figure 5) [1].

- The case of a close impact with a jump. This case occurs when a thunderbolt strikes a catenary support with a jump to the contact line, or when a thunderbolt strikes a contact line with a jump to a catenary support. The height of overvoltage is then greatly affected by the value of earthing resistance of the catenary support. Rails provide a basic connection to earth on the 25kV 50Hz electrified tracks, but in some exceptional cases other earthing equipment is used, the resistance of which, in the most adverse conditions, must be less than 5 Ω.
- The case of a close impact on a contact line without a jump. Such a thunderbolt strike is, as a rule, modeled by an electric current source. If Z_g is a thunderbolt wave resistance, and Z_v is a contact line wave resistance, then in this case $Z_g >> Z_v$. The waves spread from the site of a thunderbolt strike in both directions, and the waves voltage is a result of a part of the thunderbolt current and the waves resistance of the contact line. This is the most critical case when considering the overvoltage protection of electro traction vehicles.
- The case of a distant place of impact. In this case the atmospheric overvoltage is modeled by the voltage wave which travels along the contact line before it enters the electro traction vehicle. The maximum value of the wave is determined by the isolation level of the contact line. When the wave is moving along the contact line, the front of the wave is lengthened. Approximately, this lengthening amounts to 1 μs for every kilometer of the contact line. In estimates, a close impact may be observed as an extreme case, although it occurs relatively rarely, because it imposes considerably greater requirements on the propulsion equipment of electro traction vehicles than in the case of distant thunderbolt strikes.

PROTECTION MEASURES AND MEANS

In case of the absence of adequate protection, the atmospheric discharge current flows through the electric circuit as it is shown in Figure 6 [4,5,6]. This current may cause a strong and prohibited thermal and electrodynamic load in the whole high-voltage equipment of a vehicle (pantograph, roof disconnectors, high-voltage switch, locomotive traction transformer, earthing transformer and earthing brushes), which is prevented by applying adequate lightning conductors [7].

In the leading series of electro traction vehicles owned by “Serbian Railways” (i. e. in the ŽS 441 and ŽS 461 series locomotives and the ŽS 412/416 series electric trains), silicon-carbide (SiC) lightning conductors with spark gaps are used.

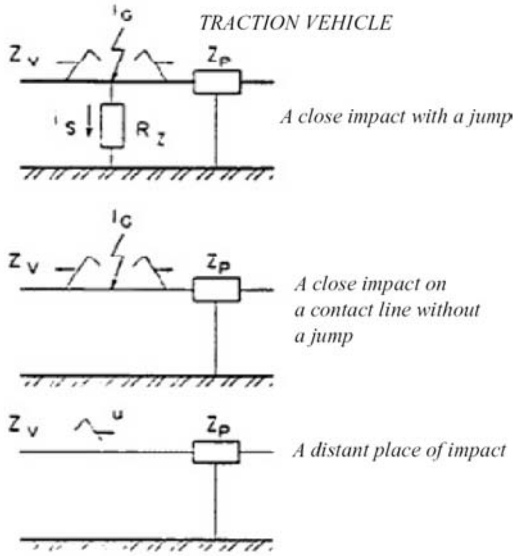

Figure 5. A substitute scheme of a contact line depending on the site of atmospheric discharge

The basic problem with the applied lightning conductors with spark gaps is cutting accompanying current with industrial frequency after the overvoltage has disappeared. Besides, in practice so far it has been noticed that the penetration of moisture into the lightning conductors housing is the main cause of lightning conductors defects. At the same time, the presence of moisture and an increase in temperature of non-linear resistance above 50^{0}C cause paraffin melting and moisture penetration into the granular structure of SiC non-linear resistance. In that way, the microstructure of non-linear resistance is changed, and it is consequently changed and degraded. This degradation of non-linear rheostats is the main cause of difficulties with conductors in exploitation.

