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Design and Test of Anti-EMI for Rail Trains

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Abstract. With the continuous improvement of the intelligence level of the rail transit system, the installation density of electrical and electronic equipment in rail trains becomes larger and larger, which causes the increasingly prominent electromagnetic interference (EMI) problem among any equipment, systems and subsystems. This paper proposes an anti-EMI design scheme for rail trains, which improves the anti-EMI capability of the entire train system from four aspects, i.e. equipment grounding, filtering, shielding and wiring. By taking Shanghai Metro Lines 4 and 6 as an example, we carried out the system implementation and testing. The test results show that the proposed scheme is verified to be effective and reliable to improve the electromagnetic compatibility (EMC) performance.

1. Introduction

With the continuous improvement of the intelligence level of the rail transit system, the installation density of electrical and electronic equipment in the rail trains becomes larger and larger, which causes the increasingly prominent electromagnetic interference (EMI) problem among any equipment, systems and subsystems [1]. The interference signals generated by various devices are superimposed on each other, and make the electromagnetic environment in the rail trains quite worse, which may cause malfunction of train equipment, frequent failure of communication networks, network degradation operation, and damage to electronic components, etc. [2]. In order to make the whole rail train system work stably, it is necessary to design an efficient anti-EMI scheme when assembling the rail trains to improve the anti-EMI capability of the entire train system.

In this paper, we at first analyze the EMI generation mechanism, and based on this, propose the basic anti-EMI method. Then according to the corresponding national standards and engineering practices, we propose an efficient anti-EMI design scheme.

2. General Rules of Anti-EMI for Rail Trains

EMI have three elements, i.e. interference source, coupling path, and interfered object. There are two ways for interference sources to transfer electromagnetic energy to the interfered objects, i.e. conduction coupling and radiation coupling. Conduction coupling includes direct conduction coupling, common impedance coupling and transfer impedance coupling. Radiation coupling is divided into field/antenna-to-antenna coupling, field-to-cable coupling and cable-to-cable coupling [3].

To realize conduction coupling, there must be a complete circuit connection between an interference source and its interfered object, and the interference signal is transmitted to the sensitive equipment along this connection circuit, causing EMI phenomenon. Radiation coupling means that electromagnetic energy spreads through the medium in the form of radiation electromagnetic wave, and the interference signal is emitted to the surrounding space in the form of electromagnetic wave, thus affecting the interfered object. Therefore, there are mainly three basic anti-EMI methods, and the implementation of each basic anti-EMI method has several different technologies, as shown in table 1.

Table 1. Anti-electromagnetic interference technology.

Basic method	Specific technology
Eliminate the interference source or reduce the intensity of EMI that it outputs to the outside	Reasonable grounding, circuit filtering, and electromagnetic shielding
Destroy the path of interference propagation or reduce the interference coupling degree	Reasonable wiring, and electromagnetic shielding
Special protection against sensitive equipment to improve its resistance to EMI	Reasonable grounding, circuit filtering, and electromagnetic shielding

It can be seen from table 1 that there are four main technologies for anti-EMI: reasonable grounding, electromagnetic shielding, circuit filtering, and reasonable wiring. Designing a proper grounding, suitable shielding, appropriate filtering and reasonable wiring method for the characteristics of electrical and electronic equipment in a rail train can improve the anti-EMI capability of entire train system. They are introduced below.

2.1. Reasonable Grounding

As a system with relative motion to the ground, in order to better realize the current loop, train body and its interior subsystems should be grounded in a proper way under normal operating environment. Grounding is usually divided into protective grounding, working grounding and shielding grounding.

Protective grounding is the grounding of the exposed conductive parts of the equipment for the purpose of ensuring personal safety and preventing direct or indirect contact with electricity.

Working grounding is a necessary condition for the normal operation of the entire electrical system of a rail train. On the one hand, it provides a channel for discharging charge or establishing a reference voltage. On the other hand, in the process of electromagnetic compatibility (EMC) design, grounding can introduce noise voltage into the earth and reduce noise interference. Correct working grounding is one of the important ways to suppress electromagnetic noise and prevent EMI.

