DEVELOPMENT OF BODY STRUCTURE FOR CRASH SAFETY OF THE NEWLY DEVELOPED ELECTRIC VEHICLE

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ABSTRACT

An electric vehicle (EV) is promising as clean energy powered vehicle, due to increased interest in fuel economy and environment in recent years. However, it requires to meet unique safety performance such as electric safety and cabin deformation although mass increase of the high-voltage battery compared with the fuel tank.

Nissan has developed a new electric vehicle which achieves electric safety and occupant protection performance in addition to maintaining enough cruising distance and cabin space. This was achieved by the development of an all-new platform for electric vehicles.

The electric safety was enhanced by the protection of high-voltage components based on consideration of component layout and body structure, high-voltage shutdown by impact sensing system and prevention of short circuit by fuse in the battery. As an example of the protection of high-voltage components, the battery which locates under the floor was protected by elaborative packaging and multi-layer protection structure.

In addition, the same cabin deformation as the internal-combustion engine vehicle similar in size in frontal crash was achieved by developing an efficient layout and structure for the motor compartment.

INTRODUCTION

The concern in oil price rising and global warming is rising in recent years, and manufacturers are expected to improve fuel efficiency and reduce carbon dioxide emission [1]. Therefore, development of vehicles such as HEV (Hybrid Electric Vehicle), PHEV (Plug-in Hybrid Electric Vehicle), EV (Electric Vehicle) and FCV (Fuel cell vehicle) has become more active as new technology for energy efficiency and environment. EV is remarkably considered as one of the promising future energy vehicle because of great reduction in carbon dioxide emission.

In general, high-voltage components such as the battery and the motor are equipped on EV instead of a fuel tank and an engine on internal-combustion engine (ICE) vehicles. Therefore, new safety performance must be considered in addition to safety performance of the existing vehicles.

First is to ensure electric safety to prevent an electric shock in the crash accident due to high-voltage components. Upgrade of electric safety standards for electric powered vehicles are accelerated globally due to the sales grow of them which include EV (See Table 1) [2],[3],[4],[5]. Car manufactures are expected to develop new technology to address this situation.

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Second is to control the cabin deformation and the body deceleration for occupant protection in the frontal impact. It is often necessary to mount a battery which is heavier than a fuel tank of ICE vehicle to secure enough cruising distance. Therefore, the energy absorption by body structures during the crash increases due to the increased mass of the battery. Namely, additional energy absorption is required to achieve the same cabin deformation as ICE vehicles.

Nissan’s new EV which is five-seater passenger car was developed by considering the items above with enough cruising distance and cabin space with an all-new platform for the EV.

In this paper, an approach of electric safety performance and occupant protection performance of the newly developed EV in the crash are explained.

OUTLINE OF THE NEWLY DEVELOPED EV SYSTEM AND COMPONENT PARTS

In this chapter, outline of the high-voltage system is introduced.

High-voltage system and components of the EV are shown in Figure 1. Firstly, DC flows from the battery to the inverter. Then it converts DC to AC, and finally AC is supplied to the motor and it rotates.

Following is an outline and function of the high-voltage system and its components.
High-voltage battery
The high-voltage battery supplies the electric power to the drive system and auxiliary system. It stores the electric power when charging and regeneration during deceleration. The nominal voltage is 360 V.

Inverter
The inverter converts battery DC into three-phase AC to supply to the motor. It controls input/output torque of the motor.

Motor
The motor generates the driving force using the electric power of the battery. It generates braking force during deceleration and regenerates the electric power to transmit to the battery.

Charger
The charger converts AC electric power from a commercial power source into DC electric power to supply to the battery.

DC/DC converter
The DC/DC converter reduces the high voltage from the battery to supply the electric power to 12 V loads.

Vehicle control module (VCM)
The VCM is a unit which controls vehicle integration.

Service disconnect switch (SDSW)
The SDSW is a switch which cuts off the high-voltage circuit for safety work at the time of maintenance or rescue.

Protection against direct contact
The first concept of protection is against direct contact. Purpose is to protect human from electric shock by not to be able to touch the high-voltage cable directly. One example is covering the components by layers or isolating by structure. In case of covering by conductive body, energizing components have to be insulated from electric conductor.

