Influence Study on Electric Vehicle-traction Network System Considering Pantograph Arcing

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Abstract. This article analyzes the influence of pantograph arcing phenomenon on the electrical quantity which is related equipment of traction power supply system. The Mayer arc model was improved by taking into account arc dissipation power, arc diameter, transverse blowing arc and so on, based on this, modeling was performed, the traction power supply system such as AT double-wire traction network model and CRH3 EMU load model was described mathematically later on, and simulation analysis was ultimately achieved using MATLAB/Simulink software. The study results show that the pantograph arcing phenomenon causes the harmonic components that are the voltage and current of the traction network to increase, at the same time, making the performance indexes of the DC-side voltage of the CRH3 EMU rectifier to change.

Introduction

For the electrified railway traction power supply system, the pantograph-catenary relationship acts an extremely important role in the normal operation of the entire high-speed electrified railway system, and the core problem in the pantograph-network relationship is the pantograph arcing [1, 2]. With the rapid development of high-speed railways, the speed of trains continues to increase, and the interaction between pantographs and catenaries has become increasingly fierce. In practice, pantograph arcing has frequently occurred [3]. These random, time-varying and non-linear off-line arcs bring about electrical quantities changes such as voltage and current. The abnormal electrical quantities often contain DC components and a large number of harmonics and inter-harmonics components, these components propagate on high-speed trains, affecting the train's related electrical equipment.

At present, there have been many researches on the pantograph arcing phenomenon in China and overseas. In the literature [4], a pantograph-catenary arc and main vehicle electrical equipment models were established, a simplified traction power supply system model was built, and the overvoltage levels under different off-line modes were simulated and analyzed, studying the off-line time, locomotive running speed and traction currents had an effect on the off-line over-voltage of the pantograph-catenary. In the literature [5], by establishing and introducing the finite element pantograph interaction model to establish the relationship between the maximum off-line spacing of the pantograph-catenary and the vehicle speed, a mathematical model of Habedank arc that considered the train speed and was suitable for the relative motion characteristics of the pantograph-catenary was established. In the literature [6, 7], the effects of vehicle body surge overvoltage in the rising and dropping pantograph, methods of vehicle body grounding, roof transformer, and influence of action instantaneous voltage phase on its amplitude were studied. In the literature [8], Mayer's arc model was improved, an arc model suitable for series faults was proposed, model parameters of the arc were enriched, and the entire process of arc generation was fully reflected. In the literature [9], by using improved Mayer model, pantograph arc current was analyzed by Fourier and it was found that pantograph-catenary arc produced a large range of harmonic components. In the literature [10], on the serious problem of the arcing of the CRH2 Electric Multiple Unit (EMU) in the process of rising and dropping pantograph, the field test of the pantograph lifting and rising and dropping pantograph of the EMU was carried out, which reduced the pantograph-catenary arc
harm and provided service performance of pantograph-catenary. So far, the researches on the pantograph arcing phenomenon focus on experiments, arc electromagnetic interference and other aspects. The effects of pantograph arcing on the electric quantities of the vehicle body and the interior of the vehicle are mainly based on the single high-voltage equipment or low-voltage components of the train. At the system level, there are less research on assessing the amount of electric quantities on the pantograph arcing.

In order to evaluate the degree of influence of pantograph arcing on the traction power supply system from the system level, a comprehensive analysis of arc and vehicle network system need to be carried out. For this reason, the paper firstly makes use of arc dissipation power and arc diameter to improve the Mayer arc model. Then in Section II mathematically describe the load of AT double-line traction network and the CRH3 EMU load to complete the modeling of the locomotive-network system. In Section III, the impact of pantograph arcing on the vehicle-system is obtained, that is, the CRH3 type EMU rectifier performance indexes and traction network voltage, current harmonic components.

