

Evaluation of the Durability and Reliability of the Power Semiconductor Device for a Hybrid Car's Motor Driver

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ABSTRACT

The reliability of the power semiconductor device for a hybrid car's motor driver was verified by clarifying the relationship between the unit life characteristics and vehicle usage environment in terms of electric current and heat generation temperature. A reliability of 99.915% or more and a shape parameter (m) of 5.5 or more were obtained. Further, an evaluation method for durability and reliability was established.

1. Introduction

Amidst the growing demand for lower fuel consumption and reduced exhaust emissions from automobiles, the Integrated Motor Assist (IMA) system has been developed as one means of satisfying these demands. This system reduces the amount of fuel consumed by applying an electric motor located between a conventional gasoline engine and the transmission to collect energy dispersed by the vehicle during deceleration, by storing this energy in a battery, and by assisting the engine with this stored energy to drive the motor during acceleration.

A power semiconductor device that can perform rapid on-off switching of a large electric current is indispensable for achieving optimum control of the drive and regeneration energy conversion that takes place in this system. It is important to accurately verify the durability and reliability of this power semiconductor device in order to guarantee

the quality of the IMA system in the market. During the development of the IMA system, a method for evaluating the durability and reliability of power semiconductor devices for motor driving was established, a description of which is reported here.

2. Overview of the IMA System

Fig.1 shows the configuration of the IMA system. This system incorporates a lean-burning variable valve timing and lift electronic control system (VTEC) engine having a 1 liter displacement as the main power source, an ultra-thin brushless DC motor for the auxiliary power source, a power control unit (PCU) for converting the electrical power, and an Ni-MH battery for storing the electrical power. This system is characterized by continuously using the engine as the main power source, and supplementing it with the electric motor as an auxiliary power source according to the driving

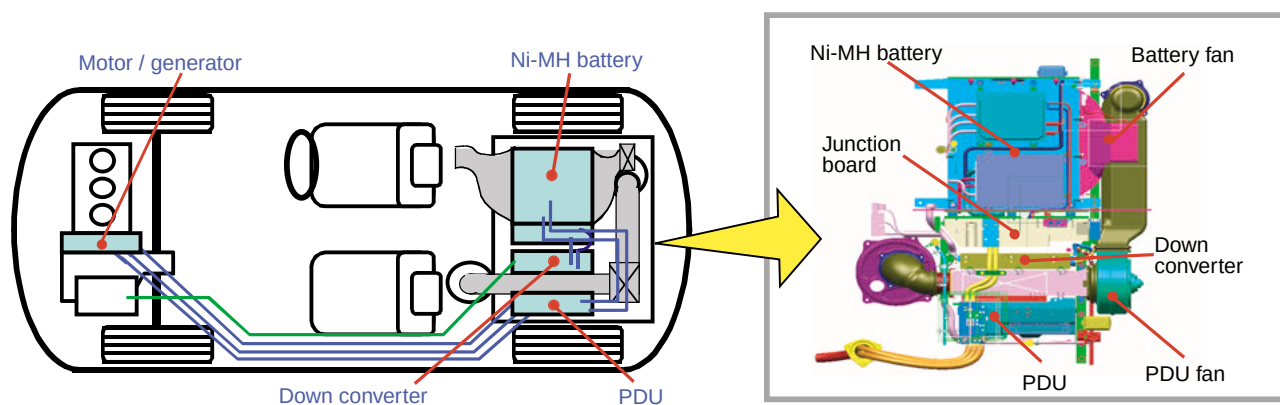


Fig.1 IMA system

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conditions. The overall system is simple, and the motor, battery and PCU can all be made compact and lightweight. The relationship between the driving conditions and system status is described next.

- During Acceleration
When a large load is applied to the engine during acceleration, the electric motor assists the engine by generating a maximum torque of approximately 5 kgf·m.
- When Cruising
The vehicle is powered by the gasoline engine alone when cruising for stable operation with low fuel consumption.
- During Deceleration
The motor fulfills the role of a generator to regenerate the deceleration energy and charge the battery which would otherwise be dispersed as heat from the brakes.
- When Stopped
Idling is stopped automatically to inhibit fuel consumption and reduce exhaust emissions.

