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The Analysis of Electric Phase Separation and Common Technical Issues of High-speed Railway System in China

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Abstract:

The electric railway, as a vital economic transportation artery, offers high efficiency and effectiveness compared to other modes of transportation. The characteristics of efficient transport, comfortable ride and environmental friendliness have effectively driven regional economic construction and industrial economy along the route, which has significantly enhanced cultural and economic exchanges between different regions, becomes the preferred mode of transportation for medium-distance and long-distance travel, and plays an irreplaceable role in China's current transportation system. Under the increasing demand for passenger flow, the high-speed and high-density tracking operation of trains has become the new normal of high-speed railway operation management. In the background of national science and technology innovation development strategy, how to further shorten the train tracking interval to improve transportation efficiency and further reduce the energy consumption of train operation to improve the energy utilization level of the railway industry is the focus of the current electric railway construction and operation management department. The electric phase separation is a special and intricate part of the traction power supply system in China's electric railway, and it is an indispensable component. The article describes that some main techniques relating to electrical phase separation are utilized extensively in China's high-speed railway, by studying the technologies of electric phase separation, a few new methods were given and shared, which will solve the issues of high energy consumption, increased breakdowns, large equipment loss, and the lower speed, to better serve economic and social development and people's travel.

Keywords: Electric railway, Traction power supply System, Contact network, Electrical phase separation

1. Introduction

In the traction power supply system of high-speed railway, the traction substation and subdivision station are equipped with an electric phase division area. For a 150km/h train, an electrical phase must pass through every ten minutes [1]. With the maturity of the construction of the electrified railway in China, the train running speed is increasing, and the time for the electric locomotive to pass the electric phase separation becomes shorter. The structure of an electric phase separation device is complicated, the high-speed train frequently automatically over phase, and a series of complicated actions. Long-term use of electrical phase separation equipment, resulting in its short life, low reliability, and safety performance decline. Heavy-duty trains have a lower speed, and the speed of the trains usually needs to be reduced when the electric phase is divided, to extend the train running time.

In this article, the researcher focuses on the analysis of the electricity phase separation of high-speed rail from traction power supply system, researches the mechanism of the electric phase separation technique, to find out the reasons for the common technical issues, and goes a step further to acquire the method to solve the problems the technique faces now.

2. Traction Power Supply System and Electricity Phase Separation

2.1 Traction Power Supply System of Electrified Railway

The traction power supply system of high-speed railway refers to a power supply system that receives electric energy from the power system of the local distribution network, through voltage reduction commutation, provides the electric energy required for the electrified train through the transmission line network set up above the railway line, and completes the transmission and distribution of traction energy and other functions to provide traction power [2]. The performance of the traction power supply system of high-speed railways directly affects the utilization rate of traction power and the control ability of the traction transmission control system.

Traction power supply systems generally include traction substations, overhead contact lines and electrified trains [3]. The three-phase AC 110kv provided by the State Grid is transmitted to the traction substation of the railway and is reduced by the transformer device of the traction substation to become single-phase AC with a rated voltage of 27.5kV and a rated frequency of 50HZ, which is supplied to the overhead contact network of the electric locomotive. The pantograph takes electricity from the overhead contact system and transmits it to the electric locomotive. The traction current flows to the rail through the grounding of the locomotive and then returns to the traction substation through the return line. The traction power supply system [4] is shown in Fig. 1.

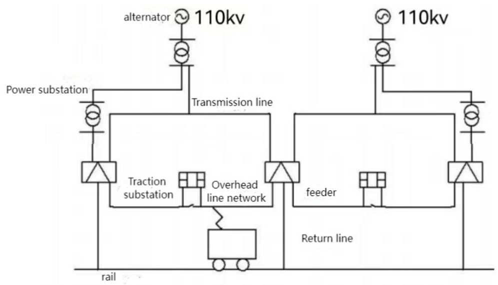

Fig. 1 Schematic diagram of traction power supply system

2.2 Electrical Phase Separation

The three-phase high-voltage alternating currents of the National Grid are converted into unidirectional alternating currents through the traction power supply system. However, the operation of the electric locomotive only uses one phase of the power supply system, while the other two phases are unloaded, which will lead to the reduction of the line power supply capacity, and the decline in the power supply efficiency will cause the imbalance of the three-phase power supply system in the incoming line, which will threaten the normal and stable operation of the local power system.