Pantograph Arcing Modeling

Improved Mayer Arc Modeling

The unimproved Mayer arc model assumes that the arc diameter is constant, the heat loss of the arc only occurs at the periphery of the arc column, the arc heat dissipation is a constant, the energy dissipation depends on the heat conduction and radial diffusion; Improved the Mayer Arc, assuming that the diameter of the arc column is a variable, it varies with the arc current and the arc velocity, and the case of long arcs is only studied, that is, the arc voltage is equal to the voltage drop of the arc column, and convective heat plays an important role in the pantograph arcing, especially with transverse blowing arc dominated, which accounts for a large part of the dissipation power by the arc column. Therefore, the dissipation of arc column energy just considers convection. The specific derivation is as follows.

The equation for the Mayer arc model is

$$\frac{1}{g_s} \frac{d}{dt} (g_s) = \frac{1}{\theta} \left( u_i i - P_{\text{loss}} \right)$$

(1)

Wherein, \( \theta \) is the time constant of the dynamic arc model, that is, the required time which energy change in the arc gap makes the arc gap conductance change by 2.73 times. In the formula, \( g_s \) is the arc conductance, \( u_i \) is the arc voltage, \( i \) is the arc current, and \( P_{\text{loss}} \) is the arc dissipation power. Conducted power, convection power, and radiated power are components of the arc energy dissipation power and they exist in the following relationship.

$$P_{\text{loss}} = P_t + P_c + P_s$$

(2)

It is known from reference [11] that the radiated power generally occupies about 10% of the total power. The vertical or transverse blowing of the arc is convection heat dissipation on the whole, so the conduction dissipation can be completely ignored. Equation (2) is simplified as.

$$P_{\text{loss}} = P_c + P_s = P_c + 10\% P_{\text{loss}}$$

(3)

In the pantograph arcing, the direction of the arc column is perpendicular to the vehicle movement direction, the effect of longitudinal blowing arc on pantograph arcing is much smaller than that of transverse blowing arc, the effect of transverse arc blowing on the arc characteristics is considered exclusively. The transverse arc of the arc is the movement of the arc relative to the air at speed \( v \), supposing that the diameter of the arc is \( d \), the air volume of per unit time passing through per unit length about arc is equal to \( vd \), Its air is heated from the temperature \( T_0 \) to the arc average temperature \( T_e \), the heat of required unit length is
In equation (4): $c$ is the heat capacity coefficient of the gas, the air is under an atmospheric pressure $P = 1$, and the relationship between the heat capacity coefficient $c$ and the temperature $T$ is

$$c \approx k_4 \frac{T}{T}$$

(5)

Wherein, $k_4$ is constant.

Then obtain the following formula,

$$\int_{T_0}^{T_e} c dT = \int_{T_0}^{T_e} k_4 \frac{dT}{T} = k_4 \ln \frac{T}{T_0}$$

(6)

Get the formula further,

$$P_k = k_4 dv ln \frac{T}{T_0}$$

(7)

$P_k$ is proportional to the speed $v$, but owing to the vortex movement, the arc average speed is lower than the actual speed of its movement. The $P_k = f(v)$ equation that is obtained from the experiment is

$$P_k = k_5 (v + 10)^{0.5}$$

(8)

In equation (8), $k_5$ is a constant, taking into account the actual situation of the pantograph arcing dissipation power dissipation, $k_5$ is taken as 10 in the simulation.

In transverse blowing arc, the arc diameter is a function which is connected to the arc current and the arc velocity, the expression is as follows.

$$d = 0.81 \sqrt{\frac{I}{v + 10}}$$

(9)

Bringing (9) formula into (8) formula obtains,

$$P_k = 0.81 k_5 \sqrt{I(v + 10)}$$

(10)

In equation (10): The unit of $P_k$ is $\text{W/cm}$, and the unit of $v$ is $\text{m/s}$.

Substituting (10) formula into (3) formula obtains,

$$P_{loss} = 0.9 k_5 \sqrt{I(v + 10)}$$

(11)

The arc time constant $\theta$ is calculated according to the following formula

$$\theta = \frac{a I}{d}$$

(12)

Substituting (9) formula into (12) formula obtains

$$\theta = \frac{a}{0.81} \sqrt{\frac{I}{v + 10}}$$

(13)

Among them, the unit of $\theta$ is $\text{s}$, $a$ is the proportional coefficient, its value is $2.85 \times 10^{-5}$, $I$ is the arc current.