3. Functional Overview of the Motor Drive Unit

A functional overview of the power drive unit (PDU) is shown in Fig.2. The major functional components of the PDU consist of a power semiconductor device in the form of an insulated gate bipolar transistor (IGBT), a diode, an intelligent power module (IPM) containing a built-in protective function, a pre-driver unit equipped with the gate drive power supply for the IGBT, an input power voltage sensor and an interface with the ECU, and an electrolytic capacitor that smooths the power supply current.

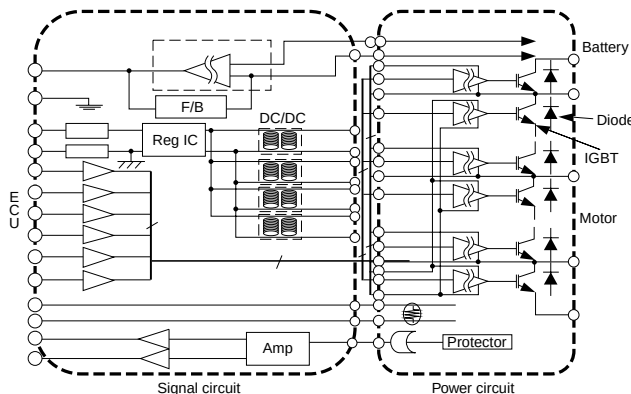


Fig.2 PDU block diagram

The motor is a permanent magnet, three-phase synchronous type. The relative positions of the stator and rotor are detected by three commutation sensors. A single cycle that is completed once for every 60° of rotation is detected by dividing into six parts, and as a result of switching six IGBTs on and off, the current and its direction of flow to the three-phase terminals U, V and W connected to the motor are switched, thereby converting electrical power from the battery to the motor or from the motor to the battery.

Drive power and regenerated electrical power are

controlled by advancing and delaying or by reducing and extending the switching timing, and by duty control.

The current that flows to the IGBT and diode relative to the current flowing to the 3-phase output can be approximated by the following expressions:

$$\begin{aligned} I(\text{IGBT}) &= 1/2 \times I_m \times (\text{Duty}/100) \\ I(\text{diode}) &= 1/2 \times I_m \times (1 - \text{Duty}/100) \end{aligned} \quad (1)$$

where I_m is the output current, and duty is the PWM duty of the input signal.

Consequently, the current flowing to the power semiconductor device can be deduced from the output current, which can be measured in an actual vehicle (motor input current), thereby making it possible to obtain the loss (calorific value) per device.

The loss characteristics of the power semiconductor device relative to the output current are shown in Fig.3.

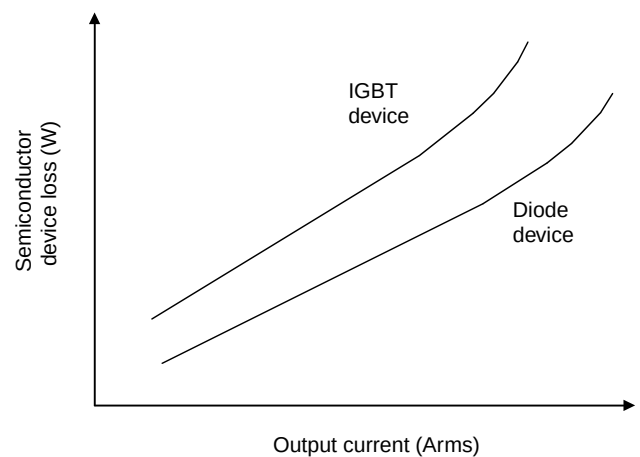


Fig.3 Power semiconductor device loss curve

4. Method for Evaluating the Durability and Reliability of the Power Semiconductor Device

The power semiconductor device, which has an important function among the constituent components of the PDU, operates at a high voltage, high current and high speed, and is exposed to harsh environmental conditions. The environment in which the components are used involves a combination of high temperature, humidity and vibration that subjects the components to stress. Since the power semiconductor device in particular generates heat, there are strict requirements for its temperature environment. Evaluations of durability and reliability were performed for the three environmental factors independently and in combination. In general, modeling these set conditions is difficult, and the establishment of a modeling technique is an important requirement. Since the power semiconductor device is a heat-generating component and is subjected to particularly severe conditions in use, load testing was conducted at various temperatures and currents to evaluate durability and reliability, the results of which are reported next.

