International Conference on Lightning Protection
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

High Voltage Impulse Experiment on Electric Automobiles and its Verification Part2

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***Abstract*— We applied impulse voltages to an electric vehicle using an impulse voltage generator. The results provide insight into the phenomenological aspects of lightning strikes and characteristics of electric discharge between the wheels and ground.**

Keywords- electronic vehicle; lightning damage; impulse voltage; puncture of tires

I. Introduction

In recent years, as one of the main causes of global warming, there is the greenhouse effect gas such as CO2 and others[1]. Gas vehicles that run by combusting fossil fuel produce large volume of CO2 emissions, and therefore, electric vehicles, hybrid cars, and others which exert smaller environmental burdens, have begun to rapidly gain popularity in lieu of gas vehicles. However, in these vehicles, a large number of electronic components are used for controls as compared to conventional gas vehicles, and in particular, in the case of electric vehicles and fuel cell cars, not only the control unit but also the drive unit adopt completely electric systems and they may become vulnerable to lightning surge and other electromagnetic disturbances. These phenomenological aspects of lightning to vehicles and problems generated by lightning have not yet been thoroughly investigated and there are many problems which have to be dealt with immediately.

In the past, authors have investigated vehicles subject to lightning damage[2,3] and vehicles with fire accidents[4] and clarified their characteristics, and at the same time, have given a warning about behavior and danger of the transient electromagnetic field which develops inside the vehicle using FDTD (Finite Difference Time Domain) method, a kind of numerical electromagnetic analysis methods[5-8].

In this study, in order to simulate a lightning strike to electric vehicles, using an impulse voltage generator (IVG, commercially available from Haefely Test AG), the impulse voltage was applied to an electric vehicle, phenomenological aspects of lightning strikes were investigated, and at the same time, characteristics of electric discharge between wheels and the ground were clarified. In addition, we applied not only voltage but also impulse current by impulse current generator to confirm induced voltage which generated to the electric devices in the vehicle body. In this paper, the results of only voltage test reported as follows.

II. Test Method

Actual lightning has characteristics of high voltage and big current. In general, the voltage of actual lightning is said to reach hundreds of millions of volts and the current a few hundred of kA. Statistical data indicates that about 50% of actual lightning provide the current crest value of about 25 kA[9]. It is practically impossible to prepare test facilities that simulate this size of high voltage and big current. Therefore, in the present experiment, by applying the voltage by a high-voltage and small-current impulse voltage generator, behavior of the electric vehicle and phenomenological aspects of lightning striking discharge in such event were clarified.

A. Discharge path verification test

In the present test, rod electrodes were arranged to identify the tendency of lightning to the vehicle body and the then phenomenological aspects of electric discharge of the vehicle and around tires.

Fig. 1 shows the vehicle body and Fig. 2 the vehicle dimensions. The vehicle body was arranged on a copper plate simulating the ground, and the copper plate (3 mm thick) were

Figure 1. Schematic of specimen placement.

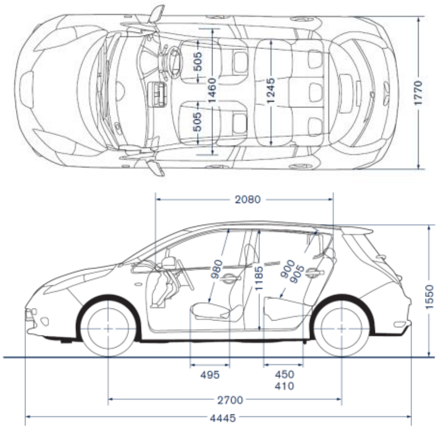


Figure 2. Specimen dimensions.[10]

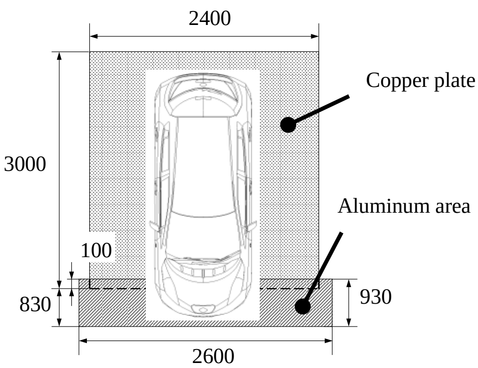


Figure 3. Dimensions of copper plate and expanded aluminum area.

