Assessments of lightning protection scheme for a metro traction power system and lightning-caused electromagnetic environment inside a carriage

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ABSTRACT: In order to assess the effectiveness of a lightning protection scheme, a computer modelling code was developed. The modelling was demonstrated for the power supply system of line no.11 of SZMTR, which included overhead contact lines, feeder lines of traction substation, pantograph with motor, and running rails as path of back flow current. The modelling was based on EMTP (electromagnetic transient program), which provides common RLC circuit components and nonlinear devices such as the lightning arrester and flashover switch in its library. The RLC parameters, especially those of vertical feeder wires were calculated by simplifying them as coupled π-type circuits. The equivalent capacitance was determined by the average potential method while the equivalent inductance was calculated with the Neumann's formula. A lightning return stroke current was then introduced into the modelling to study its impact on the traction power system. In addition, the internal structure of a subway carriage is a complicated system composed of various devices for high voltage, frequency conversion, controlling and communication uses. In order to evaluate the effect of EMF (electromagnetic filed) shielding scheme, a simplified metro carriage 3D model was built in FDTD (Finite Difference Time Domain) space. A lightning return stroke current was placed at different distances from the carriage. The results show that the lightning-induced EMF does little harm to devices especially those wrapped by double-layer metallic boxes. Horizontal electric field would become dominant when lightning channel is close to the carriage.

POWER SYSTEM OF METRO

The 1500-volt DC overhead contact line becomes more and more popular in the power supply system of urban rail transit. For example, except the line no.3, which adopted a third rail for its power supply, all other SZMTR (Shenzhen Metro Transit Rail) were fed by overhead lines.

Layout of the metro power traction system

Fig. 1 shows the structure of the power traction system for line no. 11 of SZMTR. Only the section on the ground has been investigated since the underground contact lines will not hit by lightning stroke. Ground section is composed of one message wire, two contact wires, three auxiliary feeder wires, one overhead earthing wire, two running rails and one earthing flat steel wire. Message wire and two contact

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wires were connected by droppers so they were viewed as in a same phase. The overhead earthing wire and earthing flat steel wire also have same phase. These 10 horizontal wires were modeled as a 4 phases Constant Parameter line model.

