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ANALYSIS OF VOLTAGE AND CURRENT AT CONTACT LINE POWER CLOSURE

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1. Introduction

This research work was created on base of operating requirements. During work on contact line at AC 25 kV, 50 Hz for disconnection of contact line (i.e. track closure) it is necessary to connect this line with rail at the front and also at the end of protected work area by two earth rods. The paper deals with analysis of influence (i.e. coupling ways) of neighboring track contact line under these conditions which occur during the common operation or during fault current. For this case, contact lines of both tracks can be considered as a special case of one turn air transformer with free coupling between primary and secondary winding [1] and [2]. Primary winding is represented by contact line of operating track and secondary winding by contact line of track closure.

Voltage between track and contact line at section closure can occur from two reasons:

- Electrostatic field effect caused by contact line of operating track
- Magnetic field effect caused by current passing through operating track

Both of these effects occur during accidental connection of contact line but their qualitative influence is very different and depends on used circuit diagram of contact line section closure.

For electrical connection of contact line of work section closure, it is necessary to take into consideration three circuit diagrams which arise out at section closure.

- Contact line closure is disconnected from feeder but it is not connected with rail, it hangs as insulated line above rails, see ***Fig. 1***.
- This contact line is connected at one end with rail, see ***Fig. 2***.
- This contact line is connected at both ends with rail, see ***Fig. 3***.

It is possible to think on the other circuit diagram which is represented by partial paralleling connection of line at contact line closure at double track but this is the special case of full paralleling [3]. The circuit diagram of contact line closure is changing progressively during protection of work section in above mentioned three circuit diagrams according to earth rods location by workers.

General equations (1) and (2) come from substitute circuit diagram of mentioned situation which is valid for:

$$-\frac{dU_{2x}}{d_x} = Z_{12} \cdot I_1 + Z_2 \cdot I_{2x} \tag{1}$$

$$-\frac{dI_{2x}}{d_x} = -Y_{12} \cdot U_1 + Y_2 \cdot U_{2x} \tag{2}$$

where

U_{2x} .... voltage in point from the second track (track closure) $[V]$,

I_{2x} .... current in the same point of the second track (track closure) $[V]$,

I_1 .... current in the first track (operating track) $[A]$,

U_1 .... voltage in the first track (operating track) $[V]$,

Z_{12} .... mutual coupling reactance of both contact lines $Z_{12} = j\omega \cdot M_{12}$ $[\Omega]$,

Z_2 .... impedance of the second track, $Z_2 = R_2 + j\omega \cdot L_2$ $[\Omega]$,

Y_{12} .... capacitive conductance between two contact lines on condition that ohmic component is extensively low than capacitive component, $Y_{12} = j\omega \cdot C_{12}$, C_{12} is capacity between contact lines $[S]$,

Y_2 .... capacitive conductance of the second track, (i.e. between line and earth), on condition that ohmic component is extensively low than capacitive component $Y_2 = j\omega \cdot (C_{12} + C_2)$, C_2 is capacity between track closure and earth $[S]$.

Solution of these equations:

$$U_{2x} = A \cdot \varepsilon^{j\gamma x} + B \cdot \varepsilon^{-j\gamma x} + k_2 \cdot U_1 \tag{3}$$

$$I_{2x} = \frac{1}{Z_{2v}}(A \cdot \varepsilon^{j\gamma x} - B \cdot \varepsilon^{-j\gamma x}) - k_1 \cdot I_1 \tag{4}$$

where

A, B ...... integrating constants, values of which are given by boundary conditions of electrical circuits $[-]$,

Z_{2v} .... wave reactance of the second track $Z_{2v} = \sqrt{\frac{Z_2}{Y_2}}$ $[\Omega]$,

γ .... constant of propagate wave $\gamma = \sqrt{Z_2 \cdot Y_2}$ $[-]$,

$k_1 = \frac{Z_{12}}{Z_2}$ and $k_2 = \frac{C_{12}}{C_{12} + C_2}$ auxiliary constant $[-]$,

All values of electrical parameters of contact line are considered per unit of contact line length, the best way is 1 km of length. Furthermore, it is necessary the approximate equation for $\varepsilon^{\gamma x}$. For length of work section, it is used $\varepsilon^{ax} \doteq 1 + a \cdot x$ according to Taylor progression with substation of original exponential function with accuracy $0.1\,\%$ in range of exponent value from -0.045 to 0.045, see [4].