expanded by the use of aluminum plates (0.1 mm thick). Fig. 3 shows the expanded dimensions by the copper plate and aluminum plates. The dotted part indicates the copper plate and the shaded part the aluminum plates. The copper plate and the aluminum plates were fixed by copper tape. Rod electrodes were arranged at the position about 0.7 meters above the vehicle body roof. The behavior of the vehicle, the phenomenological aspects of electric discharge between the electrode and the vehicle body, and the phenomenological aspects of electric discharge between the vehicle body and copper plate (tire surfaces) when the impulse voltage was applied between the electrode and the vehicle body using IVG were identified visually and taking photos by camera. The camera was set to the BULB mode (mode in which the shutter was held open until the button was pressed) and photos were taken by remote control. The vehicle body was surrounded by black-out curtains and windows of experimental site were shielded from light so that photos of electric discharge were easily taken. Table 1 shows observation points of cameras arranged around the vehicle body. Table 2 shows a list of rod electrodes arranged. Fig. 4 shows the position No. and one example of position No. B, where a rod electrode was located 0.7 m right above the roof. Fig. 5 is a photo when the rod electrode was arranged right above the windshield. Fig. 5(a) is the photo when the rod electrode was located 70 cm right above a windshield wiper (position No. F) and Fig. 5(b) is the photo when the rod electrode was located 0.7 m from the windshield wiper and the roof, respectively (position No. G). the applied voltage was started from 1.2/50 μs, -800 kV, which is the standard waveform of lightning impulse voltage, and when no electrical current was discharged, the voltage was increased in increments of -50 kV. After applying the voltage, the vehicle body conditions (change in appearance, physical damage, etc.) were checked visually. The application point was changed, and the voltage was repeated five times at each application point.

TABLE I. CAMERA INSTALLATION POINTS.

Camera installation point (Camera No.)	Positions observed
Diagonally forward left of vehicle body	Outer side of left wheels (approx. 0.5 m high from the ground)
Front of vehicle body	Inner side of right and left wheels
Diagonally forward right of vehicle body	Whole body (approx. 1.5 m high from the ground)
Side of vehicle body (No. 4)	Outer side of right wheels （The position was changed

TABLE II. VOLTAGE APPLICATION POINTS USED IN THE DISCHARGE PATH VERIFICATION TEST.

Vehicle's body part	Position No.	Rod electrode position
roof	A	70 cm above the roof
	B	70 cm above the roof
Front glass	C	70 cm above the roof
	D	70 cm above the roof
	E	70 cm above the roof
	F	70 cm above the wiper
	G	70 cm above the wiper and roof

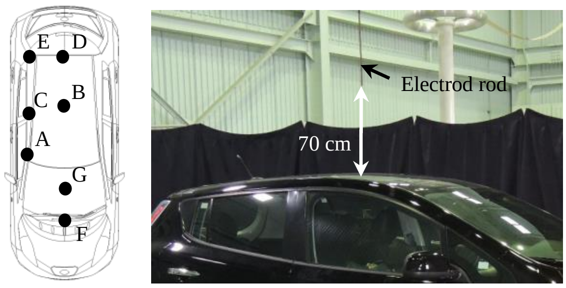
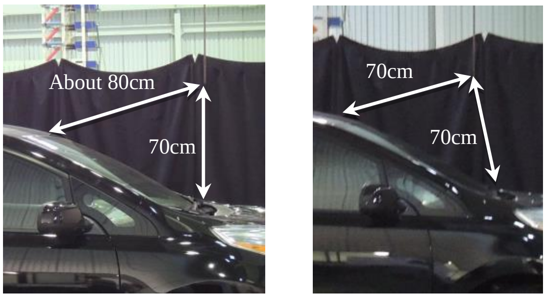


Figure 4. Placements of rod electrodes and its example.



(a) 70 cm above the wiper (b) 70 cm above the wiper and roof

Figure 5. Electrode placement above windshield.

B. *Discharge path identification test*

In this test, the high voltage was applied with the applying cable connected to the vehicle body, and the tendency of discharge locations and number of discharges at each tire was confirmed.

The rod electrodes used for the discharge path verification test were removed and the application cable was directly connected to the vehicle body. Fig. 6 shows the aspect of connections of application points and Table 3 a list of voltage-application points. The phenomenological aspects of electric discharge around tires were checked visually and by taking photos by camera when the impulse voltage was applied to the vehicle body by the use of IVG. The camera observation position was changed around the vehicle body according to conditions. For the applied voltage, 1.2/50 µs, -200 kV, which is the standard waveform of lightning impulse voltage, was used. After applying the voltage, the vehicle conditions (changes in appearance, physical damage, etc.) were checked. The application points were changed and application was repeated 10 times each for every application point. Thereafter, the applied voltage was raised to -500 kV and whether the electric discharge locations of tires were changed or not was checked. The application points were changed and application was repeated 5 times each for every application point.

