Study on Transient Magnetic Field in an Vehicle Body Caused by Nearby Lightning

Jun Kanata, Akihiro Ametani and Kazuo Yamamoto

***Abstract*-- In recent years, as control technologies for automobiles have been sophisticated, many electronic parts are included in an automobile. In case of electric vehicles, not only control but also driving circuits are electrical. Therefore, the possibility of malfunctions on electric vehicles due to a lightning stroke may be higher. To establish lightning protection methodologies for electric vehicles, it is important to clarify transient magnetic fields and current distributions in electric vehicles. Although transient magnetic fields in an electric vehicle body due to a direct lightning stroke was investigated, there is possibility that malfunction occurs in control equipment due to transient magnetic fields caused by a lightning stroke close to an electric vehicle. In this paper, the transient magnetic fields in an electric vehicle body due to a nearby lightning stroke are simulated using the FDTD method, and we compare cases of a nearby lightning stroke with a direct lightning stroke. In addition, the relation between induced current paths and transient magnetic fields is clarified, and the probability of lightning damages is discussed.**

***Keywords*: electric vehicle, lightning, transient magnetic fields, FDTD method.**

I. INTRODUCTION

IN recent years, global warming caused by increasing carbon dioxide emissions has influenced our living environment and ecosystem. For this reason, we have to reduce carbon dioxide emissions. Considering that the transport sector discharges 20 % of total carbon dioxide emission in Japan [1], the reduction of the emission in the automobile industry is effective in environmental improvements. Therefore, ecological electric vehicles and hybrid cars, etc. are popularized rapidly [2].

An electric vehicle includes more electronic parts than a gasoline-powered vehicle. Not only control but also driving circuits of the electric vehicle are electrical at variance with those of the gasoline-powered vehicle. It means that there is higher possibility of malfunctions on the electric vehicle due to electromagnetic disturbances caused by a lightning stroke [3], [4]. It is essential to establish lightning protection methodologies for the electric vehicle. As the first step, we had investigated threats of transient magnetic fields in an electric vehicle body due to a direct lightning stroke [5]-[7]. However, there is possibility that malfunction occurs in control equipment due to transient magnetic fields caused by a lightning stroke close to an electric vehicle. Thus, it is also important to clarify damages caused by not only a direct lightning stroke but also by a nearby lightning stroke.

In this paper, the transient magnetic fields in an electric vehicle body due to a nearby lightning stroke are simulated using the FDTD method [8], and we compare cases of a nearby lightning stroke with a direct lightning stroke. In addition, the relation between induced current paths and transient magnetic fields is clarified, and the probability of lightning damages is discussed.

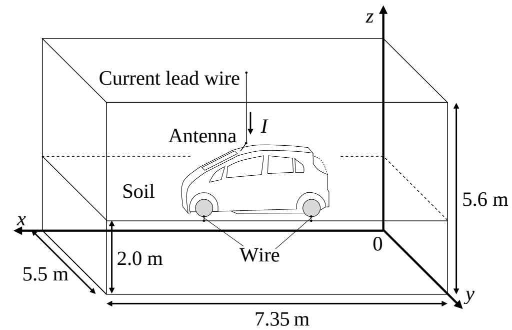
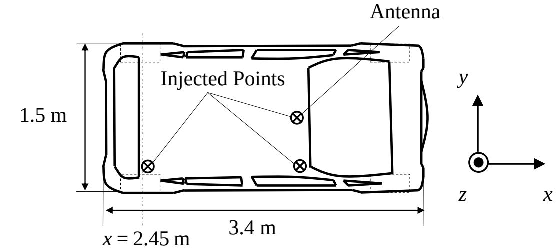
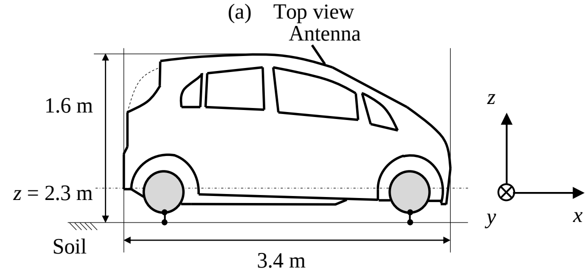


Fig. 1. Simulation setup in the case of a direct lightning stroke.



