Electromagnetic Transients of On-board Passing Neutral Section in High-Speed Railway

Li Huawei, Fan Yu, Yan Shasha, Ren Pengbiao, Wang Wei, Wu Mingli, Li Guoguo

Abstract-- **This paper proposes a case of switching overvoltage unreported characteristics based on passing neutral section in high-speed railway. It shows that closing overvoltage is about 70kV, 6kHz and lasts around 2-3 cycles of working frequency, however, opening overvoltage is about 50kV, 3Hz and lasts less than 6 minutes when a train passing neutral section. Meanwhile, overvoltages during departing from neutral section will be larger than overvoltages during entering neutral section based on entire processes simulation for passing neutral section.**

The results characterize the switching overvoltage during passing neutral section.

***Keywords*: Switching Overvoltage, Passing Neutral Section, Entire Processes, Simulation, PSCAD/EMTDC, Transients.**

I. Introduction

The electric traction power is single-phase AC 25kV 50Hz in Chinese electric railways. The single-phase traction load causes unbalance in the voltage and current of public grids. According to EN60034-1, three-phase motors may be operated when voltage unbalance may not exceed 1% continuously or 1.5% for only a few minutes. For this reason, it is necessary to compensate the unbalance.

Cyclically changed connection of traction substations is applied, as shown in Figure 1. The three single-phase substations SS_1, SS_2 and SS_3 complement a cyclic connection to the public grid. Because the voltage phase difference at the secondary side of substations is 120° respectively, the phase separation sections are located between the substations, which can ensure that trains can move through different sections without bridging the adjacent phases.

The insulated overlap is one of types of the phase separation, mainly applied in high-speed lines. The structure diagram of insulated overlaps is illustrated in Figure 2.

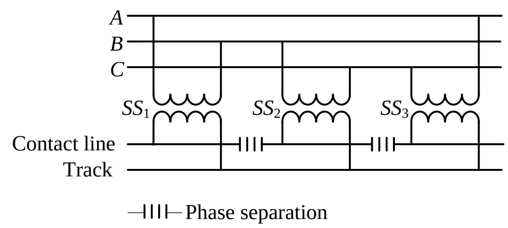

Fig. 1. Cyclically changed connection of traction substations

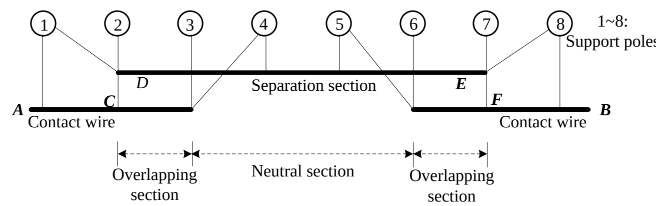

Fig. 2. Arrangement of seven-span insulated overlap

The insulated overlap is called air-gap section insulations and separates the two contact wires electrically. In Figure 2, because the separation section is not supplied with electric power and insulated by air gaps, a train shall move through contact wire A, separation section and contact wire B successively without bridging phases A and B. Poles shall support contact wires and the separation section. One-span is described as between two poles. Regions between poles No. 2 and 3, No.6 and 7 are called overlapping sections, which means that the separation section is parallel located with contact wires in these areas, consequently, it is electrified by connection to contact wires through pantographs above a train. During the neutral section, pantographs are not connected to contact wires, and the separation section operates without power supplied.

We describe the processes of trains moving through phase separation sections as passing neutral section, which includes entering and departing from phase separation sections. The separation section is electrified or not during a train passing neutral section, consequently passing neutral section will lead to electro-magnetic transients. Because the interval of adjacent two separation sections is 20-50km, a train with speed of 250km/h has to pass neutral sections every 5-12 minutes. That means electro-magnetic transients are main characteristics during passing neutral sections, which behaves like stable transients.

Stagger locations of contact wires and separation sections

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on straight tracks are not taken into account in order to explain the electric process clearly in Figure 2.

On-board passing neutral section is one of types of passing neutral section, which is mainly applied in most of high-speed lines in China. On-board passing neutral section includes a set of controller that shall deliver orders to control the operation of a train while passing neutral section.

