Research on Electronic Switch in Ground Automatic Passing Phase System

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Abstract. This article mainly designs a new type of ground automatic phase separation device. The electronic switch with thyristor as the component is used to replace the traditional vacuum switch to switch the two-phase voltage when the locomotive passes through the phase separation zone. The conversion time of the two-phase voltage is controlled from 10ms to 40ms by the new ground automatic phase passing device, which is a great improvement compared with the traditional mechanical switch of 300ms. It is verified through simulation experiments that the locomotive conversion time is reasonably shortened, and the overvoltage and impact are reduced when the electronic switch is closed and opened. The rationality and feasibility of the electronic switch are verified.

1. Introduction
My country’s electrified railways mainly adopt single-phase power frequency AC power supply[1]. In order to balance the three-phase load in the railway traction power supply, the railway power supply network adopts the method of commutation power supply. A neutral section is set between two adjacent phases, which is also commonly referred to as a no-powered area. In the existing ground automatic phase passing system, a vacuum circuit breaker is usually used to switch the electric phase splitting[2]. Vacuum circuit breakers mainly use mechanical switches. Because the mechanical switches operate for a long time, they will cause problems such as overvoltage and affect the reliability of the entire system[3]. At the moment when the mechanical switch is closed, over-voltage and over-current problems will occur due to the uncontrollable phase, which will affect the service life of the mechanical switch, and even affect the trip of the main circuit breaker of the locomotive, resulting in equipment damage and electric locomotives[4]. This method will cause serious locomotive speed loss, which does not meet the requirements of high-speed railways[5].

Therefore, in order to eliminate the effects of overvoltage and overcurrent caused by mechanical switches, we have adopted electronic switches instead of mechanical switches. According to the characteristics of the thyristor belonging to the zero-crossing shut-off current, the cut-off overvoltage of the opening can be eliminated, and the turn-on phase is controllable when closing, and the closing is in phase with the residual voltage on the neutral section[6].

2. The working principle of the electronic switch ground automatic phase separation system
As shown in Figure 1, QF is a vacuum load switch, QS is an isolating switch, and J is a position sensor. When the locomotive travels from feeder A to feeder B, QF1 and the electronic switch are closed when the locomotive enters the neutral zone from the left, and the neutral zone carries the voltage of phase A. When the locomotive enters the QF2 on the right side of QS2 and the electronic switch is closed, the
neutral zone has phase B voltage. When the train leaves the neutral zone, QF2 and the electronic switch are disconnected.

The switch-off of the entire over-phase system is controlled by the control system, no additional operations on the locomotive are required, and the switch is in an off state when no car passes, so automatic over-phase can be realized.

Figure 1 The structure diagram of the ground automatic phase passing system

3. Research on the Dead Time of Locomotive Switching under the Application of Electronic Switch

The power loss time of the electric locomotive in this equipment is mainly to detect whether the current of QF3 is zero after the corresponding sensor is disconnected from QF3. The sensor detects the current of QF3 to determine that QF3 is completely disconnected. After determining that QF3 is disconnected, set a proper phase angle to close QF4. The power-off time of the electric locomotive of this device is mainly the time from receiving the switching command to the current zero crossing plus the half cycle used by the software to confirm the QF3 disconnection margin plus the set QF4 closing phase angle. Three periods of time are used to determine the last power-off time of the locomotive.

According to the actual site, the railway traction transformer adopts the Vv traction transformer. According to the voltage difference between the two ends of the electrical phase separation zone is 60 degrees

\[
\begin{align*}
U_a &= 27.5 \sin(\omega t + \varphi) \quad kV \\
U_b &= 27.5 \sin(\omega t + \varphi + 60^\circ) \quad kV
\end{align*}
\]

3.1. Time study of transition from phase A to phase B

As shown in Figure 2, the voltages of Phase A and Phase B, and the current Ia flowing through the locomotive after the electronic switch is closed. Since the electronic switch is mainly composed of thyristors, according to the turn-off characteristics of the thyristor, the pulse signal of the turn-off voltage is actually at point 1 in the figure. In practice, the thyristor turns off because the current Ia rises at the zero-crossing point (point 2 in the figure). Before QF3 turns off, the current is negative, so QF4 should be closed when Ub is a positive voltage.

The conversion time is divided into two situations. When the phase angle of the current Ia lagging the voltage Ua is less than 60 degrees, QF4 is turned on at 3 points in the figure, and the dead time is 0~3.3ms. When the phase angle of the current Ia lagging the voltage Ua is greater than 60 degrees, the dead time of the same analysis is 13.3-20ms.

Combining the two situations, disconnect QF3 when Ua voltage rises at the zero crossing point, and close QF4 when Ub rises past the second zero point, the dead time should be 13.3ms~23.3ms.
3.2. Time study of the transformation from phase B to phase A.

Figure 3 shows the conversion process from phase B to phase A. Compared with phase A to phase B, the pulse signal is actually turned off at 1 point in Figure 3. Then the actual operating time of the switch is that the Ub voltage turns off QF4 during the rising phase of the zero-crossing point. Ib is zero at point 2 in the figure. Due to the current lag, QF3 is turned on at the rising point of the first voltage zero-crossing point of Ua (point 5 in the figure). So the dead time of the locomotive should be 6.6ms~16.6ms.

4. System equivalent model

4.1. This article mainly takes the electrified railway single-track traction network as a reference for modeling calculations[7].

The impedance per unit length of the "catenary-ground" loop:

$$Z_j = z_j + \frac{(z_1 - z_2)}{(z_1 - z_2) + (z_1 - z_0)} = 0.1559 + j0.5883 \Omega/km$$

$Z_j$ is the self-impedance per unit length of the "catenary-ground" loop; $Z_c$ is the self-impedance per unit length of the "stretch cable-ground" loop; $Z_{jc}$ is the mutual impedance per unit length between the "catenary-ground" circuit and the "support cable-ground" circuit.