(a) Top view



(b) Side view

Fig. 2. Detail views of an electric vehicle.

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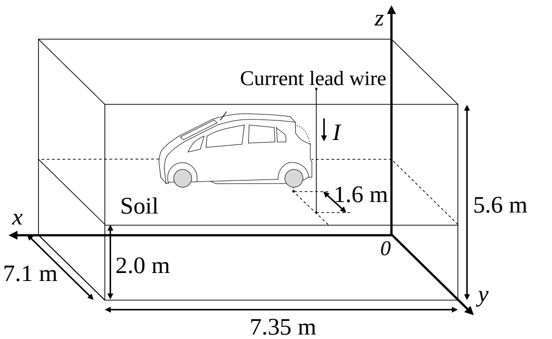


Fig. 3. Simulation setup in the case of a nearby lightning stroke.

II. Analytical Conditions

Fig. 1 shows an analytical space of cases that lightning strikes an electric vehicle directly, and Fig. 2 shows detail views of an electric vehicle. The dimensions of the analytical space are 7.35 m × 5.5 m × 5.6 m and it is divided into cubic cells with a side length of 0.05 m. The absorbing boundary condition is 2nd order Liao. The ground level is 2.0 m from the bottom of the analytical space; the earth resistivity is 100 Ωm, the relative permittivity is 10.

An analytical model of an electric vehicle is set at the center of the analytical space. The analytical model of an electric vehicle is formed according to an electric vehicle on sale. In this paper, the model is made of thin wire models [9] and conductor plate models, and it doesn't include interior equipment (inverter, motor, battery, etc.). Usually, the surface of a vehicle body is streamlined to reduce air resistance. But, in this simulation, the electric vehicle model is represented by a step approximation with cubic cells.

In our past research [6], we have studied analytically in 13 cases (cf. Table 1) that are changed the combination of current injected points and discharge points. Important equipment in the electric vehicle modeled in this study such as a motor and an inverter is placed at the rear of the electric vehicle. Therefore, transient magnetic fields around the rear portion become important. In this paper, we compare cases of a nearby lightning stroke with Case 3 in Table 1. Case 3 is the case that the largest transient magnetic fields appeared around wheels and the axle at the rear portion of the electric vehicle in the cases of current injection toward the antenna. Case 3 in Table 1 is regarded as Case A in this paper. Fig. 3 shows an analytical space of cases of nearby lightning strokes. 2 cases are studied as cases of nearby lightning strokes. The first one is a case that a current injected point is located 11.85 m away from a wheel at the left back. This case is regarded as Case B. In general, a relational expression between lightning current and striking distance is expressed by the following equation [10]:

$$r_s = kI^n \quad \cdots (1)$$

Where, r_s is the striking distance [m], I is the peak value of lightning current [kA], k, n are Constant.

TABLE I
SIMULATION CASES IN PAST STUDIES

Case No.	Current injected points	Discharge points
1	Antenna	All wheels
2		Wheel at the right front
3		Wheel at the right back
4	Right front part of the roof	All wheels
5		Wheel at the right front
6		Wheel at the right back
7		Wheel at the left front
8		Wheel at the left back
9	Right back part of the roof	All wheels
10		Wheel at the right front
11		Wheel at the right back
12		Wheel at the left front
13		Wheel at the left back

TABLE 2
SIMULATION CASES IN THIS PAPER AND MAXIMUM VALUES OF *dH*/*dt* AROUND THE REAR AXIS.