The internal construction of the IPM containing the power semiconductor device is shown in Fig.4. The locations that reach a high temperature are especially susceptible to deterioration and malfunction,⁽¹⁾ and a summary of the operating conditions and component malfunction factors is shown in Table 1. It can be seen from this table that the environmental factors and malfunction sites are clearly defined, and that the junction temperature and case temperature should be measured as control points. Changes in the control temperature for various operating temperatures and currents when used in an actual vehicle are shown in Fig.5. Typical durability characteristics relative to stress in the form of temperature, current, etc. are shown in Fig.6 with the accompanying test data, while a Weibull chart is shown in Fig.7 for determining the reliability from the time to breakdown.

The principle verification concept was to determine the life span characteristics relative to the stress of the individual component being tested, and then to determine point A in Fig.6 based on the frequency of the vehicle use and vehicle life span. Details of the procedures used to evaluate durability and reliability are given next.

- (1) Durability data were obtained for the power semiconductor device alone (refer to the durability curve of Fig.6).
- (2) Current and temperature data were measured while

driving an actual vehicle.

- (3) The data were converted to the vehicle lifetime from the frequency data obtained in (2).
- (4) The actual vehicle data were converted to a single point temperature using the acceleration coefficient of (1), above this single point is the semiconductor life span point when applied to an actual vehicle (point A in Fig.6) (here, the t_a component is the excess time relative to actual capabilities).
- (5) Life span testing is performed under the same temperature conditions as those at point A, before plotting a Weibull chart (see Fig.7).
- (6) Since point A is the number of cycles for the vehicle life span at the acceleration temperature, the reliability can be determined by plotting the Weibull chart (see Fig.7).

As shown in Table 1 for semiconductor power devices, the IGBT chip, which is a heat-generating component, and the aluminum wire and solder that extend the electrode from the diode chip are important control points for determining life span. The critical parameter that determines the life span of the aluminum wire is the current. By measuring the PDU output current from data obtained when driving the vehicle, the current per power semiconductor device can be divided as shown in equation (1). The internal junction temperature difference (DT_j) can then be determined from equation (2) shown next.

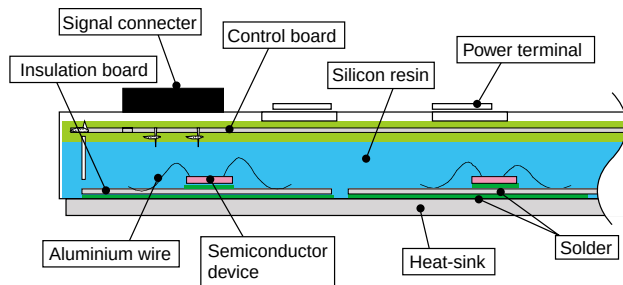


Fig.4 IPM internal diagram

Table 1 Malfunction factors

IMA driving mode	Control point	Malfunctioning point
Engine-start mode	Junction temperature	Aluminium-wire
Adjustable-speed mode	Case temperature	Chip-solder