Shield grounding refers to the grounding of cable shield. A cable shield is a layer of shielded metal mesh wrapped around a protected wire. When the EMI signal occurs, a small part of the electromagnetic energy is converted into thermal energy through the internal eddy current loss of the shielding layer, and most of them are introduced into the earth through the grounding point of the shielding layer. Therefore, the cable shielding layer must be grounded to play the role of shielding.

2.2. Electromagnetic Shielding

Electromagnetic shielding refers to the isolation of two spatial regions by a shield in order to control the induction and radiation of an electric field, a magnetic field and electromagnetic waves in one region to another region. For both external and internal electromagnetic waves from wires, cables, components, circuits or systems, a suitable shield absorbs their energy by eddy current loss, reflected their energy by interfacial reflection of electromagnetic waves on the shield, and cancels their energy by a reverse electromagnetic field on the shielding layer generated by electromagnetic induction [4]. Therefore, the electromagnetic shielding body has the function of reducing interference.

A rail train vehicle is a system integrating high voltage, frequency conversion, network communication and computer control. Its interior adopts high power supply equipment with rich harmonics, such as AC drive system and semiconductor static inverter, a large number of microprocessors for real-time control and diagnosis of traction and braking systems, and the installed systems for vehicle signals, wireless communications and passenger information. In order to guarantee the normal operation of electrical equipment on the vehicle and avoid the interference with each other, effective electromagnetic shielding measures can be taken to enclose the interference source to prevent the electromagnetic field from propagating outward through the space, and the electromagnetic shielding technique is also used to encapsulate the sensitive objects and protect them from any external electromagnetic fields.

2.3. Circuit Filtering

The circuit filtering technology is the main means to suppress the EMI of electrical and electronic equipment, especially conducted interference. It is also an important measure to protect the overall or partial shielding effectiveness of equipment. Practice has shown that even a well-designed product with the correct shielding and grounding measures still has electromagnetic disturbances entering into the device through the cable. Filters can be used to filter out related disturbances. Their role is to greatly attenuate the non-working signals, i.e. EMI.

According to different viewpoints, many types of filters are classified as follows:

(1) Filters can be divided into absorption filters and reflection filters based on the filtering principle.

(2) Filters can be divided into active filters and passive filters according to their working conditions.

(3) Filters can be classified into low-pass, high-pass, band-pass, and band-stop filters according to their frequency characteristics.

(4) Depending on the application, filters can be classified into power supply filters, signal filters, control line filters, anti-electromagnetic pulse filters, etc.

2.4. Reasonable Wiring

Due to the particularity of rail trains, there are various levels of voltage cables in the train, such as DC 1500 V/750 V/110 V and AC 380 V/220 V. There may be capacitive coupling and inductive coupling between the cables in these different circuits and functional units. The capacitive coupling between the cables occurs when the cables are laid in parallel. Its coupling degree depends on the length of the cables laid in parallel, the distance between the cables, and the height of the cable from the ground. Inductive coupling occurs in the loop conductor, and the strength of its inductive interference depends mainly on the area of the loop conductor [5].

In the process of wiring for rail trains, its coupling mechanism is mostly non-conducting coupling, which includes three ways, i.e. electric field, magnetic field and mixed mode (i.e. electric field and magnetic field work together). From the actual situation of train wiring, the most effective way to suppress electric field coupling is to reduce the distributed capacitance between the wires as much as possible, and to use the shielding layer. Herein, reducing the distributed capacitance can be achieved by increasing the distance between the wires, shortening the length of the wires, or adding a ground plane under the conductor. The most effective way to suppress magnetic field coupling is to reduce the mutual inductance between the circuits and to use a shielding layer. Herein, reducing the mutual inductance between the loops can be achieved by widening the conductor spacing, shortening the length of the conductors, making the conductors as close to the ground plane as possible and making the magnetic field directions perpendicular to each other. The most effective way to suppress the mixed mode is shielding and good grounding.

3. Anti-EMI Design for Rail Trains

From the above four aspects, an anti-EMI design scheme is proposed. Different anti-EMI measures are adopted to improve the anti-EMI performance of the train vehicle for vehicle operating environment and the different EMC characteristics of vehicle system equipment.

3.1. Grounding

For rail trains, all cabinets, brackets, and assembly framework of on-board electronic control units need to be grounded. The following grounding design is proposed based on their characteristics:

(1) The brackets of electronic control units ground the assembly architecture through the possible large surface area to ensure low impedance, and if necessary, a toothed spring washer should be used.