The maximum operating speed of the CRH3 EMU used in the thesis is 300km/h. Therefore, the operating speed of the vehicle is chosen as 100km/h, 200km/h, 300km/h. Take the current as 100A, the arc dissipation power and arc time constant of the pantograph arcing igniting arcing phase are shown in Table I.
Table 1. Effect of vehicle speed on arc time constant and arc dissipation power.

<table>
<thead>
<tr>
<th>Vehicle speed V(km/h)</th>
<th>Time constant $\theta$(ms)</th>
<th>Dissipation power $P$(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>3.06</td>
<td>8945</td>
</tr>
<tr>
<td>200</td>
<td>4.03</td>
<td>11766</td>
</tr>
<tr>
<td>300</td>
<td>4.81</td>
<td>14017</td>
</tr>
</tbody>
</table>

Traction Power Supply System Modeling

Traction network is an important part of the high-speed railway traction power supply system, achieving the traction power supply to the electric locomotive (EMU). In the engineering calculation, the traction network demands to be modeled separately on the basis of different situations, generally, the method of simplifying the equivalent circuit is adopted, but the accuracy is not high [12]. This paper establishes a unified traction network mathematical model of traction power supply system and adopts a multi-conductor transmission line model, not only maintains the spatial distribution characteristics of the traction network, but also improves the accuracy of the traction network model. The CRH3 EMU is the most typical high-speed vehicle in China. Therefore, the CRH3 EMU is selected as load model, provide a model basis for the study of the impact of pantograph arcing on the vehicle network system.

AT Double-line Traction Network Modeling

The traction substation of the high-speed railway is connected to 220kV power supply of the power system, and is reduced to 55kV by the Scott transformer to provide power for the traction network, eventually providing a relatively stable voltage for high-speed vehicles [13]. Considering that the AT line is longer than the direct supply line, the 5km line package model is adopted in the modeling. Hereafter, having been established the simulation model of the AT double-line track traction network and the CRH3 EMU model is co-simulated, and the distance between the locomotive and the AT post is 5km. Fig. 1 is the schematic diagram that is the all-parallel power supply of the AT double-line, Table II shows the traction network parameters which is used to build the model.

Table 2. Traction network parameters.

<table>
<thead>
<tr>
<th>Route</th>
<th>$T_1$</th>
<th>$R_1$</th>
<th>$NF_1$</th>
<th>$T_2$</th>
<th>$R_2$</th>
<th>$NF_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_1$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
<td>0.01+</td>
<td>$\mu_{111}$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
</tr>
<tr>
<td>$R_1$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
</tr>
<tr>
<td>$NF_1$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
</tr>
<tr>
<td>$T_2$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
</tr>
<tr>
<td>$R_2$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
</tr>
<tr>
<td>$NF_2$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
<td>0.05+</td>
<td>$\mu_{111}$</td>
</tr>
</tbody>
</table>

Figure 1. Diagram of AT all-parallel supply power mode.
CRH3 EMU Load Modeling

At present, there are many researches on the control strategy of pulse-converters, mainly including DQ Current Decoupling Control, Hysteresis Current Control, Predictive Current Control, Transient current control, and Indirect current control [14]. However, traditional Transient Current Control is still used more control strategies in current electric locomotives and high-speed EMUs at present.

Transient Current Control was on the basis of improved Double-loop Control of voltage and current, combined with feed forward control, compared with the traditional double-loop control, it has the advantages of much faster dynamic response ability and less load to the controller [15]. The control principle is depicted in Fig. 2.

\[
\begin{align*}
    i_{f}(t) &= K_{p}(d_{refL} - d_{L}) + K_{i}\int(d_{refL} - d_{L})dt \\
    i_{f}(t) &= \frac{d_{f}}{d_{L}} \\
    i_{f}(t) &= i_{f} + i_{f0} \\
    i_{f} &= i_{f0} - \left[ \sqrt{2}\mu_{ref}\cos\omega t - \sqrt{2}\mu_{d} \sin\omega t \right] K_{p} \left[ \sqrt{2}\mu_{ref}\cos\omega t \right]
\end{align*}
\]

Figure 2. Transient current control schematic diagram.