In the operation of electric locomotives in our country, a two-phase power supply system is used, and two phases are fed to the contact line of the locomotive in two different directions. To balance the load of three-phase AC, the phase commutation technology is adopted, and each section of the line is different from the two adjacent sections of the line, so the section needs to be insulated in an appropriate way to prevent out-of-phase short circuits. The electric railway is insulated by mechanical connection to prevent current from flowing into the different phases, and the structure that can achieve the above function is called electrical phase separation.

Alternating commutation technology, that is, each substation in turn to access the three-phase AC two items: UV phase, VW phase, WU phase, and then the next three substations immediately connect UV phase, VW phase, WU phase in order, starts a new commutation cycle. This two-to-two conversion can minimize the impact of the unbalance of the three-phase power system. At the same time, to avoid a short circuit between phases, the two phases should be separated.

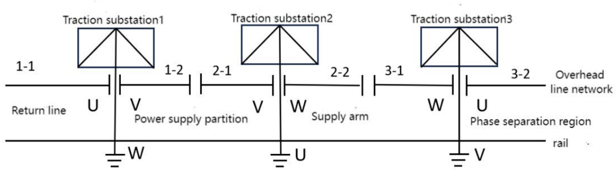

Fig. 2 Alternate commutation technology wiring

The technical connection of alternating commutation is shown in Fig. 2. Traction substations 1, 2, and 3 are respectively connected to the UV phase, VW phase and WU phase in the U, V, and W three-phase power system. The three traction substations complete a pin-two commutation cycle, and traction substation 4 starts a new round of commutation. Assuming that the traction load of the three traction substations is equal, it is theoretically a symmetrical load. In fact, due to the volatility, intermittency and randomness of the electrified railway load, even if the pair-two commutation phase is connected, the three-phase load cannot be completely symmetrical balanced, and the single-phase power supply load required by the electrified railway is large, which will inevitably produce negative sequence voltage and negative sequence current.

2.3 Electrical Phase Division Area

On the same driving line at both ends of the electrical phase division, the area between the „off" and „on" electrical signs in the same direction is called the phase division area. As shown in Fig. 3.

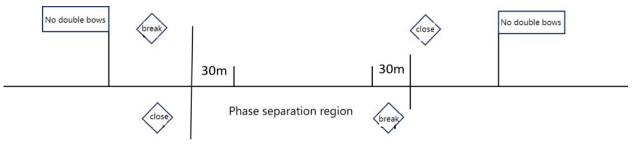

Fig. 3 Phase division

As shown in Fig. 4, the D1 interval is the no-current zone between the outer sides of the two insulated conversions post insulators near the centre of the neutral section. The D2 interval is the neutral section and is the distance between the inside of the two insulated transfer post insulators away from the centre of the neutral section. Due to the existence of the electrostatic effect, although there is no power supply in section D2, it is still in a state of power. That is, when there is no train passing through, section D2 will also have a relatively low voltage to the ground, rather than a real no power, which is called the neutral section [5].

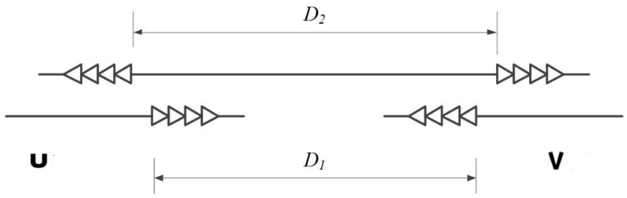

Fig. 4 No electric area, neutral segment

There's no electricity in the phase division, but when the pantograph hits the neutral section, from the moment of power to the moment of no power, the pantograph will generate an arc that could charge the neutral section. Therefore, the train must pass through a transition zone, when the voltage and current return to zero, to enter the no-power zone. Therefore, the existence of neutral segments is particularly important. The length of the neutral section is within a certain range, and if the distance is too long or too short, it will cause great harm to the safe running of the train. Therefore, the length of the neutral section is determined according to a variety of factors, such as power concentration or dispersion, number of hoisting bows, pantograph spacing, electrical connections between pantographs, and maximum operating speed, depending on the train formation [6].