(2) The assembly architecture should be connected to the vehicle framework by the possible large surface area and as many points as possible. If grounding is not possible by bolting or welding, an additional strap will be used to connect the assembly framework to the vehicle body.

(3) Doors, floors, screen cabinets, connectors, etc. should also form a highly interconnected, large-area grounding design to ensure continuity of electrical conduction.

(4) The surface treated by spraying, painting or anodizing should use the tooth-shape elastic pad to make it contact reliably.

(5) For an electrical device that may be charged in the event of a fault, any its conductive part shall be internally connected to the equipotential ground. For any electrically conductive component not belonging to the electrical equipment, it shall also be internally connected to the equipotential ground.

In addition, for all electronic control units, they are equipped with DC/DC converters with potential isolation. The reference potential of the battery should be connected to the grounding point of the chassis, and the reference potential of the electronic control unit should be connected to the assembly framework with low impedance and low inductance, and these connections should be as short and wide as possible.

3.2. Shielding

Four main parts of rail trains need to be shielded, as shown below:

3.2.1. Shielding design of train body

(1) Highly conductive materials (i.e. copper, aluminum and steel), or metal plating and conductive coatings should be selected as shielding materials.

(2) Minimize the electrical discontinuity of the structure in order to control the leakage radiation through the casing and cabinet.

(3) Vents are designed to use perforated metal plates, as long as the diameter of the holes is small enough to achieve the required shielding effectiveness. If the requirements for ventilation are high, the honeycomb panel must be used; otherwise the shielding and ventilation requirements cannot be balanced.

(4) Measures to improve the shielding effectiveness of the gap include increasing its depth, reducing its length, adding an electromagnetic sealing gasket on the joint surface, and applying a conductive coating on the joint.

(5) When lap jointing with screws or by riveting, ensure that the fastening method has sufficient pressure to minimize the distance between the screws so as to maintain good surface contact when there is deformation stress, impact and vibration.

(6) Shielded pipe joints are used at the entrance and exit holes of the box, and metal pipes or metal braided net sleeves are connected.

3.2.2. Shielding design of electronic control unit

(1) If the assembly structure or casing is used for shielding, they shall be composed of a conductive material, and all the outer casing members shall be connected with low impedance, low inductance, large area, and ensure continuity of electrical conduction.

(2) If there is equipment in the cabinet that generates strong interference radiation, shielding should be provided between these equipment and sensitive equipment. For example, using metal plates, these boards and assembly areas are supported for multi-point low-impedance connection.

(3) The power supply filters and signal filters should have a reference ground plane and be connected to the casing or assembly structure. The filters should be placed at the entrance of the circuit.

(4) Doors, covers, etc. should be electrically connected to the framework and its side at multiple points. The connection can be pulled at the hinge of the door, connected by fasteners at the cover, and there should be other contact faces at the edge of the door.

(5) Unshielded signal cables need to be shielded when entering into the shielded area or filtered at the entrance to the shielded area.

3.2.3. Shielding design of signal and data line

(1) Both ends of the shield of the signal and the data line are grounded, because only the shield with both ends grounded can provide effective shielding to the interference field, and the filtering technology is not suitable for the signal and data lines.

(2) The shielding layer should be in contact with the possible widest surface area, and the low impedance and low inductance should be guaranteed to be connected.

(3) The cable shielding layer should be directly connected to the casing entrance to prevent interference current from flowing into the interior of the casing through the shielding layer.

(4) If it is not possible to maintain a minimum space between conductors that cause considerable interference, and the conductors are kept parallel over long distances, particularly sensitive conductors, such as data buses, must be placed separately in a metal conduit, and connected to the vehicle ground.

3.2.4. Shielding design of motor equal power unit

(1) The electronic power device is placed in a closed metal box to achieve shielding. The ventilation hole should be a punching plate, a metal grid, etc., and the cover, the cover plate and the ventilation hole should be sealed together with the motor casing;

(2) All outlets of the motor casing shall be shielded, filtered or electrically isolated.