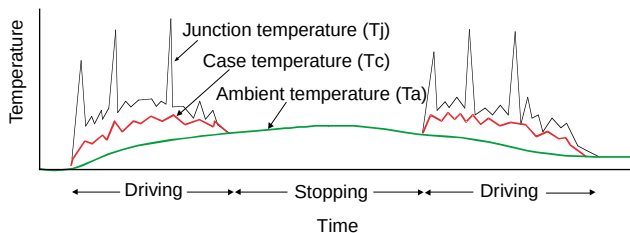


Fig.5 Vehicle temperatures transition

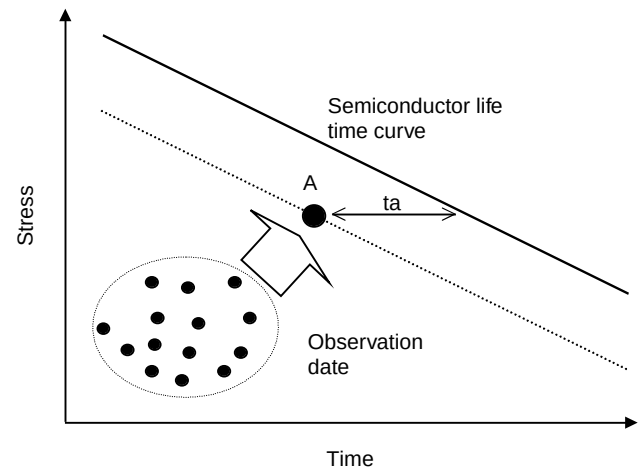


Fig.6 Durability curve

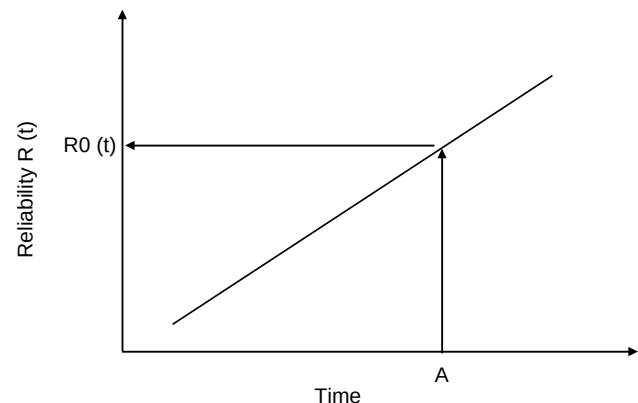


Fig.7 Weibull chart

$$\Delta T_j = R_{th} \times \{ (I_m \times V_{sat}) + P_{sw} \} \quad (2)$$

where T_j is the internal junction temperature, R_{th} is the thermal resistance of the IPM package, I_m is the PDU output current, V_{sat} is the power semiconductor ON voltage, and P_{sw} is the switching loss.

The temperature stress of the solder was determined by measuring and using the temperature directly below the IGBT chip. On the other hand, the current and temperature that determine the individual life span of the power semiconductor device were verified from the life span data obtained from a power cycle test (PCT) and thermal fatigue test (TFT).

PCT is a life span test that accelerates the deterioration of an aluminum wire carrying a heavy current, and TFT is a life span test that accelerates the solder deterioration caused by temperature changes.

5. Durability and Reliability Evaluation Results

5.1. Evaluation of the Reliability Relative to Current

Start-up current test conditions were determined by taking into consideration the engine oil type and viscosity characteristics at low temperatures as environmental effects during engine start-up. Since the run-on torque changes according to the position of the engine crank angle and the current duration also simultaneously changes, the current duration was set according to the characteristics of the various elements and vehicle data. The vehicle start-up test results are shown in Fig.8.

The longest current duration during start-up is t_1 in Fig.8. The number of times the power semiconductor device is used over the course of the vehicle life span refers to the number of times the ignition key is turned on and the number of times the engine is started after it has been stopped after idling. This number is larger than the number of times the

vehicle is started in conventional gasoline-powered vehicles. When the reliable vehicle lifetime has been reached and determined from the Weibull chart that had been prepared by plotting actual vehicle data for PCT durability under the same conditions as those for vehicle lifetime point A, the value was found to be 99.915%. In addition, although the IPM prototype installed in the IMA was a trial product made on a line that was nearly identical to the mass production line, the form of breakdown at this time was such that the shape parameter (m) was sufficiently larger than 1 ($m = 6.2$) according to the Weibull chart, thereby confirming durability deterioration.

5.2. Evaluation of the Durability and Reliability Relative to Temperature

The environmental temperature during vehicle use can be classified into radiant heat from the outside air, vehicle chassis or road surface, heat from other parts, and heat effects from the heat generation of the part itself. In consideration of market use, an environmental dynamo bench was used in vehicle tests settings, using that assumed a high-temperature environment with respect to the amount of solar radiation and so forth. Although the particular environment varies according to the location where the vehicle is used in terms of air temperature, amount of solar radiation and other parameters, a particularly harsh environment was defined in consideration of global specifications. The life span was also verified by testing vehicles in extremely hot and cold regions and gathering the test data from those vehicles.

Fig.9 shows the current, temperature and vehicle speed during general driving simulated on a dynamo bench. The case of a similar test performed while changing only the driving conditions to those for hard driving is shown in Fig.10. For both general driving and hard driving, the case temperature (base plate temperature) was 10-12°C higher than the outside air temperature. Next, driving tests were performed in the U.S., the data gathered during general