2.4 Common Electrical Phase Separation Devices

In the over-phase area of traction electric locomotive, the power supply arm of different phases is equipped with an insulating device, namely electrical phase division, at the intersection of the contact line. In the electrified high-speed railway system, the following forms of electrical phase division are mainly adopted: anchor segment joint type electrical phase division and device type electrical phase division[7].

2.4.1 Device type electrical phase separation

On some low-speed lines, high-speed trains generally operate at speeds of no more than 80km/h. In this type of circuit, the device-type electrical phase is commonly used, which is generally divided into three components and four components. The non-electric zone in the electrical phase division is composed of an insulated rod with a length of about 30m.

The insulation method of the device-type electric phase separation device is physical insulation isolation, and there are hard points between the contact line and the insulation rod. The traditional device-type electrical phase separation is composed of three insulated rods, each of which is connected to the contact wire to form two joints. Each set of device-type electrical phases has six connectors, each of which produces a hard point on the contact network [8]. For example, an electrical phase is usually set up every 30-50km on a straight road, and about 10 electrical phases are set up for 140km of a heavy freight train. During the train, the pantograph crossed over about 60 hard points, causing the pantograph and the electric phase separation device to suffer many times of wear. The hard points of the pantograph cause accelerated wear of the contact wire, and also limit the maximum speed of high-speed trains. When the electric train passes through the device's electric phase separation, the speed is very fast, and the pantograph and several hard points will inevitably collision, and the serious impact will cause physical damage to the pantograph, resulting in the occurrence of the pantograph and power grid accidents.

Due to the impact of the hard point and pantograph and the very serious wear and tear, to reduce this type of loss, the speed of high-speed rail will be very strict limits. To make the train pass the electric phase division area safely and smoothly, it is necessary to carry out a series of operations such as lowering the bow. Due to the frequent and complex operation, arcing can occur between contacts, causing damage to the pantograph and possibly burning in severe cases.

To effectively solve the hard spot phenomenon of catenary, improve the relationship between pantograph and catenary, and reduce the limit of train running speed, the electrical phase separation of the catenary is transformed from device type to insulated anchor joint type.

2.4.2 Joint electrical phase separation of insulated anchor segment

With the increment of the requirements for train running speed and running status in the electrified railway, the device-type electric phase separation cannot meet the current design and operating conditions. In the process of the transformation and construction of the electrified railway, the Guangzhou-Shenzhen high-speed railway first adopts the anchor segment joint type electric phase separation, which improves the performance of the arch mesh contact and can increase the running speed to more than 200km/h. It has changed the current situation of using the device-type electric phase separation in our country for a long time and has extremely important significance for the development of railway electrification in our country [9].

The anchor segment of the insulated anchor segment joint is divided into sections of the catenary. The overlapping part between the two adjacent anchor segments is called the "anchor segment joint" [10], which has electrical and mechanical breaking effects. Such joints are called insulated anchor segment joints.

2.4.2 .1 Definition and structure of anchor segment joint electrical phase separation

The phase separation structure of the anchor segment joint is composed of two insulated segment joints and one neutral phase separation segment. The essence of the joint electrical phase separation is to embed one or two small length anchor segments between two completely independent anchor segments and realize the electrical phase separation through the air insulation gap of the insulation joint. It is formed by the combination of two to three insulating joints, and its physical structure can be divided into two fractures and three fractures [11], as shown in Fig. 5.