3.3. Filtering

On the rail train, a low-pass filter is generally used to filter its power supply, and a band-pass filter is used to filter its signal devices. In order to maximize the filtering efficiency, the following filter design is proposed:

(1) The filter should be placed directly at or near the shield entrance. The filter shell or filter reference ground is connected to the bracket, shielded sheath or cabinet with low impedance and inductance.

(2) The input and output wires should be arranged separately. If a bypass capacitor or bypass filter is used, it should be bolted to the shielding ground.

(3) The filter leakage current cannot flow to the internal reference potential, and should be connected to the shielding or vehicle ground through a low impedance and low inductance connection.

(4) If the assembly area is not a shielded area or the filter is outside the shield, the connection from the filter to the electronic devices should be shielded.

(5) If the filter is located in the shielded area, the wiring from the shield to the filter should be shielded. All battery-powered electronic control units should be equipped with suitable power filters.

3.4. Wiring

The motor wires, inverter wires and auxiliary equipment wires of the rail trains are particularly prone to generate the interference, while the signal lines, data transmission lines, antenna leads, and audio and video wires are particularly sensitive to field inductive coupling.

Table 2. Cable type.

Cable category	Cable model
A1	Power supply cable
A2	Motor cable, brake resistor cable, heating cable, grid side filter (converter side) cable, power supply cable of auxiliary equipment, starter cable of internal combustion engine, transformer and four quadrant inverter leads, auxiliary equipment leads, reactor leads on the side of the reverse transformer
B	110V battery lead, control cable, unshielded signal cable
C	Shielded cables such as data buses, signal transmission wires (e.g. PT100, speed sensors, etc.), antenna cables, speaker cables, audio and video transmission cables

The wiring should comply with the regulations on EMC in TB/T 3153—2007 [6]. In order to ensure that the rail vehicle cabling meets the standard requirements, the cables are divided into three categories, as shown in table 2.

Different types of cables should be routed separately. To ensure adequate decoupling, the minimum spacing between different types of cables should be in accordance with table 3.

Table 3. Minimum spacing between different types of cables.

Cable category	A1	A2	B	C
A1		0.1 m	0.1 m	0.2 m
A2	0.1 m		0.1 m	0.2 m
B	0.1 m	0.1 m		0.1 m
C	0.2 m	0.2 m	0.1 m	

To achieve the EMC performance and improve the system ability to resist EMI, the following design is proposed:

(1) Separate the different categories of cables and try to maintain the spacing recommended in table 3.

(2) If the minimum spacing of different cable types is not guaranteed, especially for Class C cables, they can be separated by metal conduits and metal trunking, which are connected to the ground.

(3) If different types of cables cross at right angles, there is no need to consider the minimum spacing.

(4) In order to utilize the attenuation effect, the cables should be placed as close as possible to the vehicle ground, such as metal cable tubes, conduits, etc.

4. Test Results

The anti-EMI test is carried out on Lines 4 and 6 of Shanghai Metro to verify the stability and reliability of the proposed anti-EMI design for the rail trains.

4.1. Internal Interference Test

In order to verify the EMC performance between the electronic equipment inside the rail train and its various subsystems, we carry out its internal interference test [7]. The reference standard is GB/T 28806–2012/IEC 61133: 2006 [8]. This test consisted of three subtests as shown below.

4.1.1. Interference test of main and auxiliary converters on control circuits

All vehicle-mounted electrical appliances are powered on, and then the rail trains are in three operating states: stationary, full acceleration, and maximum braking force deceleration. Observe the three work states of the brake control units of electronic control circuits, traction/auxiliary/battery units, door control units, heating ventilation and air conditioning (HVAC) system, passenger information system (PIS), train central control units, and then read information from event recorder.

4.1.2. Interference subtest between main and auxiliary converters

All vehicle-mounted electrical appliances are powered on, and then the rail trains are in three operating states: stationary, full acceleration, and maximum braking force deceleration. Observe the operating conditions of the main inverter electronic control circuits and auxiliary inverter electronic control circuits in three states, and then read the information from the event recorder.

4.1.3. Transient pulse interference subtest when opening/closing switches, relays and contactors

All vehicle-mounted electrical appliances are powered on, and then the rail trains are in three operating states: stationary, full acceleration, and maximum braking force deceleration. In the three states, the switches, relays and contactors in the main and auxiliary circuits are turned on and off, and their operating conditions are observed and the data information is read from the event recorder.