Case No.	Current injected points	Discharge points	Maximum values of dH/dt [10^5 A/m·s]	
			z-direction	*x*-direction
A	Antenna	Wheel at the right back	14	39
B	11.85 m from Wheel at the left back	——	0.9	4.4
C	1.6 m from Wheel at the left back	——	9.0	52

Equation (2) is used by IEC Standard [11] and Fig. 4 shows the characteristic of striking distance obtained from the figure.

$$r_s = 10I^{0.65} \quad \cdots (2)$$

The present external lightning protection system under IEC standard adopts the rolling sphere method (cf. Fig. 5) based on the relationship between lightning current and striking distance. If current peak value is 10 kA, striking distance is 44.7 m from Equation (2). By using Pythagorean theorem in Fig. 5, *d* (distance between a current injected point and an electric vehicle) is 11.85 m. Thus, it is generally considered that the probability of occurrence of a nearby lightning stroke within 11.85 m from electric vehicle is low, if lightning current is 10 kA. For these reasons, current injected point is located 11.85 m away from a wheel at the left back in Case B. The second one is a case that a current injected point is located 1.6 m away from a wheel at the left back. This case is regarded as Case C. This case is supposed a severe situation (e.g., a case that lightning strikes trees or outside lights in the immediate vicinity of parked electric vehicles). In this case, distance between a wheel at the left back and a current injected point is same as vehicle height. Cases discussed in this paper are shown in Table 2. As shown in Table 2, current injected points are the antenna, 11.85 m away from a wheel at the left back and 1.6 m away from a wheel at the left back. As shown in Fig.

6, the injected current has comparatively steep wave front, and its peak value and wave front duration are 1 A and 1μs, respectively. In cases of a nearby lightning stroke (Case B, C), between all wheels and ground are opened. In other words, these cases are supposed that discharges do not occur between wheels and ground.

III. Calculation Result

Fig. 6 shows an injected current waveform. Output planes, shown in Fig. 2, are *xy* plane at z = 2.3 m (*xy* plane including axles), *yz* plane at x = 2.45 m (*yz* plane including an axle at the rear position). The perpendicular magnetic fields on each output plane are calculated, then, time derivatives of magnetic fields (dH/dt [A/m·s]) are outputted, the maximum value distributions of dH/dt in Case A, B and C are drawn in Fig. 7, 8 and 9 on heat and cold colors. Important equipment in the electric vehicle modeled in this study such as a motor and an inverter is placed at the rear of the vehicle. Therefore, transient magnetic fields around the rear portion become important. Large transient magnetic fields also appear near windows because there are large gaps. However transient magnetic fields in the vicinity of windows aren't important, because there are no vital electronic parts around there. For this reason, maximum values of dH/dt around wheels and the axle at the rear portion of the electric vehicle are listed in Table 2. Fig. 7 shows calculation results of Case A (Current injected point: Antenna, Discharge point: A wheel at the right back). In Case A, transient magnetic fields spread widely around the wheels and the axle at the rear portion of the electric vehicle, because current passed through the axle. Fig. 8, 9 show calculation results of Case B, C in which a nearby lightning stroke occurs. In Case B and C, transient magnetic fields spread at the rear of the electric vehicle, because induced current flows through a closed circuit including a rear axis.

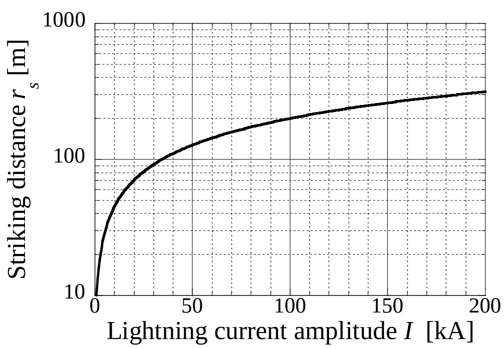


Fig. 4. Striking distance vs. lightning current amplitude.