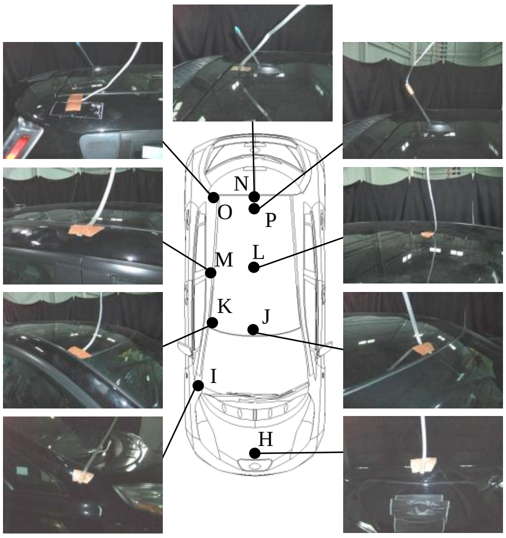


Figure 6. Connections of voltage-application points.

TABLE III. VOLTAGE APPLICATION POINTS USED IN THE DISCHARGE PATH VERIFICATION TEST.

Vehicle's body part	Voltage application point	Area of voltage application
Bonnet	H	Upper part of logo
	I	Upper part of right front light
roof	J	Center forward
	K	Forward right end
	L	Center
	M	Center right end
	N	Under of antenna
	O	Rear right end
antenna	P	Antenna

III. TEST FACILITIES AND MEASURING INSTRUMENTS

Table 4 shows IVG specifications. A total of four Canon single-lens reflex cameras, namely one EOS 60D and three EOS Kiss X4's, were used to take pictures with the EF-S18-55 lens used.

TABLE IV. IVG SPECIFICATIONS.

Item	Specifications
Model	SGSA 1200–60
Maximum charge voltage	1200 kV
Output waveform	1.2 µs ± 30% / 50 µs ± 20%
Impulse capacitance	Approx. 83 nF

IV. TEST RESULTS

A. *Discharge path verification test*

Table 5 shows the vehicle conditions when the test was started. The conditions assumed the situations when vehicles were parked usually. Fig. 7 shows the number of electric discharge of each tire in the discharge path verification test. The number of electric discharges was counted by dividing the inside, outside, and interior of the tire. The tire interior indicates not the creeping discharge of wheel but the through discharge from the tire tread surface. As one example, the through discharge of the left front wheel inside is shown in Fig. 8. The total number of applications was 53 times, which included nine additional applications right above B (two times of which were preliminary experiments later discussed), one additional application right above C, and one additional application right above D, and seven failures in taking pictures. Fig. 7 stipulates the electric discharge probability with respect to the total number of applications, too.

TABLE V. VEHICLE CONDITIONS STARTING LIGHTNING SIMULATION TEST.

Vehicle's body part	Condition
12V-Battery	Connect
Ignition	Power OFF
Shift Position	Power OFF
Parking Brake	On
Merter display	Non lighted
Head light	Non lighted
Tire Condition	Stop

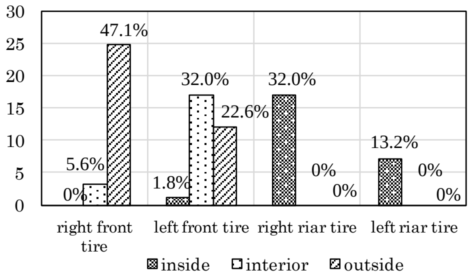


Figure 7. Number of creeping discharges on each wheel in discharge path verification test.

Figure 8. Photograph of electric discharge interior of left front wheel.

Table 6 shows the positions which lightning struck and the number of lightning strikes according to applied point No. For example, Table 6(a) shows that when the rod electrode was installed right above A, lightning struck the vehicle body 5 times at the -900-kV applied voltage.

In the first phase of the test, electric discharge at the left front wheel inside shown in Fig. 8 was frequently observed. It was assumed that as the test was repeated, the discharge path was formed and electrical current tended to be easily discharged at the same portion. In the present test, with the formation of discharge path taken into account, the contact areas of tires were changed several times during the test. The contact areas were four surfaces of 0°, 90°, 180°, and 270°, and the contact area right after the test was started was set to 0°. In addition, when the distance between the aluminum wheel rim end unit and the copper plate (hereinafter called the "tire

TABLE VI. APPLICATION VOLTAGES AND LIGHTNING AREA AND NUMBER.

(a) Electrode position: point A.