On-board passing neutral section will lead to overvoltages and accidents of contact wire failure as the result of transients [1~9]. Simulation and corresponding theoretical analysis are mainly based on entering neutral section or departing from neutral section respectively [1]. Characteristics of overvoltages are studied by tests measurement results from the field [1, 3, 4]. Reference [5] analyzed mechanism of closing overvoltage based on locomotive SS7 mainly. Reference [6] computed residual voltage of neutral section. Reference [7] analyzed closing overvoltage. All previous references have not proposed low-frequency characteristics of opening overvoltage during passing neutral section. Reference [8] showed us low-frequency phenomena during passing neutral section with no investigation on the reason.

In this paper, the reason why opening overvoltage is low-frequency during passing neutral section in electric railways is proposed by simplified circuit analysis. Meanwhile we explain why overvoltage during departing from neutral section is higher than overvoltage during entering neutral section with initial values theory. Without entire processes analysis of passing neutral section, the results will not be obtained.

Arcs are not considered in this paper.

II. Model for Overvoltage in On-board Passing Neutral Section

The repetition electrification of the separation section will lead to overvoltages during passing neutral sections in Figure 2. We model a closed switch to simulate the process of the separation section being electrified when a train moves from poles No. 2 to No.3 and from No.6 to No.7. The corresponding overvoltage is determined as closing overvoltage during passing neutral section. Similarly, we model an opened switch to simulate the process of the separation section not being electrified when a train moves from poles No. 3 to No.6. The corresponding overvoltage is determined as opening overvoltage during passing neutral section. Figure 3 shows the electric equivalent circuit of overvoltages during passing neutral section of Figure 2.

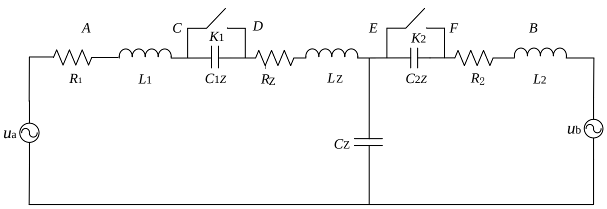

Fig. 3 Electric equivalent circuit of Figure 2

In Figure 3, K_1 and K_2 represent entering and departing from phase separation sections respectively. The two states of each switch describe the two operations of the phase separation section: electrification or not. R_1 and L_1 model the resistance and inductance of phase A contact wire respectively. R_z, L_z and C_z describe the resistance, inductance and capacitance of the separation section respectively. Similarly, R_2 and L_2 model the resistance and inductance of phase B contact wire respectively. The capacitances C_{1z} and C_{2z} describe the air gap between contact wires and separation sections.

We assume a train moves from traction substation A to traction substation B with the speed of 250km/h. Point A means phase A contact wire, points C, D, E, F are located in overlapping section, point B means phase B contact wire.

A. *Closing Overvoltage*

When a train moves from contact wire A to the separation section, the switch K_1 is closed. During the process, closing overvoltage will be generated as the result of changes of topology and parameters in the circuit.

A highly simplified circuit is applied for the purpose of theoretical qualitative analysis, as shown in Figure 4.

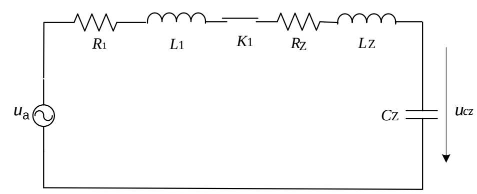

Fig. 4 Closing overvoltage equivalent circuit

The model of the train, the capacitance between contact wire and separation section and impact of phase B on phase A are all ignored in Figure 4. For this reason, the equations describing closing overvoltage can be proposed as shown:

$$LC_Z \frac{d^2u_{C_Z}}{dt^2} + RC_Z \frac{du_{C_Z}}{dt} + u_{C_Z} = u_{\mathrm{a}} \tag{1}$$

With

$$L = L_1 + L_Z \qquad R = R_1 + R_Z \qquad u_a = U_{\mathrm{m}} \sin(\omega t + \phi) \tag{2}$$