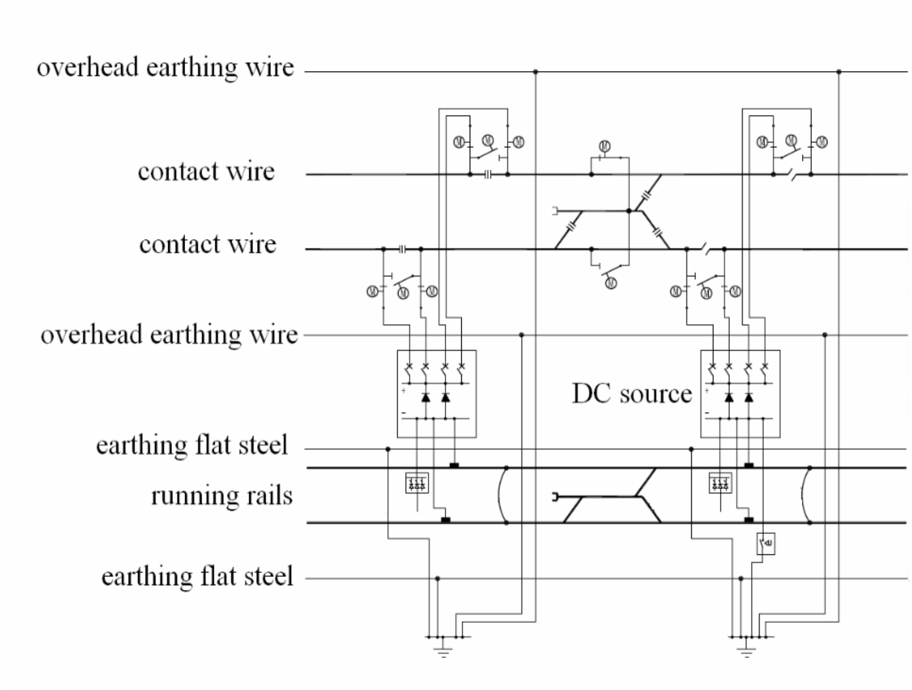

Fig. 1 Layout of the power system within two substations for line no.11 of SZMTR

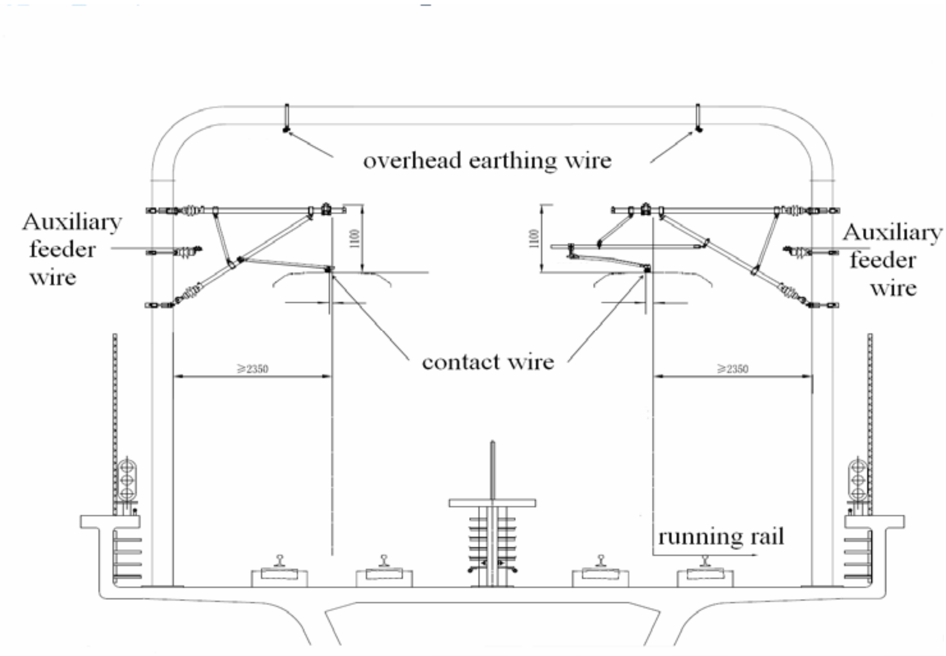

Fig. 2 Layout of horizontal wires for the system in Fig. 1

Fig. 2 shows the spatial separation of these horizontal wires and Table. 1 shows all the parameters of the transmission line model for the system in Fig. 1. Ground conductivity was set to 0.01 s/m. Two different propagation modes exist in this transmission line model. According to Table 1 and line spacing in Fig. 2, two modes surge impedances are estimated as 416 ohms and 156 ohms per 250 meters respectively.

Table 1 Specific parameters of horizontal conducting wire for the system in Fig. 1

Wire name	Number	Radius (mm)	Resistivity (Ohm/km)	Phase
Message Wire	1	6.9	0.123	1
Contact wire	2	6.2	0.1475	1
Auxiliary feeder wire	3	6.9	0.123	2
Running rail	2	13.8	0.111	3
Overhead earthing wire	1	6.2	0.155	4
Earthing flat steel	1	13.8	0.111	4

The contact wires were fed by the DC 1500V substation via five 400 mm^2 single core copper cables. The average distance of two successive substations is about 2 km. RLC parameters of vertical conducting structure such as feeder wires, pantograph, lightning arrester's downward earthing cable, and carriage were calculated by simplifying them as coupled π-type circuits, with the ground as a mirror. Equivalent capacitance and inductance was determined by the method mention in [Du et al., 2001]. In the calculation, only 10/350 μs and 8/20 μs waveforms have been investigated. According to [Dai, 2001], the upper cut-off frequency of these two waveforms is less than 0.68 MHz. So the scale of carriage is still smaller than 1/10 of the minimal wavelength. It is reasonable to model the carriage as a coupled π-type circuit.

Lightning protection scheme

Lightning arresters are installed at intersection positions between contact lines and feed cables of traction substations and contact lines at every 250 meters on ground section. Furthermore, grounding resistance of these arresters is assumed to be less than 10 ohms. To improve the effect of lightning protection, earthing wires are raised up as overhead lightning conductors. The overhead earthing wires are connected to ground through a discharge gap at every 200 meters. The electric locomotive takes electricity from contact lines by a pantograph which is protected by lightning arresters beneath it. In general, the lightning arresters connected to overhead contact wires and DC source are given higher priority of operation than the arresters on the locomotive since substations have larger energy absorption capability. Residual and rated voltages of arresters on the locomotive are larger than that of arresters on contact wires [Zhang et al., 2012]. The current-voltage characteristics of two types of arresters adopted in this model are shown in Table 2. Electric potential of running rails should be under 96 volts by over voltage protection devices placed at metro stations and parking lot. The potential restriction device is modelled as a flashover switch connecting to ground with a response time of 20 milliseconds [Wang, 2004].