Vehicle's body part	-800 kV	-850 kV	-900 kV
Body	0	0	5
Antenna	0	0	0
Wiper	0	0	0
Front glass	0	0	0

(b) Electrode position: point B.

Vehicle's body part	-800 kV	-850 kV	-900 kV
Body	2	3	9※
Antenna	0	0	0
Wiper	0	0	0
Front glass	0	0	0

(c) Electrode position: point C.

Vehicle's body part	-800 kV	-850 kV	-900 kV
Body	0	0	6
Antenna	0	0	0
Wiper	0	0	0
Front glass	0	0	0

(d) Electrode position: point D.

Vehicle's body part	-800 kV	-850 kV	-900 kV
Body	0	0	0
Antenna	1	0	5
Wiper	0	0	0
Front glass	0	0	0

(e) Electrode position: point E.

Vehicle's body part	-800 kV	-850 kV	-900 kV
Body	0	0	0
Antenna	0	5	0
Wiper	0	0	0
Front glass	0	0	0

(f) Electrode position: point F.

Vehicle's body part	-800 kV	-850 kV	-900 kV
Body	0	0	0
Antenna	0	0	0
Wiper	3	1	1
Front glass	0	0	0

(g) Electrode position: point G.

Vehicle's body part	-800 kV	-850 kV	-900 kV
Body	0	0	0
Antenna	0	0	0
Wiper	0	0	0
Front glass	0	5	0

*Including two preliminary experiments

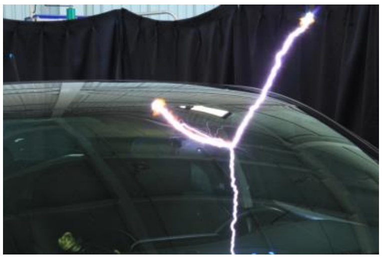


Figure 9. Creeping discharge of the front glass.

pressure”) was measured, both front wheels measured 6.7 mm and both rear wheels measured 7.3 cm, and no change was observed in the numerical values even after the tire ground contact area was changed.

In the mid-phase of the test, when the electrode was allocated in a gap length of 0.7 m from the wiper and the roof as shown in Fig. 5(b), the lightning surge took place in a form of creeping discharge on the surface of windshield and gained entry through the roof end part into the vehicle body panel inside. Fig. 9 shows the photo of electric discharge.

In the final phase of the test, cases in which discharge occurred not only in a tire at one place but also in the tires at two or more places were observed. As a result, in many cases, electric discharge occurred in all tires. After the test, the surface and the tread surface of each tire were checked, but visually, it was unable to confirm any change on the tire surface. Apart from tires, electric discharge was identified at the right front wheel spring portion, too. This was assumed that the electric discharge took place from the spring to the tire wheel via the spring sheet (insulation) surface.

Table 6(b) includes the result of preliminary experiments. Authors conducted similar experiment with other electric vehicle in the past[10], and obtained the knowledge in that there was a possibility for an electrical current to be easily discharged at places with small tire pressure. Therefore, as shown in Fig. 10, a braided wire was connected to the metal part of vehicle body bottom surface and a path through which an electrical current was easily discharged was intentionally formed. The braided wire was adjusted to provide about 2 cm gap length with respect to the copper plate (about 14 cm long: the lowest ground height of the specimen assumed to be 16 cm). When the voltage is applied under this condition, discharge was able to be identified not at the tire but at the braided wire part.

(a) Photograph of body bottom (b) magnification

Figure 10. Braided wire connected body bottom.

The auto dimming mirror (hereinafter called the mirror) was located at the terminal of the power system wiring and the mirror itself did not fail. In recent vehicle roofs, the power system wiring is frequently installed. In the stage in which the lightning surge discharged on the windshield surface broke into the roof panel and flew into the copper plate, the induced current may be generated in the mirror power wire.

The foregoing results indicated that measures against lightning of automobiles must be provided with consideration given not only to the tire surroundings but also to insulated parts of windshields, etc. In the literature[2,3], when lightning strikes the vehicle insulated parts, there are cases in which the lightning surge does not discharge on the surface but breaks the insulated parts. In particular, depending on vehicle types, some vehicles are equipped with a sun roof, suggesting that measures against lightning for insulated parts are assumed to be essential.