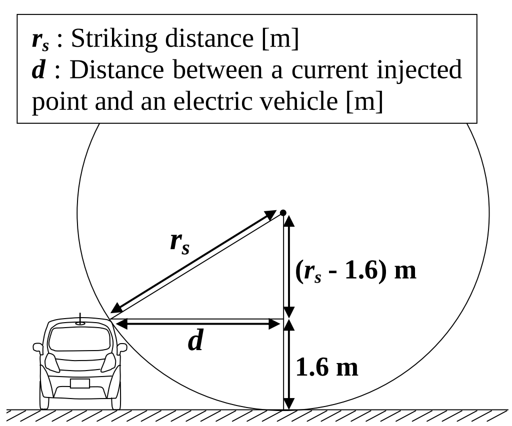


Fig. 5. Rolling sphere method.

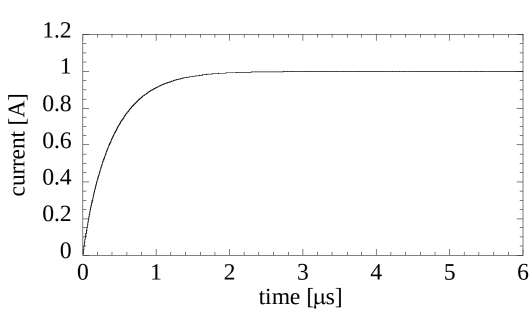
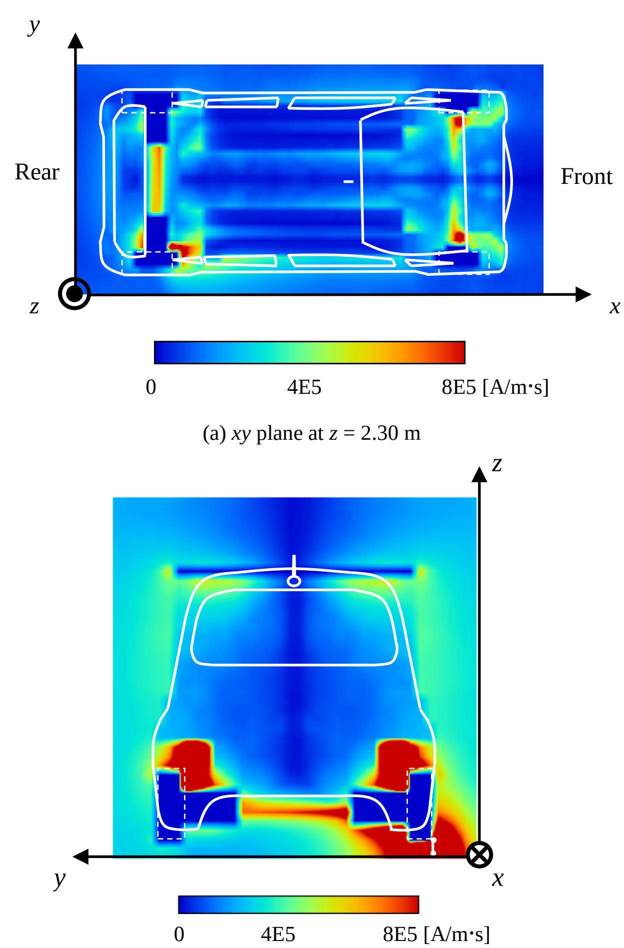


Fig. 6. Injected current waveform.

A. *Case A (Current injected point: Antenna, Discharge point: A wheel at the right back)*

Fig. 7 shows calculation results of Case A. In Case A, larger dH/dt appears not around wheels but also in the middle



(a) *xy* plane at z = 2.30 m

(b) *yz* plane at x = 2.45 m

Fig. 7. Maximum value distributions of time derivatives of magnetic fields (Case A).