Protection against indirect contact
The other protection is against indirect contact. This structure is to avoid electric shock by ensuring equipotential between high-voltage components and a vehicle body in case of the direct contact protection failure. One example is to connect between each high-voltage components and the vehicle body by bonding wire or earth it. It is important to secure both the direct and the indirect protection during and after the crash for EV.

ELECTRIC SAFETY DESIGN OF THE EV
In this chapter, details of the protection against direct contact in the crash are explained. The details consist of two parts. One is about EV packaging and the other is about protection structure of high-voltage components.

EV packaging
Firstly, high-voltage components of the EV are placed outside of the passenger compartment (See Figure 2) and inside of framework structures such as side members and body sills. In other words, it protects from electric shock in the crash by preventing direct contact to the high-voltage components. Additionally the components are protected by the structures.

CONCEPT OF ELECTRIC SAFETY
This chapter describes concept of electric safety. The concept consists of two types of protections which are against direct and indirect contact to avoid electric shock [6].
Multiple protections of high-voltage components

Secondly, multiple protection system is applied to high-voltage components outside of the passenger compartment. In particular, electric shock due to direct contact between occupants and high-voltage components is prevented by the following.

1) Component layout and body structure.
2) High voltage shutdown device with sensing system.
3) Fuse in the battery pack.

Example for 1) and 2) are explained.

**The high-voltage battery protection** The battery is protected by consideration of layout and multi-layer protection structure in the EV.

a) Layout

The battery was placed under front and rear seats outside of the cabin by considering floor shape. Namely, the location is farther away from common front and rear crash impact zones, so the battery is protected by the zone body structure as shown in Figure 3.

![Figure 3. High-voltage battery layout.](image)

b) Multi-layer protection structure

In addition to the considered layout, the battery was protected by multi-layer protection structure (See Figure 4).

In side impact, using not only the body sill but also fore-aft member as load path enabled the high energy absorption by small crushable space (See Figure 5-(a)).

Also, structure of floor cross members was studied for battery protection. In case of ICE vehicles, impact energy is often absorbed by floor cross members which is fixed to the body sills in side impact. However, the battery may be deformed by the force from the body sills to floor cross members when it is mounted between the body sills. Therefore, floor cross members were separated from the body sills in the EV as shown in Figure 5-(b). In the result, this design reduced the amount of force transferred through the floor and floor cross members to the battery during side impact.

c) Vehicle crash test configuration for evaluation of high-voltage battery protection and the results

Vehicle crash test with various modes of collisions designed to mimic real-world crashes were conducted for evaluation of high-voltage component protection including the battery (See Figure 6). Photographs of batteries after each vehicle crash tests are shown in Figure 7. The battery frame was not deformed. The electric isolation between body and high-voltage system remained intact. Figure 8 shows force-deformation curve of the EV and the ICE vehicle similar in size in side impact pole test. The body deformation was reduced by control of the body reaction force.
High voltage shutdown system In addition to protection against direct contact explained in the previous section, electric shock prevention after the crash performs even better by adopting shutdown system.

The high voltage shutdown system is described by the block diagram shown in Figure 9. Firstly, an airbag control unit (ACU) detects frontal, side or rear impact using airbag sensors. Secondly, ACU send signal to VCM which controls electric system. Finally, VCM judges to shutdown the relay in the battery.

OCCUPANT PROTECTION PERFORMANCE OF THE EV

This chapter describes the idea about occupant protection performance of the EV. At first, the unique consideration about occupant protection performance of the EV is explained. Secondly, details of the idea are described below.
The unique consideration about occupant protection performance of the EV

Curb weight of the EV increases from the ICE vehicle similar in size due to mass increase of the battery compared with the fuel tank as shown in Figure 10. Furthermore the additional mass is added to the floor. Therefore, the additional energy absorption by the body is required to achieve the same cabin deformation as the ICE vehicle in frontal impact.

In general, there are two ways to increase the energy absorption by the body. One is to reinforce the body to reduce the body deformation. The body deformation consists of deformation of the motor compartment and the cabin. The other is to increase crushable space of the motor compartment and the motor compartment deformation. However, there is a limit to increase the space because of some reasons such as vehicle size.