2. Method of solution

2.1 Isolated contact line

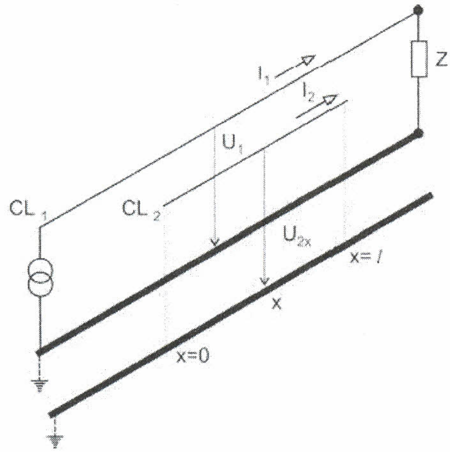

Fig. 1 *Isolated contact line*

Boundary conditions for this circuit diagram come from the fact that the current can not pass through at the ends of isolated section and then $I_{2\,0} = I_{2\,\ell} = 0$. Under this presumption and equation usage (3) with using approximate equation for $\varepsilon^{\gamma x}$, we obtain:

$$U_{2\,x} \doteq k_2 U_1 = \frac{C_{12}}{C_{12} + C_3} U_1 \tag{5}$$

$$I_{2\,x} \doteq 0 \tag{6}$$

Conclusions for isolated contact line:

- Voltage between isolated contact line and rail is given by only capacitive distribution independently on the position at contact line.
- Resistance of this voltage source is very high (i.e. low values of capacity), so this voltage is "soft" and under load is decreasing.
- No current passes through isolated contact line.

In operation, this mentioned voltage occurs between point of earth rod, which is connected with rail, and contact wire during their approach.

2.2 Contact line one-sidedly connected with rail

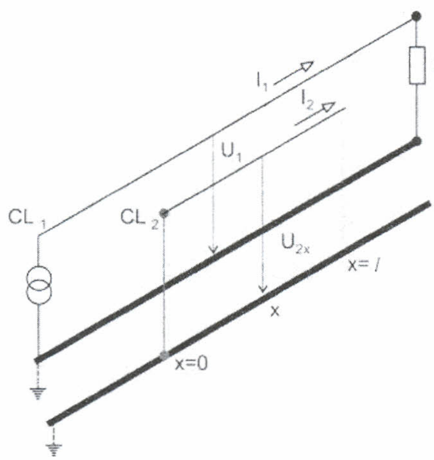

***Fig. 2** Contact line one-sidedly connected with rail*

Presumption for deduction of boundary conditions:

- Voltage in the point of contact line connected with rail is zero.
- Current is not passing through on the opposite end of contact line which is isolated.

Under presumption that connection between contact line and rail is localized to origin of length coordinate x and length of contact line is ℓ and then $U_{2\,0} = I_{2\,\ell} = 0$. For voltage and current in any location of section closure, we obtain:

$$U_{2x} \doteq -Z_{2v} \cdot k_1 \cdot \gamma \cdot I_1 \cdot x = -j\omega M_{12} \cdot I_1 \cdot x \tag{7}$$

$$I_{2x} \doteq -k_2 \frac{U_1}{Z_{2v}} \cdot \gamma(\ell - x) = -j\omega C_{12} \cdot U_1(\ell - x) \tag{8}$$

Conclusions for line one-sidedly connected with rail:

- Voltage, which is induced in contact line of the second track, is directly proportional to length of one-sided connected section and then directly proportional to current which passes through operating contact line of the second track.
- Current, which passes through in the point of connection of the second track of contact line with rail, is given only by mutual capacity both lines and voltage of operating line.