The transient current control mathematical expression is as follows

\[
\begin{align*}
    i_{f}(t) &= K_{p}(d_{refL} - d_{L}) + K_{i}\int(d_{refL} - d_{L})dt \\
    i_{f}(t) &= \frac{d_{f}}{d_{L}} \\
    i_{f}(t) &= i_{f} + i_{f0} \\
    i_{f} &= i_{f0} - \left[ \sqrt{2}\mu_{ref}\cos\omega t - \sqrt{2}\mu_{d} \sin\omega t \right] K_{p} \left[ \sqrt{2}\mu_{ref}\cos\omega t \right]
\end{align*}
\]

The current reference value on the AC side of converter consists of two parts, \(i_{ref1}\) is output value of voltage outer loop. The PI controller adjusts the DC side voltage value \(u_{dc}\) so that it can stably track the voltage reference value \(u_{dref}\) and ensure a constant voltage output. \(i_{ref2}\) is the output value of load current feed forward control, for the purpose of guaranteeing system's rapid response performance, the load current feed forward control is introduced to reduce the pressure of voltage outer loop PI controller in the feedback control of voltage outer loop. The main parameters of vehicle can be used in the model are shown in Table III.

<table>
<thead>
<tr>
<th>parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWM equivalent gain, (K_{pem})</td>
<td>1</td>
</tr>
<tr>
<td>Current loop integral coefficient, (K_{i})</td>
<td>0</td>
</tr>
<tr>
<td>Current loop proportional coefficient, (K_{p})</td>
<td>10</td>
</tr>
<tr>
<td>Voltage loop integral coefficient, (K_{v})</td>
<td>20</td>
</tr>
<tr>
<td>Voltage loop proportional coefficient, (K_{v})</td>
<td>0.3</td>
</tr>
<tr>
<td>DC-link capacitance, (C_{d})</td>
<td>6mF</td>
</tr>
<tr>
<td>Equivalent load resistance, (R_{r})</td>
<td>10Ω</td>
</tr>
<tr>
<td>Second order resonant circuit capacitance, (C_{2})</td>
<td>3mF</td>
</tr>
<tr>
<td>Second order resonant circuit inductance, (L_{2})</td>
<td>0.84mH</td>
</tr>
<tr>
<td>Sampling delay time, (T_{s})</td>
<td>0.001s</td>
</tr>
</tbody>
</table>
Simulation Tests

Pantograph Arcing $u-i$ Characteristics

The arc model was incorporated into the vehicle network system for simulation. The locomotive operating speeds are taken as 100km/h, 200km/h and 300km/h respectively, and the influence of the train running speed on the arc voltage is analyzed. The simulation waveform is shown in Fig. 3.

![Figure 3. Arc voltage simulation waveforms at different speeds.](image)

Can be seen from Fig. 3, with the increase of the vehicle speed, arc peak voltage and extinction peak voltage of the arc both increase continuously. According to the theory of arc gap energy balance, it can be seen that large amount of energy dissipation will cause the arc temperature to drop, the arc gap resistance to increase, and the arc re-striking will become more difficult, so the corresponding arc peak voltage will increase. The increase in the power dissipation of the arc causes the thermal inertia of the electrode and arc column gas to decrease, the corresponding arc extinction arc peak voltage increases.

![Figure 4. $u-i$ characteristic curve of pantograph arcing.](image)

The $u-i$ characteristic curve of arc is composed of two parts, namely a voltage curve and a current curve. The arc voltage is small before the current passes through zero, and the current changes with sine. When the current is over zero, the arc gap voltage rises from the arc voltage which before the current crosses zero to the supply voltage. As shown in Fig. 4. The simulation curve of the arc $u-i$ characteristic in Fig. 4 is compared with that of the literature [16]. The curve direction is basically the same. Therefore, the modified Mayer arc model and its set parameters are suitable for describing pantograph arcing phenomenon.