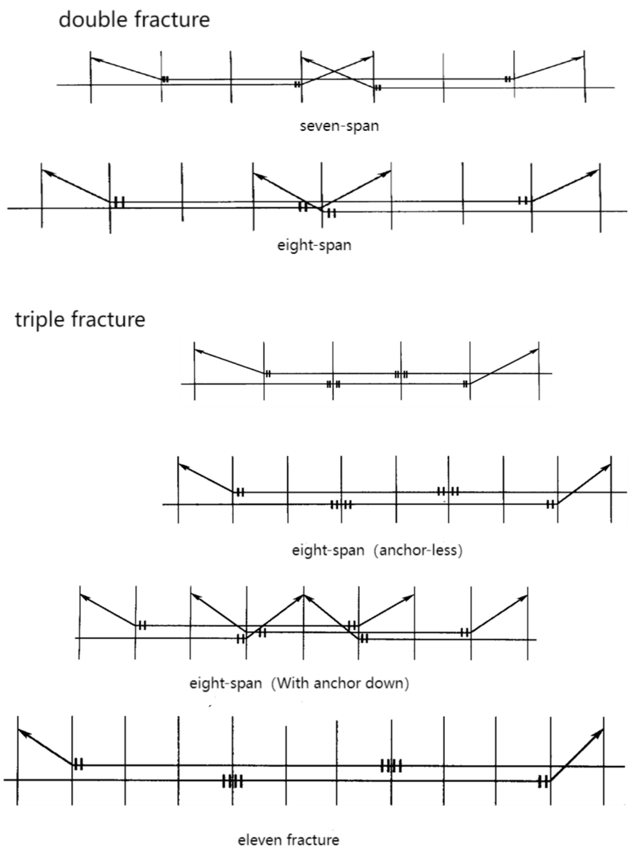

Fig. 5 Joint electrical phase separation structure of anchor segment

According to the length of the neutral segment and bow distance, the short segment can be divided into short segments and long segments. The short segment is a six-span articulated segment composed of two four-span insulated anchor segment joints, in which the neutral segment is less than 200m. The long phase separation is an 11-13 span electric phase separation composed of two insulated anchor joints and two to three span intermediate columns, of which the neutral segment is greater than 220m.

The anchored joint electrical phase division used in the contact line of electrified railway in China can be divided into seven-span, eight-span and nine-span. Guangzhou-Shenzhen Line catenary line uses a seven-span anchor segment joint electrical phase, the Hengguang Line catenary line uses an eight-span [12] anchor segment joint electrical phase, the Wuheng Line and Harbin Line catenary line uses a nine-span anchor segment joint electrical phase [13].

2.4.2 .2 Two-fracture electric phase separation technology

The following takes the widely used two-fracture seven-span joint electrical phase separation as an example to share the electrical phase separation technology.

The seven-span anchor joint electrical phase separation has seven spans, which is composed of two four-span anchor joints overlapping one span, and the air insulation gap of the anchor joint is used to achieve the phase separation effect.

As shown in Fig. 6, eight pillars from L1 to L8 are set up in the seven-span joint electric phase splitting structure. The main circuit breaker of the vehicle is disconnected before the electric train is over-current phase splitting, so that the pantograph does not drop through. The neutral section at the L2 pillar is 50 cm above the catenary. The neutral section of the L3 pillar is equal to the catenary and the parallel distance between them is 50 cm [14]. Here, the pantograph is connected to the neutral section and catenary at the same time. After the electric train passes through the L3 pillar, the neutral line of the L4 pillar is 50 cm lower than the catenary. In Fig. 6, the sections L2-L3 and L6-L7 are called “transition zones”, the electric train pantograph is simultaneously connected to the line and the neutral section, and the section L3-L6 is called “no power zone”. Since the neutral section is not charged, the insulation requirements are set according to the voltage level of 25 KV. Because of the parallel contact suspension at the joint of the anchor segment, there is no hard point between the bow mesh, and the electric train pantograph can be smoothly transferred, and the basic conditions for the operation of high-speed EMU trains can be met. Nowadays, the anchor joint electrical phase separation is the main form of high-speed railway in China.