In operation, this mentioned voltage occurs in the place where the worker places the second earth rod (i.e. on the opposite end of work section closure than where earth rod is already placed). In case of higher currents in the neighboring operating section, this voltage can get dangerous values. Current, values of which are deduced from equation (8), passes through earth wire of the first rod and it has not practical meaning from viewpoint of its negligible magnitude.

2.3 Contact line two-sidedly connected with rail

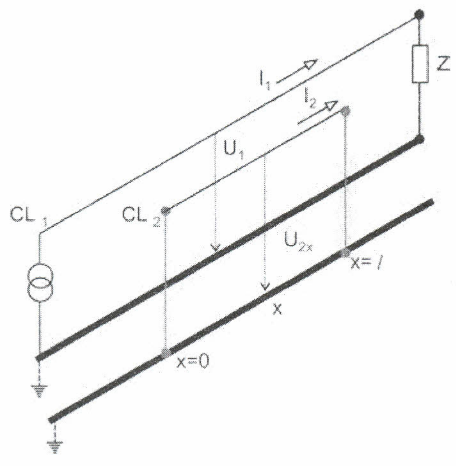

Fig. 3 Contact line two-sidedly connected with rail

Boundary conditions for this case arise from the circuit diagram, so that voltage at both ends of examined line is zero (i.e. in the place of both earth rods) and then $U_{20} = U_{2\ell} = 0$. By using the equations (3), (4) and usual simplification of exponential function, we obtain:

$$U_{2x} \doteq k_2 \cdot U_1(1 - \frac{2 - \gamma \cdot \ell}{2 - \gamma \cdot \ell}) = 0 \tag{9}$$

$$I_{2x} \doteq -j\omega C_{12} \cdot U_1 \cdot \frac{\ell - 2x}{2 - \gamma \cdot \ell} - k_1 \cdot I_1 \qquad (10)$$

Conclusions for line two-sidedly connected with rail:

- Voltage is zero in the whole length of section between earth rods in the points which are located over themselves.
- Current, which passes through this part of contact line, consists of two components: inductive and capacitive.
- Inductive component depends only on k_1 and directly proportional to current of operating track. It neither depends on length of section nor location of point at track closure.
- Capacitive component depends on voltage of contact line of operating track. It is zero in the centre of examine section (i.e. in the middle of earth rods) and increases linear to both earth rods but with different polarity.

Inductive component is applied significantly in operation whereas capacitive component has not impact (i.e. its values are insignificant). Inductive component can get the high values which require very good condition of earth wire cable at earth rods. This was confirmed by measuring [3].

3. Conclusion

Fro numerical values of equations mentioned above, it is necessary to use numerical values of particular constant of contact line. From this reason, results from measuring are utilized [3]. The value for impedance of one track of contact line was measured $Z_2 = 0{,}222 \div 0{,}485j = 0{,}534\angle 65{,}5^\circ \Omega \cdot km^{-1}$. Reactance of mutual coupling of both contact lines is $Z_{12} = 0{,}133\ \Omega \cdot km^{-1}$. This value is given by (7) inducted voltage at one-sidedly connected line. Measured voltage is $U_2 = 0.133\ V \cdot A^{-1} \cdot km^{-1}$. Capacity of contact line to earth was measured $C_2 = 0.0155\ \mu F \cdot km^{-1}$. Capacity between contact lines, which was calculated by roles of potentials between conductors, is $C_{12} = 0.0136\ \mu F\ km^{-1}$. It is possible to calculate other coefficients from numerical values by their definition equations $\gamma = 2.21 \cdot 10^{-3}$, $Z_{2v} = 242\ \Omega \cdot km^{-1}$, $k_1 = 0.250$ and $k_2 = 0.467$.

Voltages and currents for three circuit diagrams were calculated by equations:

- Voltage for isolated contact line by (5), when the voltage in operating track is $25\ kV$, is $U_2 = 11.7\ kV$. This value does not depend on length of section closure and in its any possible place. Internal resistance of this source is given by capacity C_{12} and its value is hundreds $k\Omega$ which decreases with length of section.