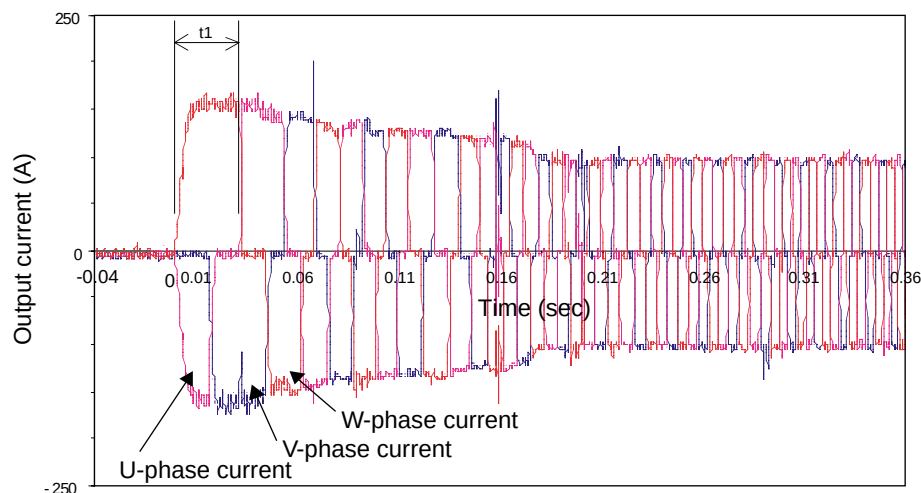


Fig.8 Starter current waveform

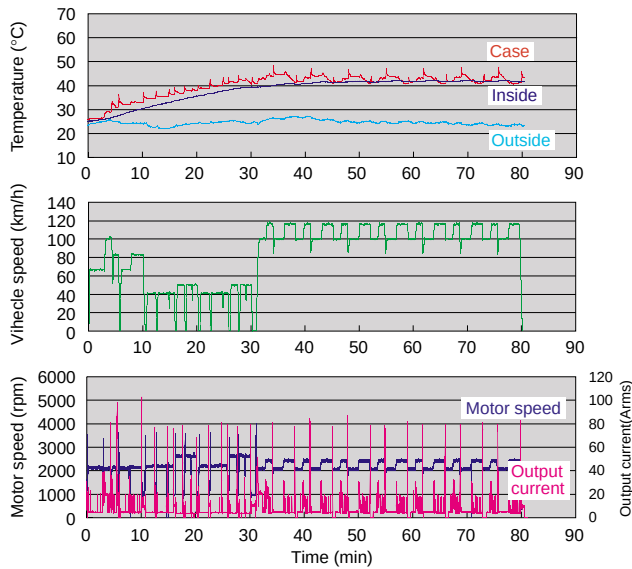


Fig.9 General driving test on dynamo bench

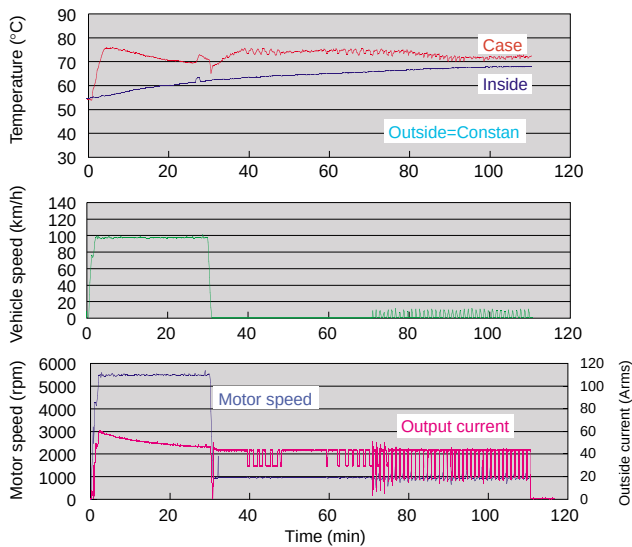


Fig.10 Hard driving test on dynamo bench

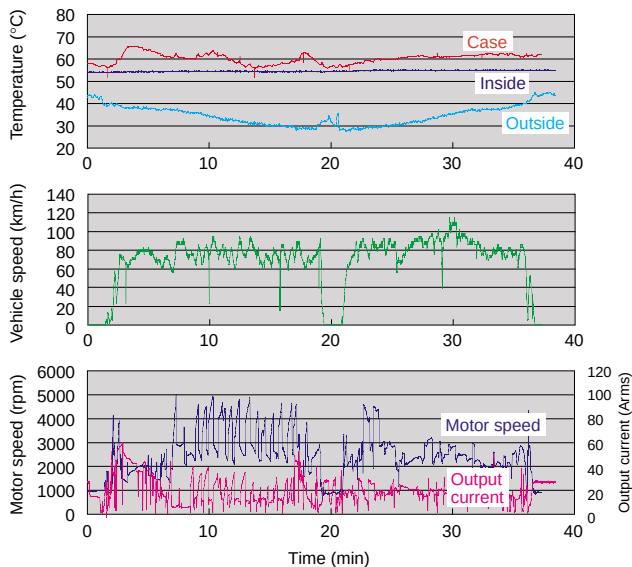


Fig.11 General driving test in U.S.