The moisture arrested in lightning conductors also has an adverse influence on spark gaps. It has been proved that isolation parts between spark gaps electrodes lose their isolating properties. A decreased dielectric firmness of spark gaps causes difficulties in switching off an accompanying current after the conductors have been activated due to overvoltage. In such conditions, the accompanying current can be established again, although overvoltage has disappeared, and the conductor is under a nominal propulsion voltage. The inability of a permanent cut-off of the accompanying current causes the destruction of conductors with the most serious consequences.

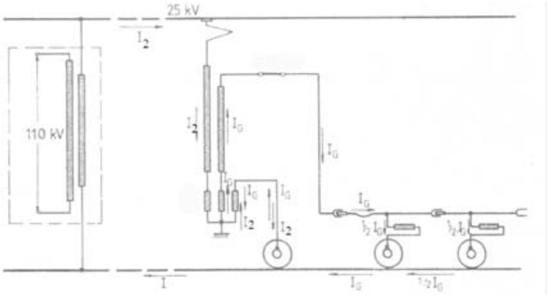

Figure 6. An electric circuit of atmospheric discharge current in the absence of lightning conductors

Due to the perceived disadvantages of silicon-carbide lightning conductors, they should be replaced by an improved construction of spark gaps, in which the arc is stretched under the influence of the magnetic field in the chamber for switching the arc off, or rather, by metal-oxide lightning conductors.

We should also point out the fact that the international and domestic standards comprise the problems of lightning conductors on electro traction vehicles, but the control of accuracy in exploitation is not regulated completely [3]. Namely, according to some opinions, the optimal period of checking lightning conductors should be every three years. Besides, if the alternative working voltage is smaller than *1.5 Un* of conductors, or smaller than the highest values given by the manufacturer, the conductor is declared defective and should be replaced by an accurate one immediately. If the alternative working voltage is bigger than *2.1 Un*, a detailed check in VN laboratories is recommended, and when the alternative working voltage is bigger than 2.4 *Un*, the conductor is declared defective and its replacement is recommended. In order to keep step with the developed countries in this important field of overvoltage protection in electro traction vehicles, it is recommended that the cause of malfunction of each conductor found defective should be analyzed. Only a systemic surveillance of lightning conductors' behavior in different microclimatic conditions and installation places may offer useful data for their safer operation.

However, in spite of the mentioned problems with lightning conductors, the earthing line in electro traction vehicles must be so dimensioned that even the strongest currents of atmospheric and switching discharges are, via monobloc wheels, guided to the rails and to the ground. So far, in exploitation, this problem has not been given sufficient consideration, in spite of the perceived occurrences of thermal strain and damage to monobloc wheels in certain electro traction vehicle series [7].

CONCLUSIONS

Switching overvoltages cannot be avoided but it is possible to affect their height, steepness and frequency. The basic measure for their decrease is a choice of good-quality high-voltage switches in an electro traction vehicle, i. e. the ones in which, at the moment of turning off, there is no occurrence of cutting off the electric current before it passes through the natural zero, or the level of cutting off is small.

When lightning conductors react, the earthing line in electro traction vehicles must be so dimensioned that even the strongest currents of atmospheric and propulsion discharges are, via monobloc wheels, guided to the rails and to the ground. So far, in exploitation, this problem has not been given sufficient consideration.

Due to the perceived disadvantages of silicon-carbide lightning conductors, it is recommended that a new generation of lightning conductors (metal-oxide without spark gaps) should be installed, in a sealed housing made of silicon gum or polymer materials, resistant to moisture penetration.

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РИСКЪТ ПРИ ВКЛЮЧВАНЕ И АТМОСФЕРНИТЕ СВРЪХНАПРЕЖЕНИЯ ЗА ЕЛЕКТРИЧЕСКИТЕ ЖЕЛЕЗОПЪТНИ ВОЗИЛА

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СЪРБИЯ

Резюме: *– Докладът представя резултатите от теоретичните изследвания на риска от включване и атмосферните свръхнапрежения за електрическите железопътни возила. Освен това докладът представя подходящи защитни мерки за ограничаване на тези свръхнапрежения.*

Ключови думи: *електрическо железопътно возили, включващо свръхнапрежение, атмосферни свръхнапрежения.*