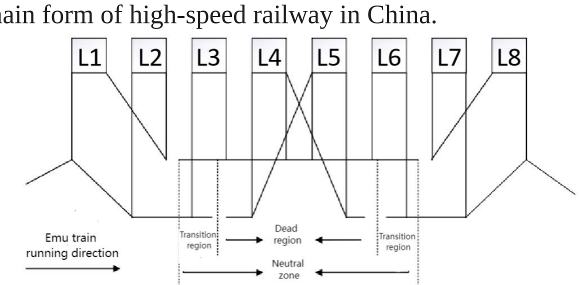

Fig. 6 Structure diagram of seven-span anchor segment joint electrical phase division

2.4.2 .3 Three-fracture electric phase separation technology

Because the three-phase articulated Catenary can meet the demand for double-train EMU, this technology is applied to double-train EMU.

The three-break anchor joint electric phase splitting can meet the needs of double EMU without high voltage bus connection with different double bow spacing and can meet the needs of multiple electric trains reconnecting and connecting the lifting bow. It can reduce the probability of inter-phase short circuit faults caused by human factors and equipment reasons. This technology can be popularized and used on mixed passenger and cargo transportation lines.

2.5 Setting of the Electrical Phase Division Area

With the rapid development of electrified railways in China, the train is going faster and faster. The length of the electric phase division zone is also set according to the different speeds of the train.

The speed of a high-speed railway taking into account freight transport can reach 200-250km/h. The electrical phase division of the overhead contact system adopts the short neutral phase division whose neutral section length is less than the distance between two working pentagrams, that is, the electrical phase division of a six-span anchor segment composed of two four-span insulated anchor segment joints, and the neutral section of the short neutral section is less than 200m.

The intercity speed of high-speed railway and EMU trains can reach 200-250km/h and 300-350km/h respectively, and it is appropriate to adopt the long no-power zone scheme, that is, the no-power zone is greater than the distance between two working pantographs, consisting of two insulated anchor joints plus two or three span intermediate columns, and the no-power zone distance should be greater than 220m.

For the special case that the CATenary electric phase division can only be located on a large ramp or near the exit of the station, the short neutral phase division scheme can be adopted, that is, the neutral section length is less than the double arch distance, and the six-span anchor joint is composed of two four-span anchor joints. It is stipulated that the CATenary electrical phase separation zone shall not be set in more than 6% of the ramp [15].

3. Electrified Railway Phasing Technology

The common over-phase modes of electrified railways in China are divided into manual over-phase and automatic over-phase, which are constructed according to the actual situation [16].

3.1 Manual through the Electrical Phase Separation

Manual through the electrical phase separation means that the driver manually completes the operation of the controller so that the train can smoothly and safely pass the electric phase division area.

The operation method of manually passing the electrical phase division: when the electric locomotive is near the electric phase division in the process of running, the visual “break” sign, the driver must first control the speed of the train, and cannot slow down when going uphill, and the control speed cannot be increased when going downhill. To the “off” sign, the driver controller speed control handle is pushed to the “0” level, the step-down operation, the traction load current becomes smaller, the auxiliary unit and the main circuit breaker are closed, relying on the train inertia through the electric phase, after the train reaches the “on” sign, the main circuit breaker and the auxiliary unit are closed, the driver manual controller speed control handle is advanced, the first 3,4 to 7, 8. And limit the current increase rate to avoid “flickering”. At the same time, when going downhill, the driver should also control the speed of the train to not exceed the maximum speed limit to ensure safe driving [17].

The success of this operation depends on the skill level of the driver and the indication of road signals. China’s electrified railway will have an electric phase separation every 25-30km. With the continuous improvement of the speed of high-speed railways, the frequency of the train passing through the electric phase has increased greatly. High-speed rail, for example, runs at an average speed of 150km/h and passes through an electrical phase every 10 minutes. Therefore, the manual way of overcharging the phase increases the work intensity of the driver, and the operator is easy to miss the “together” and “off” prompt signs. When the operator’s wrong operation, it will cause the train to be charged through the electric phase, which seriously affects the safe and stable operation of the traction power supply system. To match train speed with personnel operation, the development of automatic phasing technology is urgently needed.

3.2 Automatic through the Electrical Phase Separation

In the case of high-speed train operation, relying on the driver’s manual over-phase operation has serious safety problems, missing operation and error operation will cause arc burning and damage to the overhead contact line, and cause short circuits between the overhead contact lines in serious cases, which will cause major accidents. Therefore, automatic phasing technology must be adopted in the phase separation area of overhead contact lines during the operation of modern high-speed railways [18].