On the other hand, it is an advantage for occupant protection performance to increase the motor compartment deformation in frontal impact. Kinetic energy of an occupant is absorbed by the body deformation and restraint system which includes seatbelts and airbags etc. in frontal impact. As a consequence, larger energy absorption by the body deformation means smaller absorption by restraint system. That is an advantage for occupant protection performance since it is flexible to design restraint system.

For these reasons, it is an advantage to increase deformation of the motor compartment in occupant protection performance point of view in frontal impact.

Study of crushable length of front side members

At first, additional energy absorption in frontal impact was considered by mounting the motor on the front suspension member.

A power source is generally mounted on front side members by mounting brackets in the ICE vehicle of a front-engine/front-drive configuration (See Figure 11). One of the reasons is NVH (Noise, Vibration and Harshness) performance. The mount brackets may prevent the front side members from crushing. As a result, the energy absorption by the front side members may decrease.

On the other hand, the motor of the EV can be mounted on front suspension member due to the different frequency character from an ICE vehicle (See Figure 12). That resulted in increasing crushable length of front side members.

Study of motor compartment crushable space

Efficient crushable motor compartment structure was studied to increase the motor compartment deformation and reduce the cabin deformation in frontal impact. In particular, two detail ideas are explained below. One is to increase crushable length of front side members. The other is to increase crushable space of the motor compartment.

Details of the idea to increase energy absorption of the motor compartment in frontal impact

Efficient crushable motor compartment structure was studied to increase the motor compartment deformation and reduce the cabin deformation in frontal impact. In particular, two detail ideas are explained below. One is to increase crushable length of front side members. The other is to increase crushable space of the motor compartment.

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Study of motor compartment crushable space

In addition, crushable space of motor compartment was increased by the optimization of motor compartment layout, considering dynamic behavior of DC/DC converter.

As shown in Figure 13-(a), DC/DC converter is mounted on an inverter member which is fixed with front side members. By controlling the fracture
between front side members and inverter members, DC/DC converter could rotate during the crash and resulted in motor compartment crushable space increase (See Figure 13-(b)).

(a) Mounting system of DC/DC converter on the body

(b) Dynamic behavior of DC/DC converter

Figure 13. Optimization of motor compartment layout.

The body characteristic of the EV in frontal vehicle crash tests In these ways, the EV achieved the same cabin deformation as the ICE vehicle in frontal impact. Cabin deformation of the EV and the ICE vehicle in vehicle frontal crash tests is described in Figure 14. The motor compartment deformation of the EV increases by about thirty percent from the ICE vehicle and the cabin deformation of the EV is the same as the ICE vehicle. Also, energy absorption by the body deformation in kinetic energy of an occupant was compared between the EV and the ICE vehicle. Ratio of energy absorption by the body deformation to kinetic energy of an occupant was calculated by the method as shown in Figure 15. The ratio for the case of driver-side HybridIII dummy in 56 km/h full-lap frontal test is shown in Figure 16. Energy absorption by the body deformation in the EV was increased by about twenty percent compared to the ICE vehicle similar in size.

Figure 14. Body deformation of the EV and the ICE vehicle in 64km/h offset deformable barrier frontal test.

Figure 15. Calculation method of ratio of energy absorption by body structures to occupant kinetic energy in frontal impact.

Figure 16. Comparison of the ratio of energy absorption by body deformation to kinetic energy for the case of driver-side HybridIII dummy in 56km/h full-lap frontal test.

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CONCLUSIONS

In this paper, electric safety and occupant protection performance of the newly developed EV was explained and the following points were shown,

- It was shown that 1) layout and body structure offers protection of the high-voltage components; 2) high voltage shutdown is achieved by the impact sensing system; 3) electric shock is prevented by fuses which prevent short circuits.

- As an example of high-voltage components protection, multi-layer protection structure was presented. Vehicle crash tests were conducted and the protection of the battery was confirmed.

- Cabin deformation of the EV in frontal impact was the same as the ICE vehicle similar in size even with mass increase of the battery compared with the fuel tank. This was achieved by optimization of efficient motor compartment structure and layout.

Areas of future study are as follows.

- In order to achieve longer cruising distance, it is important to further reduce the total mass without compromising the electrical system safety and occupant protection performance.

REFERENCES