The eigenvalues are p_1 and p_2.

$$p_{1,2} = -\alpha \pm j\omega_{\mathrm{d}} \tag{3}$$

With

$$\alpha = \frac{R}{2L}, \omega_{\mathrm{d}}^2 = \frac{1}{LC_Z} - (\frac{R}{2L})^2 \tag{4}$$

Adding the initial value, $U_{CZ}(0+) = U_{01}$

The solution has been proposed:

$$u_{CZ}(t) = \frac{U_{\mathrm{m}} X_{C_z}}{|Z|} \sin(\omega t + \phi - \varphi - \frac{\pi}{2}) + \frac{U_{\mathrm{m}} e^{-\alpha t}}{|Z| \omega_{\mathrm{d}} C_{\mathrm{Z}}} \sin \omega_d t \sin(\phi - \varphi) + \left[\frac{U_{01}\omega_0}{\omega_{\mathrm{d}}} + \frac{U_{\mathrm{m}} X_{C_z}}{|Z| \sin\beta} \cos(\phi - \varphi) \right] e^{-\alpha t} \sin(\omega_{\mathrm{d}} t + \beta) \tag{5}$$

Where

$$\varphi = \arctan \frac{X_L - X_{C_z}}{R}, |Z| = \sqrt{(X_L - X_{C_z})^2 + R^2}$$
$$\omega_0 = \frac{1}{\sqrt{LC_Z}}, \beta = \arctan \frac{\omega_d}{\alpha} \tag{6}$$

B. *Opening Overvoltage*

When a train moves from overlapping section to neutral section, the switch K_1 is opened. During the process, opening overvoltage will be generated as the result of changes of topology and parameters in the circuit.

A very simplified circuit is applied for the purpose of theoretical qualitative analysis, as shown in Figure 5. The model of the capacitance between contact wire and separation section and impact of phase B on phase A are all neglected.

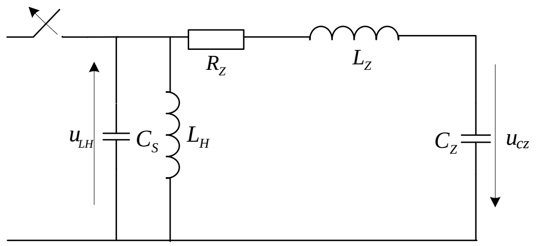

Fig. 5 Opening overvoltage equivalent circuit

C_S and L_H represent pantograph capacitance and potentical transformer magnetizing incuctance respectively, which can be regarded as the model of a train. Power consumption of the train shall be brought to zero when entering the phase separation section , which can be explained in details in Figure 7. Because *Cs*,*Lz*, and *Rz* are very small, we neglect them in the following equations. Consequently, the equations describing opening overvoltage can be proposed as shown:

$$u_{C_Z}(t)+u_{L_H}(t)=0 \tag{7}$$

$$L_H C_Z \frac{d^2 u_{C_z}}{dt^2}+u_{C_z}(t)=0 \tag{8}$$

The eigenvalues are p_1 and p_2.

$$p_{1,2}=\pm j\frac{1}{\sqrt{L_H C_Z}} \tag{9}$$

Adding the initial values,

$$U_{CZ}(0+)=U_{02}, I(0+)=I_0 \tag{10}$$

The solution has been proposed:

$$u_{C_z}(t)=U_{02}\cos\frac{1}{\sqrt{L_H C_Z}}t-\frac{\sqrt{L_H C_Z}}{C_Z}I_0\sin\frac{1}{\sqrt{L_H C_Z}}t \tag{11}$$

III. PARAMETERS CALCULATION

The main parameters in the formula (1)~(11) are calculated as follows.