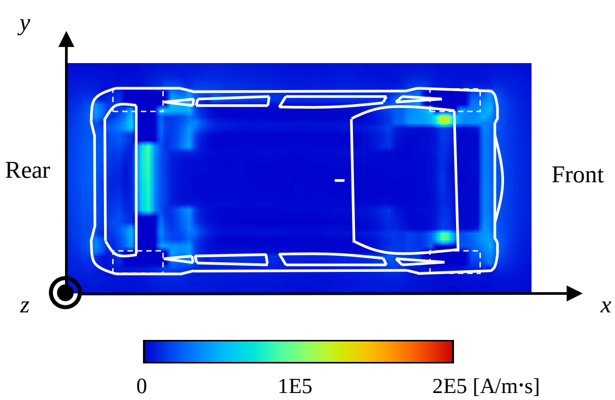
of the vehicle body because current was discharged from only one wheel and current passed through the vehicle body partially, therefore good Faraday cage wasn't formed by the vehicle body effectively. In Case A, because the current injected point and the discharge point were located as asymmetrically, relatively larger currents passed the axle between two bearings along routes shown in Fig. 10(a). Its maximum value is 12 % of the peak value of the injected current. A maximum value of dH/dt of z direction and x direction at the rear portion of the vehicle body are 1.4×10^{6} [A/m·s] and 3.9×10^{6} [A/m·s], respectively. The current passing through the axle between two bearings is 12 % of the injected current, that is, 88 % of the injected current flows into the discharged wheel from the bearing close to the wheel. When large current flows into a wheel from a bearing, there is possibility of damage at the junction of the axle and the bearing due to the discharge. However, countermeasures for such damages aren't taken in electric vehicles. Large scale wind turbine generator systems are often struck by lightning. Therefore, bypass circuits made of small gaps and brushes are installed for such damages between the main axle and the bearing [12], [13]. It is important that such lightning protections are taken in an electric vehicle.

B. Case B (Current injected point: a point at 11.85 m away from a wheel at the left back)

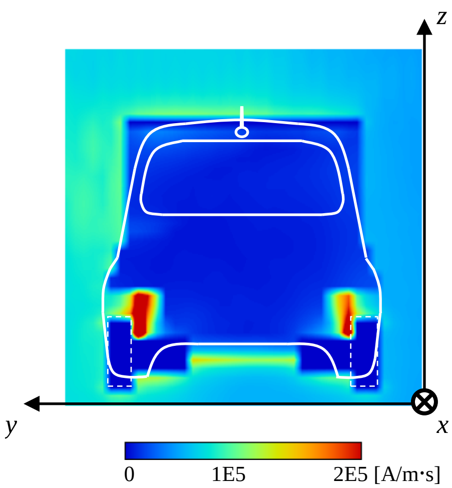
Fig. 8 shows calculation results of Case B. In this case, injected current point was decided by considering the rolling sphere method based on relationship between striking distance and lightning current of 10 kA. In this case, dH/dt in the electric vehicle becomes comparatively smaller because distance between the electric vehicle and the current injected point is larger than the other cases.

As shown in Fig. 8, 10(b), transient magnetic fields spread around the wheels and the axle at the rear portion of the electric vehicle, because induced current passed through the closed circuit including the rear axle. Magnetic fields due to injected current and induced current are canceled each other inside this closed circuit. But, outside this closed circuit, these magnetic fields are strengthened each other. Thus, as Fig. 8(b) shows, dH/dt under the rear axle becomes larger than inside of the closed circuit including the rear axle.

A maximum values of dH/dt of z direction and x direction at the rear portion of the vehicle body in Case B are 9.0×10^{4} [A/m·s] and 4.4×10^{5} [A/m·s], respectively.