4.1.4. Results

Table 4 shows the test results. In the three subtests, all the observed objects do not have over-voltage, under-voltage and under-current problems in three operating states of the rail trains, and the control circuits corresponding to each object work properly. Meanwhile, the event recorder does not report an error. It can be concluded that the EMC design between the internal electronic equipment and each subsystem can meet the requirements of the standard, and it has good anti-EMI capability.

Table 4. Internal interference test results of rail trains.

Three working states: Static/full acceleration/maximum brake deceleration			
Subtest name	Over-voltage, under-voltage,or under-current	Control circuit operation	Errors in event recorder
Interference of main and auxiliary converters to control circuits	No	Normal	No
Interference between main converters and auxiliary converters	No	Normal	No
Transient impulse interference when opening/closing switches, relays, and contactors	No	Normal	No

4.2. Radiation Immunity Test

In view of the fact that the distance between the antennas of mobile communication devices and the sensitive devices on the rail train is less than 1 m, the radiation emission intensity generated by the former is sufficient to interfere with the normal working intensity of in-vehicle electronic devices, which may lead to their performance degradation or even the loss of some important functions. Therefore, the test was set up to verify the immunity performance of the rail train to radiation interference sources, such as portable radio equipment.

The interference sources selected in this experiment mainly include the following two parts:

(1) Public communication equipment used by passengers or train employees.

(2) Hand-held walkie-talkie or wireless communication system used by train employees.

According to the standard requirements and daily operation, the selection of the equipment to be tested is based on the location where the mobile communication device is easily accessible. Therefore, the test equipment of this test includes train monitoring display, driver console, driver room door control, driver room machine control, passenger room display, guest room dynamic map, guest room door control, and guest room video camera.

The rail train used for the equipment test is stationary and should be in normal operating conditions without any addition or reduction of equipment. Devices that may form interference coupling paths are not allowed to appear because these interference coupling paths may affect its electromagnetic vulnerability. All equipment should be operated in accordance with established normal procedures. Use a variety of frequency bands to test the impact of interference sources on the devices under test.

The specific steps of the test are as follows:

(1) Check if the devices under test are installed correctly.

(2) Calibrate the interference intensity of the interference sources (i.e. mobile phone/interphone on the corresponding frequency band) and determine the distance from the equipment under test.

(3) Place the selected mobile phone/interphone next to the in-vehicle devices to be tested, keep the current position of the phone (just bell, and do not answer the call), observe the working status of the devices under test or check the interfered intensity of each device through the train control and communication units, and record the results truthfully.

(4) If there is a sensitive phenomenon and the performance level does not meet the requirements, adjust the distance between the mobile phone and the devices under test, and record the disturbed distance as the basis for subsequent analysis.

The test results are shown in table 5. It can be seen from table 5 that all the tested equipment work normally under various interference sources and have high radiation immunity.

5. Conclusion

This paper proposes an anti-EMI design scheme for rail trains. From the four aspects of grounding, shielding, filtering and wiring, the scheme integrates the characteristics of each part of the rail trains. The assembly tests are carried out on the Shanghai Metro Line 4 and Line 6 to verify its effectiveness and reliability. The test results show that the proposed scheme can provide useful reference for the subsequent anti-EMI design of railway trains, improve the reliability of train systems, ensure the safety train operation, passenger safety and reduce the operation and maintenance cost of rail trains.

Table 5. Test results.

Test site	Working status	Test site	Working status
Monitoring display	Normal	SIV controller	Normal
In-vehicle radio display	Normal	Driver room light controller	Normal
Broadcast control	Normal	Headlight controller	Normal
In-vehicle radio keyboard	Normal	Brake mode controller	Normal
Broadcast control keyboard	Normal	Drivers cab camera	Normal
HMI screen	Normal	Flute controller	Normal
HMI screen indicator	Normal	Dashboard and surrounding	Normal
Mode control display	Normal	Right door switch controller	Normal
MMI display	Normal	Left door switch controller	Normal
Speed control device	Normal	LCD screen	Normal
Door operation console	Normal	Guide screen	Normal
Lighting console	Normal	Surveillance video cameras	Normal

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