A. Phase Separation Section

$$C_Z=\frac{1}{1.8\times10^{10}\times\ln\frac{2h}{r_{eq}}}(F/m) \tag{12}$$

Equivalent resistant r_{eq} is dependent on the radius of contact wires and the mean distance between contact wires and catenary wires. The parameter, h, means the height of the separation section.

$$X_Z=0.1445\lg\frac{\sqrt{D_1D_2}}{r_{eq}}+\frac{0.0157}{2}=0.18(\Omega/km) \tag{13}$$

The parameter, X_Z, means the inductive reactance of the separation section. The parameters D_1 and D_2 represent the mean distances between contact wires and separation sections.

$$R_Z=\frac{\rho\cdot l}{S}=0.179\cdot l(\Omega) \tag{14}$$

The length of separation section, *l*, is 250m. Its unit is kilometers in the formula. Therefore, the capacitance, inductance and resistance of separation sections are 2.735e-9F, 1.43239e-4H and 0.04475 Ω .

B. Contact Wire

AT means the auto-transformer, which is one of the most important traction power supply systems. We apply AT network for the model of Phase A and B contact wires, whose structure is shown in Figure 6.

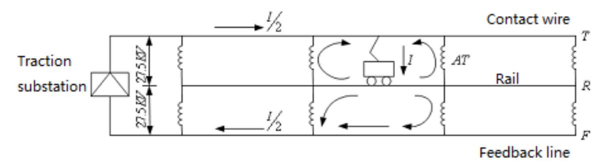

Fig. 6 AT network diagram

We obtain the equivalent parameters of contact wire through simulation measures. The resistances $R_{1,2}$ and inductances $L_{1,2}$ are 1.886757 Ω , 0.019385823H respectively.

C. Electric Multiple Units (EMU)

The electric connection diagram of EMU is shown in Figure 7.

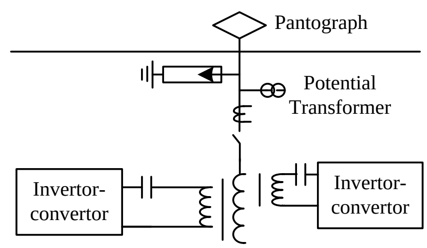

Fig. 7 Electric connection diagram of EMU

When the EMU is passing the neutral section, power consumption of the train shall be brought to zero. As a result, the pantograph and potential transformer are still connected with power supply system.

The capacitance of pantograph C_s and magnetizing inductance of potential transformer L_H are 3.61e-11F, 99472H[5].

D. Power Supply Voltage

The rated voltage of traction stations is 25kV (R.M.S.) and 50Hz working frequency, which is supplied to AT networks.

IV. ANALYSIS OF ENTIRE PROCESSES SIMULATION

Based on the previous models and parameters, we simulate the whole processes of on-board passing neutral section with program of PSCAD/EMTDC.

The whole processes are illustrated as Figure 8, which are divided into the two parts: 1) entering neutral section (from 0.1155s to 1.0155s) 2) departing from neutral section (from3.7155s to 4.6155s).

Figure 8 describes the voltage waveform of separation section when a train passed the neutral section. We can obtain the characteristics of overvoltages, frequency and magnitude, based on the waveform.

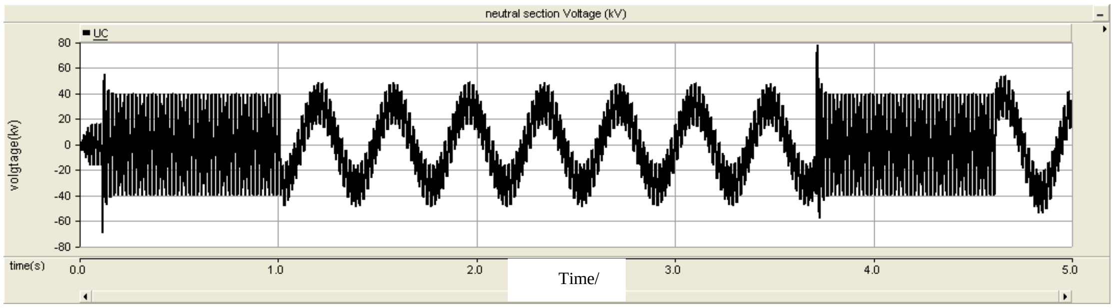

Fig. 8 Whole processes of passing neutral section

A. *Entering Neutral Section*

During the process, the switch K_1 is closed at t=0.1155s. The voltage of the separation section is shown in Figure 9, and the waveform in details is shown in Figure 10.