Table 2 Current-Voltage characteristics of Zinc Oxide arresters model

Current (A)	125	500	1000	5000	10000	20000
Voltage of arrester for contact wires and DC source (V)	3690	3890	4100	4500	4900	5400
Voltage of arrester for locomotive (V)	5200	5520	6000	6900	7420	8400

Results

Lightning current with a peak value of 75 kA was injected into the overhead contact line. A value of 75 kA was selected according to GB50057-2010. The results show that when the lightning strike point on the contact line is 1250 meters away from the metro carriage, the peak current of traction motor is 560 A. When the strike point is just above the carriage, the peak current of traction motor is 821 A. As mentioned in [Zhang et al., 2012], the maximum current in a traction inverter should not exceed 859 A for safety. So the traction system in the carriage is safe under this lightning protection scheme.

Besides the direct lightning strike on the contact line, induced current on the traction system of the metro carriage caused by a close lightning strike was also investigated. The finite difference time domain method (FDTD) was adopted, which directly solves the Maxwell curl equations to obtain numerical simulation of electromagnetic wave propagation and its interaction with structures. All the horizontal wires were represented by thin wire model plus their resistances [Noda and Yokoyama, 2002]. Vertical structures were simplified as RLC components in FDTD space. The calculation had a span of 2 km since the average DC sources separation distance was 2 km. Lightning channel was set to 3 km long with a peak value of 75 kA and its rise time was 10 microseconds. The regional FDTD grid for power system was 0.06×0.06×1.5 m due to the requirement of thin wire approximation and FDTD grid for lightning channel was 50×50×50 m. It was found that the induced current in driving motor would not exceed 120 A when the lightning channel was 10 meters away from the train carriage. The induced current would not exceed 180 A when the bottom of lightning channel was 5 meters away. Such induced currents could not cause damage to the system since they were comparable to the rating current of the traction motor of 132 A [Tao et al., 2012].

ELECTROMAGNETIC ENVIRONMENT OF CARRIAGE

A lightning return stroke was placed near the carriage. Both the lightning channel and carriage were modelled in FDTD space.

Modelling of Lightning return stroke

Modified transmission line model (MTL) of return stroke was adopted. The model current at a given height *z* was represented as:

$$I(z,t) = A(z)I(0,t-\frac{z}{v}) \quad \text{when } t>z/v$$

$$I(z,t)=0 \quad \text{when } t<z/v \qquad (1)$$

Where $A(z)=\exp(-\frac{z}{\lambda})$, λ=2000m [Cooray, 2003] and *I(0,t)* was a double exponential current waveform wider than the typical 8/20 µs one and was set to be 15/80 µs during the validation part. The lightning return stroke channel was 3000 meters long during the simulation. Propagation speed of the return stroke front *v* was set to 1/3 of light speed c. The FDTD grid for lightning stroke was 10×10×10 m.

Validation of the proposed FDTD scheme was done by comparing its results with that of an analytical electric field expression in free space. The analytical electric field expression as a function of the return stroke channel current was adopted from Chapter 5 in [Cooray, 2003]. Since the analytical electric field expression is valid only when the source-observer distance is much larger than the length of lightning channel, the validation was done for a source-carriage distance of 30 km with both the FDTD and analytical calculation methods. The comparisons were shown in Fig. 3. There was no more difference in the calculated electric field curves between the two methods.