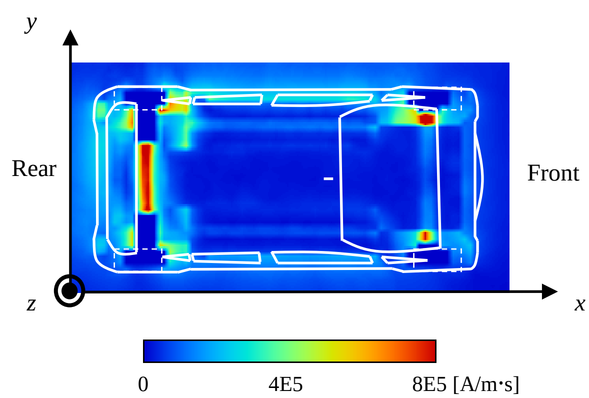


(a) *xy* plane at *z* = 2.30 m

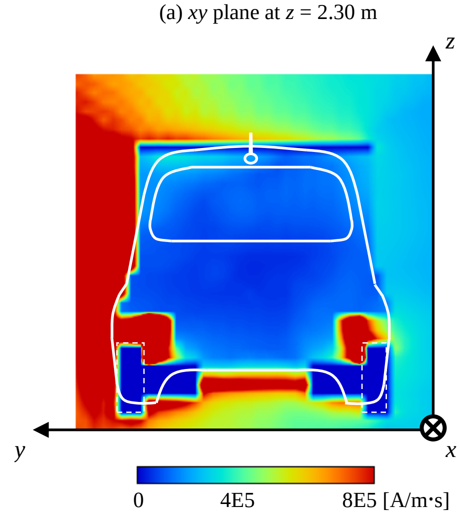


(b) *yz* plane at *x* = 2.45 m

Fig. 8. Maximum value distributions of time derivatives of magnetic fields (Case B).



(a) *xy* plane at *z* = 2.30 m



(b) *yz* plane at *x* = 2.45 m

Fig. 9. Maximum value distributions of time derivatives of magnetic fields (Case C).

C. Case C (Current injected point: a point at 1.6 m away from a wheel at the left back)

Fig. 9 shows calculation results of Case C. This case is supposed severe situations (e.g., a case that lightning strikes a tree or an outside light in the immediate vicinity to parked electric vehicles). In Case C, transient magnetic fields spread around the wheels and the axle at the rear portion of the electric vehicle like Case B, because induced current passed through the closed circuit including the rear axle as shown in Fig. 9, 10(b). In Case C, a maximum values of *dH*/*dt* of *z* direction and *x* direction at the rear portion of the vehicle body are 9.0×10^5 [A/m·s] and 5.2×10^6 [A/m·s], respectively. Because current that passes through the rear axle in Case C is induced current, it is not larger but steeper than current on the vehicle body due to direct lightning stroke in Case A. Additionally, as shown in Fig. 10(a), (b), in case A, the injected current spread from antenna to all directions, while the injected current pass through the current lead wire only in case C. Therefore, transient magnetic fields become larger around the current lead wire. Thus, a maximum value of *dH*/*dt* of *x* direction at the rear portion of the vehicle body in Case C becomes larger than one of Case A that lightning strikes electric vehicle directly.

IV. Overvoltage Appearing at Electronic Parts

It is usually hard for electromagnetic fields to invade the inside of the vehicle body because the Faraday cage is formed by the conductive body. However, as Fig. 7, 8 and 9 imply, magnetic fields invade the inside of the vehicle body from gaps around windows, bottom of the vehicle body and wheels, because the vehicle body doesn't form a space completely closed by conductors. In consequence, comparatively larger transient magnetic fields appear widely in the vehicle body. When an electric vehicle has a motor and control equipment at the rear of the vehicle, there is possibility of a malfunction of electronic parts caused by such transient magnetic fields. For example, as shown in Equation (3), voltage of about 100 V might be induced in a square circuit of 0.1 m × 0.1 m which placed at a spot that *dH*/*dt* is 8.0×10^5 [A/m·s] (red place in Fig. 7 and 9) on the assumption that an injected current's peak value and wave front duration are 10 kA and 1μs, respectively (permeability of vacuum: μ_0 [N/A^2], cross section area of circuit: *S* [m^2], peak value of current: *I* [A]).

$$\boldsymbol{V} = \mu_0 \cdot \boldsymbol{S} \cdot \boldsymbol{I} \frac{\boldsymbol{dH}}{\boldsymbol{dt}} \tag{3}$$
$$= 4\pi \cdot 10^{-7} \cdot 0.1^2 \cdot 10 \cdot 10^3 \cdot 8 \cdot 10^5 = 101 \text{ [V]}$$

In case B, voltage of about 25 V might be induced in a square circuit of 0.1 m × 0.1 m which placed at a spot that *dH*/*dt* is 2.0×10^5 [A/m·s] (red place in Fig. 8) in the same assumption as above.