- Inducted voltage for one-sidedly contact line with rail at the opened end (i.e. the high value at this point) which is calculated by (7), is $U_2 = 0.133\ V \cdot A^{-1} \cdot km^{-1}$. Current passes through the point of connection (i.e. contact line and rail), which is calculated by (8) at 25 kV in operating track, is $I_2 = 0.107\ A \cdot km^{-1}$. This value is negligible.
- Voltage for two-sidedly contact line with rail is calculated by (9) and (10). Voltage in any possible place of operating contact line is zero. Induced component of current passing thought in the point of connection of contact line closure with rail by (10) is $I_2 = 0.250\ A \cdot A^{-1}$. The capacity component of this current is $0.053\ A \cdot km^{-1}$).

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Resumé

NAPĚŤOVÁ A PROUDOVÁ ANALÝZA PŘI VÝLUCE STOPY TROLEJOVÉHO VEDENÍ

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Článek se zabývá problematikou elektromagnetického rušení (EMI) u trakčního systému 25 kV, 50 Hz. Tento obor v současnosti stále více nabývá na významu a s tím i související důsledky pro jednotlivá provozovaná zařízení u Českých drah. Složité drážní systémy jak z hlediska infrastruktury tak z hlediska provozovaných dopravních prostředků nutí provozovatele věnovat dostatečnou pozornost právě EMI. Pozornost je soustředěna na oblast vazeb mezi dvěma sousedními stopami, z nichž jedna je výluce. Za této situace vznikají tři rozdílná schémata pro zajištění úseku při práci na trolejovém vedení. Jedná se o tyto případy: vedení izolované, vedení jednostranně spojené s kolejnicí a vedení oboustraně spojené s kolejnicí. Pro uvedené případy je provedena analýza, která byla vyvolána na základě provozních požadavků. Z výsledků analýzy jsou

provedeny závěry, které jsou zobecněny pro snadné využití. V závěru jsou podrobně uvedeny jednotlivé situace z hlediska elektrických veličin, kterých mohou nabývat tyto zmiňované případy zapojení. Článek spadá do části zabývající se výzkumem v uvedené oblasti EMI a může tvořit základ pro další řešení problematiky u trakčního systému 25 kV, 50 Hz.

Summary

ANALYSIS OF VOLTAGE AND CURRENT AT CONTACT LINE POWER CLOSURE

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The paper represents a part of research work on the field of elektromagnetic interference (EMI). Nowdays the railway techniques is very complicated and sophisticated both from viewpoint of railway infrastructure and from viewpoint of transport means. This research work was created on base of operating requirements. During work on contact line at AC 25 kV, 50 Hz for disconnection of contact line (i.e. track closure), it is necessary to connect this line with rail at the front and also at the end of protected work area by two earth rods. The paper deals with analysis of influence (i.e. coupling ways) of neighboring track contact line under these conditions which occur during the common operation or during fault current. The analysis is focused on the three circuit diagrams which arise out at section closure: isolated contact line, contact line one-sidedly connected with rail, contact line two-sidedly connected with rail. Generalize findings are mentioned in the conclusion of this paper. This work can be used as one part of background for research work on the field of traction system.

Zusammenfassung

ANALYSE DER SPANNUNG BEI ELEKTRISCHER FAHRLEITUNGSSPERRE

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Der Artikel befasst sich mit der Problematik der EMI beim Fahrsystem AC 25 kV, 50 Hz. Diese Thematik wurde durch die Forderung der elektrischen Sicherheit bei Arbeiten an gesperrter Fahrleitung zweiglessiger Strecke entwickelt. Die Analyse gibt Information über die Spannung auf der elektrisch gesperrten Fahrleitung im Falle, daß die Fahrleitung des anderen Gleises unter Fahrspannung liegt. Es sind drei Teilschemen analysiert, uzw. abgeschalteter Fahrleitungabschnitt, einseitig mit Schiene verbundener Fahrleitungabschnitt and endlich zweiseitig mit Schiene verbundener Fahrleitungabschnitt. Für diese Teilschemen sind Spannung- und Stromwerte rechnerisch abgeleitet und mit Messergebnissen verglichen. Diese Thematik passt zu der allgemeingültigen Studie über elektromagnetische Verträglichkeit, namentlich über EMI.