driving are shown in Fig.11, while the data taken during hard driving are shown in Fig.12. A temperature rise of 30–32°C was obtained, which is slightly higher than the data obtained on the dynamo bench. In addition, test data from cold climate region driving are shown in Fig.13. Since air cooling is used in cold- climate regions, the temperature difference until the fan operating temperature is reached is larger, with the temperature rising to about 45°C. On the basis of the above results, when the reliability for the vehicle lifetime had been determined from a Weibull chart according to point A by plotting various types of driving test data for TFT durability, values could be obtained ranging from 99.97% to 99.99%. Moreover, when the shape parameter (m) was determined from a Weibull chart in the same way as that used for evaluating the reliability relative to current, the m value was found to be 5.5, thereby confirming durability against deterioration.

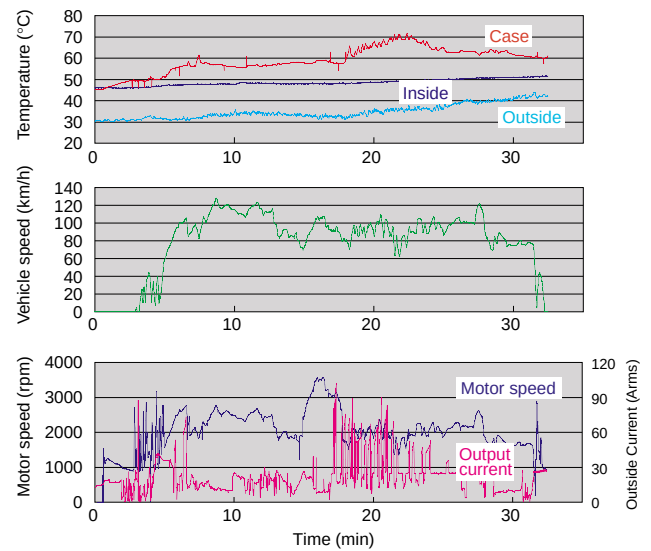


Fig.12 Hard driving test in U.S.

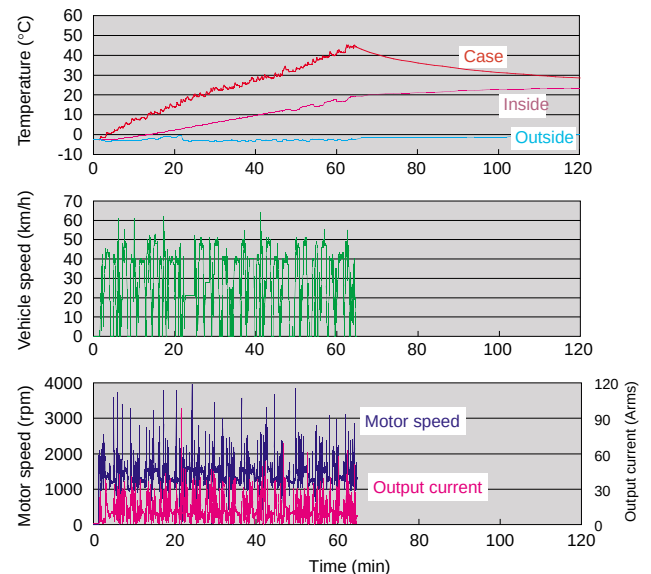


Fig.13 Cold-climate region driving test

6. Conclusion

Durability and reliability were evaluated by focusing on the currents and temperatures that affect the lifetime of power semiconductor devices. Reliability was determined using a Weibull chart drawn from various vehicle driving data and environmental test data, as well as from individual life span test data for the power semiconductor device. As a result, the reliability was determined to be 99.9% or better, and the shape parameter (m) ranged from 5.5 to 6.2, thereby confirming durability against deterioration. In addition, a method for evaluating durability and reliability under a large current load and high temperature applied to the motor driver installed in a hybrid car was also established.

References

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