These induced voltages are considerable for lightning protection of the electronics equipment. Therefore, we need to place such equipment in a spot where it is hard for transient magnetic fields to invade, and put such equipment into a shielded box. In addition, as in IEC standard [14], we should adopt the zoning concept in electric vehicle and install SPD on wire harness at boundaries of zones.

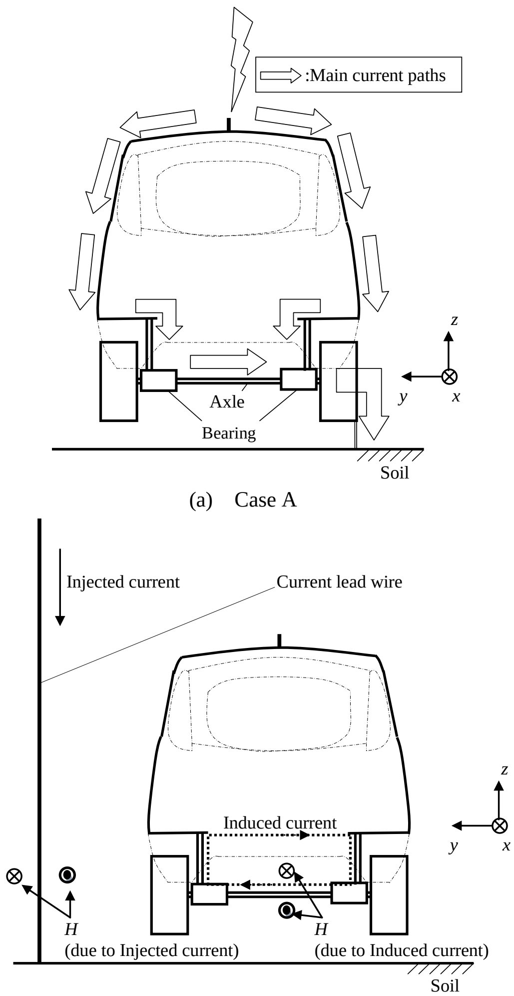


Fig. 10. Main current paths.

V. Conclusions

In this paper, the transient magnetic fields in an electric vehicle body due to a nearby lightning stroke are simulated using the FDTD method, and a nearby lightning stroke is compared with a direct lightning stroke. From the simulation results, it becomes possible to estimate the level of overvoltage appearing at electronic parts, and discuss about probability of lightning damages.

Magnetic fields easily invade the inside of the vehicle from gaps around windows and wheels because the inside of the vehicle isn't completely shielded by the vehicle body from electromagnetic fields. When an electric vehicle has a motor and control equipment at the rear of the electric vehicle, there is possibility of serious accidents caused by malfunctions of electronic parts. It is important to take lightning protections against such malfunctions.

In cases of a nearby lightning stroke, transient magnetic fields spread around the wheels and the axle at the rear portion of the electric vehicle, because induced current passes through the closed circuit including a rear axle. It seems that this characteristic depends on the shape of the vehicle body. However, it means that there is higher possibility of malfunctions on the electric vehicle due to electromagnetic disturbances caused by a nearby lightning stroke. Therefore, it is important to make countermeasures against lightning damages.

All simulations in this paper have been done using an electric vehicle model because electric vehicles are thought to be more vulnerable to electromagnetic disturbances than gasoline-powered vehicles. However, recent gasoline-powered vehicles are usually controlled electronically; the results in this paper are also effective for not only electric but also gasoline-powered vehicles.

In this paper, transient magnetic fields in an electric vehicle are simulated using the vehicle model only including the vehicle body. As the next step, a model with interior equipment (inverter, motor, batteries, etc.) and wire harness will be investigated.

VI. References

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