B. Discharge path identification

Fig. 11 shows the number of creeping discharges on each tire when the applied voltage is -200 kV. The number of discharges was counted by dividing the tire inside and the tire outside. The total number of voltage applications was 94 times, which included one trial application, one discharge failure, two failures of photo taking (one of which was the case in which the creeping discharge was able to be taken by camera but the discharge location was unable to be identified). In Fig. 11, the electrical discharge probability with respect to the total number of voltage applications was stipulated. During the test, the electrical discharge on the right front wheel outside was frequently observed but as the test was repeated, the electrical discharge location was changed to the left front wheel outside. It was assumed that a discharge path was formed on the left front wheel while the test was repeated.

Fig. 12 shows the number of creeping discharges of each tire when the applied voltage was -500 kV. The total number of voltage applications was 58 times, in which three failures of photo taking were included. In Fig. 12, the discharge probability with respect to the total number of voltage applications is stipulated. In this test, electrical discharge was generated on the left front wheel outside in almost all cases. In this test, no electrical current was discharged from the tire tread surface and therefore, the tire contact area was not changed. Possibly due to the aftermath, creeping discharge continued at the place of the same tire.

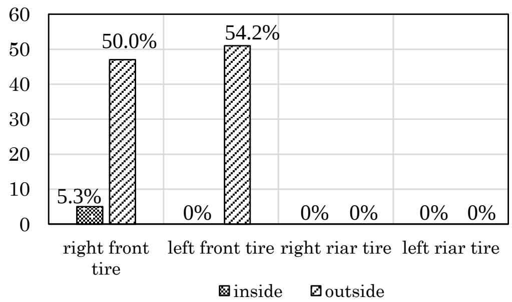


Figure 11. Number of creeping discharges on each wheel in discharge path verification test. (Charge voltage -200 kV)

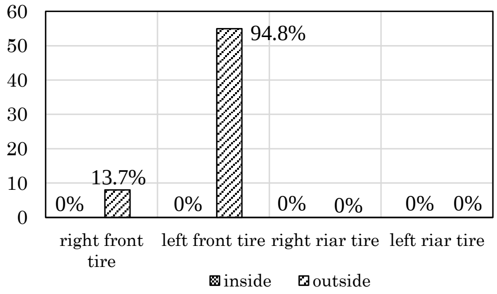


Figure 12. Number of creeping discharges on each wheel in discharge path verification test. (Charge voltage -500 kV)

The reason why the electric discharge was concentrated on the front wheel was assumed to be attributed to the location of small tire pressure which was easy to cause electrical discharge. As an additional test, the tire pressure was changed from 7.3 cm to 5.0 cm and the test was conducted. The reason why the left rear wheel was chosen was because the left rear wheel gave rise to the least number of discharges and it was judged that comparatively small effect was exerted on formation of a discharge path. Under such condition, the voltage of -500 kV was applied. As a result, from the left rear wheel, an electric current was discharged with a probability of 100% (in 11 times of voltage applications, an electric current was discharged 11 times).

Based on the foregoing results, it was clarified that the discharge location depended on the tire pressure. According to road conditions and tire air pressure conditions, the distance between the wheel and the ground was assumed to be changed, suggesting that the discharge path between the wheel and the ground may be changed dependently on the conditions when vehicles were hit by lightning.

V. SUMMARY

In this paper, using a high-voltage impulse generator, the impulse voltage was applied to an electric vehicle and the phenomenological aspects of lightning strikes were investigated, and at the same time, the characteristics of discharge between the wheel and the ground were clarified. Using a large-current impulse generator, the impulse current was applied to the tire surface and the lightning resistant characteristics of tires were clarified. As a result, the following knowledge was obtained:

- The electric discharge between the vehicle and the ground frequently occurs on the surface of the tire between the wheel and the ground and less occurs between the vehicle bottom surface and the ground.
- In the right front wheel spring part, electric discharge was confirmed, too, but since no important components were allocated around the spring part, effect of discharge was small and the criticality of measures was low.
- An electric current was discharged in the tire at one place or in the tires at a plurality of places. In the event that the vehicle was hit by lightning, there were various lightning surge outflow paths and all cases must be assumed.
- The electric discharge from the tire tread surface was confirmed, too. The lightning surge that penetrates the tire tread surface and flows out to the ground may blow out the tires.
- Depending on the road conditions and the tire air pressure conditions, the distance between the wheel and the ground was assumed to be changed and there is a high possibility in that the discharge path between the wheel and the ground may be varied dependently on the conditions when vehicles are hit by lightning.
- The electric discharge progressed on the windshield surface and the lightning surge infiltrated in the vehicle body panel inside. The induction voltage may be generated in the power wire connected to the mirror. This indicates that measures against lightning for insulated parts of vehicles are necessary.
- The lightning current flows from the roof to the tire wheel via the vehicle body and flows out to the ground. In the future, the path through which the lightning current flows must be identified.

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