The Electrical Quantities of EMU Influence Analysis

Fig. 5 shows the DC-side output voltage and current waveforms that the dual four-quadrant pulse rectifier of the CRH3 EMU after simulation. Fig. 6 shows the voltage and current waveforms of the DC side which is simulated when the arc is incorporated into the vehicle network system and the arc action time is 1-2. In Fig. 5 and Fig. 6, $u_i$ is the input voltage and $i_i$ is the input current of rectifier, and $u_d$ is the DC side voltage of rectifier.

![Figure 5. Waveforms of single locomotive.](image)
From Fig. 5 and Fig. 6, it can be obtained that the DC side voltage performance indexes of dual pulse rectifier are shown in Table IV and Table V.

Table 4. The dc side voltage performance indexes of dual pulse rectifier.

<table>
<thead>
<tr>
<th>Performance indexes</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overshoot (%)</td>
<td>33.8</td>
</tr>
<tr>
<td>Adjusting time (s)</td>
<td>0.17</td>
</tr>
<tr>
<td>Peak time (s)</td>
<td>0.0162</td>
</tr>
<tr>
<td>Voltage fluctuation (V)</td>
<td>±80</td>
</tr>
</tbody>
</table>

Table 5. The dc voltage performance indexes of dual pulse rectifier considering pantograph arcing.

<table>
<thead>
<tr>
<th>Performance indexes</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overshoot (%)</td>
<td>27.7</td>
</tr>
<tr>
<td>Adjusting time (s)</td>
<td>0.24</td>
</tr>
<tr>
<td>Peak time (s)</td>
<td>0.0463</td>
</tr>
<tr>
<td>Voltage fluctuation (V)</td>
<td>±70</td>
</tr>
</tbody>
</table>

From the data in Table IV and Table V, it can be concluded that overshoot and voltage fluctuation of DC side voltage of rectifier considering pantograph arcing are less than overshoot and fluctuation of DC side voltage without the arc. However, the adjusting time and peak time increase.

Traction Network Electrical Quantities Influence Analysis

Taking the fundamental frequency of the 50 Hz power grid as a reference analyzes harmonics by Fourier. Fig. 7(a) and Fig. 8(a) are the frequency domain diagrams of the traction network voltage and current. Fig. 7(b) and Fig. 8(b) are the traction network voltage and current frequency domain diagrams considering pantograph arcing.

The total harmonic distortions THD shown in Fig. 7(a) and Fig. 7(b) are respectively 0.09% and 2.47%. The distortion of the traction network voltage waveform considering pantograph arcing is more serious and the high harmonic content is more abundant, meanwhile, the DC component of Fig. 7(b) is larger, but even harmonic components decrease.

Figure 7. (a) Traction network voltage and (b) Traction network voltage considering pantograph arcing.

Compare the frequency domain spectra of Fig. 8(a) and Fig. 8(b), the direct current component of the traction network current frequency domain spectrum considering pantograph arcing is greater.
Odd harmonic components are also relatively larger. The total harmonic distortion of Fig. 8(a) is less than Fig. 8(b), which shows that distortion of the traction network current waveform considering pantograph arcing is more serious.

Conclusion

Through analysis of the improved Mayer arc model and traction power supply system model, the following conclusions are drawn.

1) The dissipation power of pantograph arcing increases, under the same conditions, with the increase of train running speed $v$, making arc peak voltage and extinction arc peak voltage of arc increase continuously.

2) The pantograph arc phenomenon causes the overshoot and voltage fluctuations of the CRH3 EMU rectifier to be reduced, but the adjusting time and peak time of rectifier become larger.

3) The pantograph arcing enlarges the harmonic component of the traction network voltage and current, meanwhile the DC component of the traction network current also increases significantly.

Acknowledgment

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