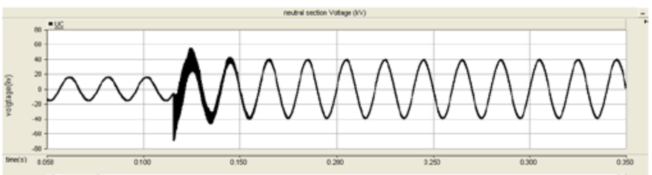

Fig. 9 Closing overvoltage Waveform

Fig. 10 Details of closing overvoltage waveform of Fig.9

When the switch is closed, overvoltage is about 70kV and 6kHz, and lasts 2-3 cycles of working frequency.

The switch K_1 is opened at t=1.0155s. The overvoltage is about 50kV and 3Hz, and lasts less than 6 minutes.

Consequently, the characteristics of closing overvoltage are different to that of opening overvoltage. The characteristics of closing overvoltage are higher amplitude, higher frequency, and stronger damping, because it lasts short time. The characteristics of opening overvoltage are smaller amplitude, very low frequency and weak damping, because it lasts long time.

We can explain the reason of higher frequency in closing overvoltage with formula 5. Based on the parameters in part III, the frequency of closing overvoltage, ω_d, is near 80kHz. Compared with 6kHz in Figure 10, the error is big, but this result can give us a quantitative concept for closing overvoltage frequency. We think the error will be smaller if we improve our equivalent circuit of Figure 4.

We can analyze the opening overvoltage with formula 11. The frequency of opening overvoltage, is near 1.21Hz. Compared with 3Hz in Figure 8 corresponding duration (1.0155s, 4.6155s), the error is not big. The result can give us a quantitative concept for opening overvoltage frequency.

We think the error will be smaller if we improve our equivalent circuit in Figure 5.

The test results from Lanxin fields [1,3] can be repeated based on our simulation system. And reference [1] showed us a low-frequency (around 8Hz) opening overvoltage waveform, but the author did not define it as the characteristics of opening voltage.

Therefore， the low-frequency performance of opening overvoltage during passing neutral section is not proposed in other papers.

B. *Departing from Neutral Section*

During the process, the switch K_2 is closed at t=3.7155s, and is opened at t=4.6155s.

The phenomena are similar to those in entering neutral section. The overvoltage of departing from neutral section is higher than entering it. That is the result of initial value. Based on Figure 8, the initial value of entering neutral section is around 16kV and the initial value of departing from neutral section is about 50kV, which leads to overvoltage of departing from neutral section is higher, shown in formula 5 and 11.

V. METHODS TO DECREASE OVERVOLTAGE

The RC absorption unit can decrease the switching overvoltage during passing neutral section [1~8].

We let $R=100\Omega$ and $C=0.42\mu F$ in the absorption branch, which is located in the separation section, the simulation result is shown in Figure 11. The overvoltage is decreased below to 50kV.

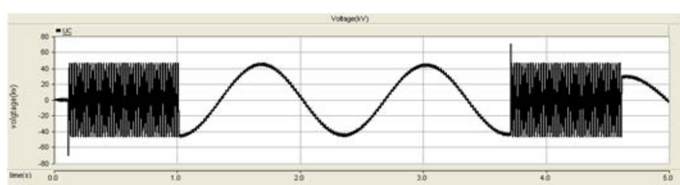

Fig. 11 RC absorption unit decreasing overvoltage

In Figure 11, details of the voltage waveform are ignored. We are focus on the decreased voltage amplitude.

VI. CONCLUSIONS

Our analysis and simulation results show that:

1. Passing neutral section will lead to switching overvoltage. Overvoltages of departing from neutral section are larger than that of entering neutral section.

2. Closing overvoltage during trains passing neutral section

has properties of higher amplitude, higher frequency, and stronger damping, based on our AT network.

3. Opening overvoltage during trains passing neutral section has properties of smaller amplitude, very low frequency and weak damping, based on our AT network.

4. Experiments in field trials confirmed the results.

5. Simulation step will influent the results.

VII. ACKNOWLEDGMENT

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