Resistance per unit length of "rail-ground":

$$Z_r = \frac{R_g}{2} + 0.05 + j0.1446 \log \frac{D_g}{\sqrt{R_gd}}$$

$$= 0.118 + j0.553\Omega/km$$

$R_g$ is the rail resistivity; $R_e$ is the equivalent radius of the rail; $d$ is the distance between the rails; $D_g$ is the equivalent depth of the "rail-ground" loop.

The mutual impedance of the "contact wire-ground" circuit and the "rail-ground" circuit:

$$Z_{12} = 0.05 + j0.1446 \frac{D_g}{d_{12}} = 0.049 + j0.392\Omega/km$$

$d_{12}$ is the geometric average distance between the two circuits, and $d_{12}=1800$mm.

Two loop equivalent unit length impedance:
When the length of the neutral zone \( l = 0.35 \text{km} \), the equivalent impedance is
\[
Z'_{n} = Z_{n} \times l = 0.0499 + j0.11 \Omega
\]

Take the height of the neutral zone from the ground \( H = 6 \text{m} \), the length of the overlapping zone between the neutral section and the contact line is 100m, and the spacing \( Dz = 0.5 \text{m} \), and the vacuum dielectric constant is \( 8.85 \times 10^{-12} \text{F/m} \).

### 4.2. Train load modeling

The train load is mainly simplified into pantograph, voltage transformer, main circuit breaker, traction transformer, main converter, etc.

Capacitance of pantograph to ground
\[
C_{p} = \frac{1.13\varepsilon_{0}}{2} + \frac{1.222\varepsilon_{0}}{1.5} + \frac{0.846\varepsilon_{0}}{0.32} = 3.565 \times 10^{-11} \text{F}
\]

The distance between the high-voltage cable and the roof is 500mm, and the length \( l = 14.55 \text{m} \), then the high-voltage cable-to-ground capacitance is
\[
C_{c} = \frac{2\pi\varepsilon_{0}l}{\ln \left( \frac{2H}{\sqrt{l}} \right)} = 3.5665 \times 10^{-10} \text{F}
\]

The capacitance of the pantograph and the high voltage lead to ground is the sum of 2 capacitances to ground,
\[
C_{t} = C_{s} + C_{i} = 3.923 \times 10^{-10} \text{F}
\]

Excitation inductance of train traction transformer

The traction network voltage is 25kV, the secondary side voltage of the on-board traction transformer is 1.770kV, the secondary side no-load current is 4.21A, and the transformer no-load loss is 855W, the excitation impedance parameters are as follows:
\[
\begin{align*}
Z_{m} &= \frac{U_{m}}{I_{m}} = 420.43 \Omega \\
R_{m} &= \frac{E}{I_{m}} = 48.24 \Omega \\
R_{n} &= \frac{R_{m}}{U_{m}} \left( \frac{U_{m}}{I_{m}} \right) = 9623.67 \Omega
\end{align*}
\]

Equivalent inductance:
\[
X_{s} = \sqrt{Z_{m}^{2} - R_{m}^{2}} \left( \frac{U_{m}}{I_{m}} \right) = 8336.2 \text{H}
\]

Train equivalent impedance

If the traction power of the train is 5500kW and the power factor is 0.98, the equivalent impedance of the train is
\[
Z_{t} = \frac{\hat{U}}{J} = 125 \angle 11.5^\circ = 125 + j24.9 \Omega
\]

Set the transformation ratio of the high voltage voltage transformer to 25000/100, the rated capacity is 20VA, and the equivalent resistance=3000Ω. In the unsaturated state, the reactance of the high voltage voltage transformer is
\[
L_{0} = \frac{U_{0}^{2}}{2\pi fQ} = 99472 \text{H}
\]

### 5. Simulation

This design uses MATLAB/simulink for mathematical simulation verification. In order to verify the effectiveness of the entire electronic switch in the over-phase system, the following simulation system is constructed. Modeling through parameter calculations constructs the simulation circuit diagram shown below.
In the simulation experiment, the phase angle of the closed QF4 is adjusted and the voltage value of the neutral zone is measured, and the neutral zone voltage at the time of closing is related to the phase angle of the closing phase voltage. As shown in Figure 5 below.

It can be seen from Fig. 5 that there will be overvoltage generated at about 90 degrees and 250 degrees, and there is almost no overvoltage generated at 160 degrees and 330 degrees.

During the over-phase operation, the electronic switch composed of the thyristor valve group can accurately control the phase angle when closing, which can well suppress the generation of overvoltage.

Under the premise of ensuring that there is no overvoltage in the neutral zone, after determining the appropriate closing phase angle and measuring the voltage waveform of the neutral zone when the train passes through the neutral zone, as shown in Figure 6.
Figure 6 shows the current of the locomotive load during the corresponding time. When the train travels to the neutral zone, the valve group QF3 is turned on to supply current to the locomotive, and after a short period of time, QF4 is turned on to supply current to the locomotive. It can be observed from Fig. 6 that the lost point time of the locomotive is 20ms, which meets the design requirements within 30ms of the design requirements.

6. Conclusion
This article introduces the application of electronic switches on the ground in over-phase separation. Several conclusions can be drawn through simulation analysis[8]. By controlling the phase angle when the thyristor is closed, the overvoltage can be effectively suppressed. Explain the feasibility of the electronic switch in the new type of ground automatic phase passing.

At the same time, it is also verified that the power-off time of the locomotive has been greatly shortened by using electronic switches instead of vacuum circuit breakers. Verify the rationality of the program

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