At present, the over-phase sensing devices of high-speed railways in China are generally divided into two kinds: ground sensing devices and automatic switching devices of on-board equipment.

3.2.1 Automatic switching device for vehicle equipment

The automatic switching device of on-board equipment consists of four ground sensors, the on-board ground sensing signal receiver at the bottom of the locomotive, the control system in the locomotive room and the signal indicating system in the driver's cab.

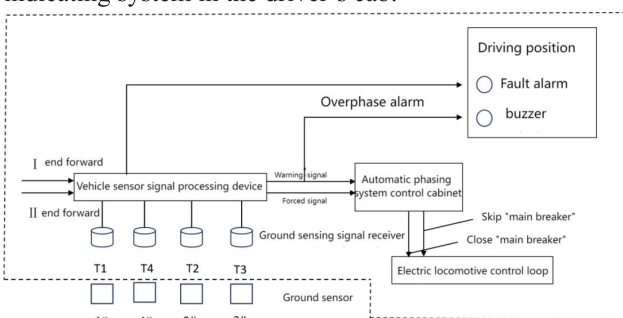

Fig. 7 Structure diagram of vehicle automatic phasing system

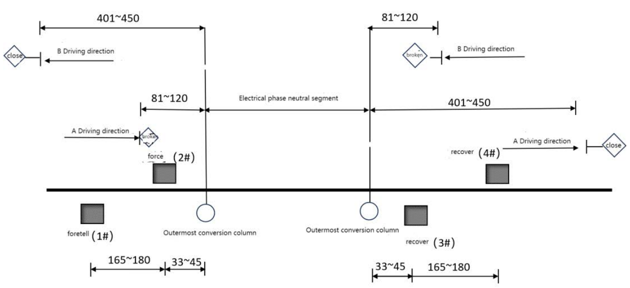

Fig. 8 Schematic diagram of ground switch layout

As shown in Fig. 7, the high-speed train is moving forward to the 1# ground sensor ground sensor. The onboard sensor signal processing device receives the ground sensor signal and the receiver senses the ground positioning signal in advance. The signal processing device sends a warning signal to the control cabinet, and the control cabinet controls the motor current of the train to drop steadily to 0 according to the speed of the train at this time. The control cabinet sends out the "main circuit breaker" command to the electric locomotive control circuit, which controls the locomotive split camera and main circuit breaker to enter the warning power failure mode. A buzzer at the driver's desk sounds for 3 seconds to alert the driver that they are passing through the phase division zone [19].

As shown in Fig. 8, when the ground sensor receives the signal normally, the 2# ground sensor signal does not work. When the ground sensor signal receiver receives the 3# ground sensor signal after the electric locomotive passes through the no-power area, the onboard sensor signal processing device processes the received closing ground positioning signal. The signal sends a "main circuit breaker" signal to the control cabinet of the automatic phasing system through the warning signal, and the buzzer located at the driver's station rings for 3 seconds to remind the driver that it has passed the electric phase division area. The control cabinet issues the "main circuit breaker" command to the electric locomotive control circuit, which controls the locomotive switch camera and the main circuit breaker. After the preparation, the control cabinet control motor current was slowly restored to the initial condition. When the 3# ground sensor receives the signal normally, the 4# ground sensor does not work [20].

When the 1# ground sensor fails, after the electric locomotive runs to the 2# ground sensor, the on-board induction signal processing device receives the forced ground positioning signal received by the induction receiver, the signal processing device sends a forced signal to the control cabinet, and the system control cabinet immediately reduces the motor current to 0. Send off the "main circuit breaker" signal to the electric locomotive control circuit to control the electric locomotive break camera, break the main circuit breaker, and enter the forced power failure mode.

In the reverse operation, compared with the forward operation, the 1#, 2#, 3# and 4# ground sensors correspond to 4#, 3#, 2# and 1# respectively.