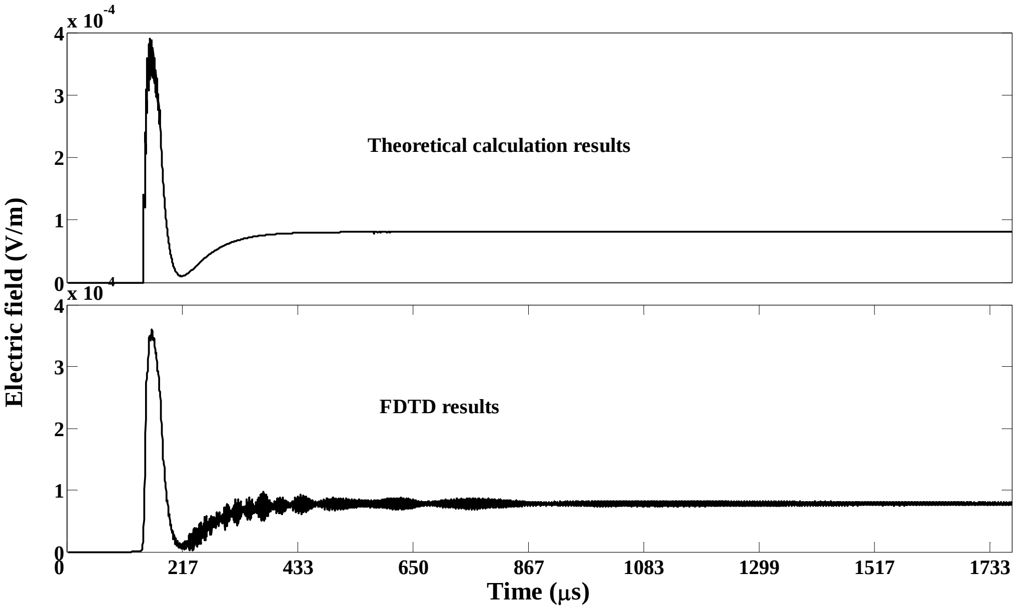

Fig. 3 Validation of lightning return stroke model in FDTD space

Modelling of carriage

In the simulation, the dimension of a metro train carriage was set to a 20×3×3 m and the thickness of the carriage wall was set to 0.1 m. There were three doors (each 2×2 m) and two windows (each 1.5×1 m) on each side of the carriage. All materials of the carriage walls were simplified as aluminium alloy with a conductivity of 2.5×10^7 s/m [Ray and Bolz, 1970]. Since the metro train carriage was much smaller than lightning channel, the regional FDTD grid for carriage was set to 0.1×0.1×0.1 m.

Simulation results

Lightning channel were placed at 1000 m and 500 m away from the metro carriage. Current waveform of 10/350 μs with a peak value of 75 kA was adopted in the simulation. Results show that electric fields inside the carriage increases with time. Horizontal electric field is much larger than that in vertical direction since the doors and windows left gaps in horizontal directions. The electric field behind the windows at 60 μs is about 1700 V/m and 7000 V/m respectively, when the lightning is 1000 m and 500 m away from the carriage. In contrast, the electric field behind the walls at 60 μs is just about 1500 V/m when the lightning is 500 m away from the carriage.

As mentioned in [Lu et al., 2008], materials with high magnetic permeability and high electric conductivity were good for electromagnetic field shielding. To test such a proposal, a screening cage was inserted into the carriage to wrap the sampling point. The screening cage was set to have a conductivity of 2×10^6 s/m and a relative permeability of 100, which was similar to nickel-iron alloy. In contrast to the case without screening cage, the electric field with screening cage would drop to 100 V/m. If the screening cage was replaced by a plate in front of the sampling point, the electric field would increase instead. Only the magnetic field would be reduced by this plate slightly (from 6×10^{-7} T down to 4×10^{-7} T).

CONCLUSIONS

An EMTP-based computer model has been developed to assess the effectiveness of a lightning protection scheme for a metro rail transit (MTR) against a direct lightning stroke. The model was demonstrated for the power supply system of line no.11 of SZMTR, which included overhead contact lines, feeder lines of traction substation, pantograph with motor, and running rails as path of back flow current. It was found that the surge current on the metro traction motor increases as the distance of the lightning striking point on the contact lines to the metro traction motor decreases. The existing lightning protection scheme of the SZMTR would be able to protect the traction motor from a lightning peak current of 75 kA or less.

Besides, a FDTD-based 3D metro carriage computer model has been built up to evaluate the effect of electromagnetic field (EMF) shielding of a metro carriage against a distant lightning stroke. Application of the model to the SZMTR shows that distant lightning stroke does little harm to the metro carriage. When the lightning channel is close to the carriage, the electric field inside the carriage is mainly in horizontal direction and is dominant by static field. In such case, a single-face shielding plate (even two layers) could not reduce the electric field but only the magnetic field. A double-layer cage would be a good way to protect vulnerable devices.

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