4. Results and Discussion

4.1 Applicable Principles of Electrical Phase Separation Type

1. The electrical phase separation in the form of a two-fracture anchor joint with a neutral section is generally adopted in China's high-speed railway contact line. The phase separation process is carried out using the air insulation gap.

2. For the insulation network applicable to the freight train, the three-phase split structure is generally adopted, to adapt to the short-distance multi-bow combination caused by the traction locomotive connection, and better reduce the loss of the bow network [21].

3. For the section of the liaison line in the hub area, the anchor segment joint electrical phase separation is generally used, but when the railway construction and line reasons cannot be arranged, the device phase separation can be used instead [22].

4. For the mainline railway, when it is necessary to use the three-port structure or use the device type phase separation, it needs to go through the quality audit of the relevant department [23].

4.2 Precautions for Phase Separation Installation

To avoid short-circuits between phases caused by excessive phase of electric locomotive, the total length of the phase separation insulation area is not less than 30m, and the train must drop the bow when passing the phase separation insulator, so the word "close" and "break" sign should be set at 30m away from the phase separation insulator in the ascending and descending directions, and the sign "No double bow" should be set at 75m away from the phase separation insulator. For the line with a large slope, the conditions are not available, and the phase separation insulator is not installed [24].

The insulation component of the phase separation insulator is generally installed at 4.1 meters away from the pillar, and the effective length of the installation of the insulation component should be greater than 1.5 meters, and the body should be stable, the bottom should be smooth, and there should be no hard points [25].

4.3 Advantages and Disadvantages of Automatic On-board Equipment

In the process of high-speed railway construction in China, the automatic phase-over-phase scheme of on-board equipment has been widely used. This scheme simulates the process of manual phase over phase by the combination of an electric locomotive control system and ground signal through a series of signal reception and feedback. The construction cost and maintenance cost of the ground sensor are very small, and the running speed of the electric locomotive has little influence on the over-phase control system, which can meet the requirements of high-speed train operation. At the same time, it avoids the frequent operation of the train driver, reduces the influence of human factors in the over-phase, and improves the safety and reliability of the electric locomotive in the over-current phase separation.

However, the on-board equipment is automatically over-phase in use, which requires the length of the neutral zone, which will cause the running speed of the locomotive to be reduced, so it is still necessary to further improve this technology.

4.4 Solution of the Common Issues

To effectively solve these problems caused by the two-phase power supply in locomotive traction substations, according to the primary information, one way is to replace a more efficient insulating electrical phase separation device, although this method depends on investment in equipment renovation, which was confirmed by the technological advances. This method avoids the high energy consumption of the train, and the short life of the parts improves the running speed of heavy-load trains accordingly. Another way is to shorten the distance to a limited range, which is feasible and safe. Consequently, the time will be shortened when the train passes through the electrical phase separation area, so the speed of each type of train will be increased, and the new maximum train speed will be available.

5. Conclusion

At present, the Electric phase separation technique of the high-speed railway system in China is stable and feasible. With the rapid development of electrified railways in China. The train is going faster and faster, the relevant technology is continuously updating.

The power supply mode of electrified railway traction power supply system is mainly based on the heterogeneous power supply system. Due to the asymmetry of traction load, the increase of traction power of high-speed and heavy-duty trains also greatly reduces the power quality in the power supply system, which affects the normal operation of the substation. Meanwhile, in the process of dynamic running of the locomotive, the alterations in the system are intricate, and many random factors will affect the normal operation of the train when the locomotive is overpowered and divided into phases. For example, the phase angle of the voltage when entering the electric phase separation, the current returns to zero state, etc, the situation is very complicated in the actual train operation.

Two of the three-phase alternating currents of the State Grid are the origin of electric phase separation, which causes a series of common issues. Therefore, the same phase power supply device of the electrified railway solved a series of problems caused by the electric phase separation of the electrified railway, power supply device in the same direction has high stable performance and provided power quality, and the same phase system is reliable and safe.

The same-phase power supply has higher requirements and dependence on high-technology equipment, and the line environment must meet certain conditions, so the system is not popular. The development of the electrified railway in China needs to be further optimized.

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