

PDU for FCX Clarity

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ABSTRACT

A Power Drive Unit (PDU) has been developed for the 2009 model year FCX Clarity that conforms to the “Dynamic Full-cabin Sedan” concept established for the vehicle.

In previous models, the PDU and the driving motor were mounted separately and were connected by exposed, waterproof high-voltage shielded cables for the distribution of electric power. The newly developed PDU has been integrated with the driving motor, and the three-phase power lines are connected internally. The new configuration was enabled by the use of FEM simulations in order to develop measures to counteract wobbling, the use of vibration tracking analysis to counteract motor vibration, the employment of cooling terminals to reduce heat transfer, and the adjustment of the level of electrostatic coupling between the control circuits and the PDU case in order to reduce electrical noise.

In addition, the size of the PDU itself has been reduced by the miniaturization of components and the use of a high-density layout.

As a result of the measures indicated above, the height of the PDU and the driving motor in the motor room has been reduced by 240 mm. This has contributed to the realization of the body design concept of the 2009 model year FCX Clarity.

1. Introduction

The global rise in environmental awareness today has brought further demand for vehicles with lower CO₂ as a measure against warming. Honda sought to meet these expectations by developing the Honda FCX fuel cell car as the ultimate environmentally-compliant vehicle. Leading the rest of the world, Honda delivered fuel cell vehicles to the Japanese government and to the city of Los Angeles in the United States in 2002⁽¹⁾. The New Honda FCX (hereafter referred to as the 2005 model year FCX)⁽²⁾ was then developed. In order to promote even more widespread use of fuel cell vehicles, this model was equipped with a stack manufactured by Honda for enhanced low-temperature performance. Delivered to the State of New York in 2004 and to Hokkaido in 2005, the 2005 model year FCX was the first practical fuel cell vehicle in the world to enable operation in temperatures below freezing⁽³⁾.

In July 2008, Honda brought to the market the 2009 model year FCX Clarity (hereafter the FCX Clarity) using its original fuel cell stack, the V Flow FC Stack, as the core technology⁽⁴⁾. This model was given an eye-catching design and revolutionary packaging to make it instantly

recognizable as a fuel cell vehicle because only a fuel cell vehicle could possibly convey that vivid a sense of the future. This model also realized a whole new dimension of drive feel, and the FCX Clarity delivered not only the ultimate in clean performance, but also the embodiment of new value and appeal as a car.

The FCX Clarity realized the body design concept of a Dynamic Full-Cabin Sedan that presents innovative packaging and powerful driving performance. This was accomplished by making the entire power plant more compact and placing it in an appropriate layout. This paper will describe the development of the PDU for the FCX Clarity.

2. Development Goals

Based on the concept of the Dynamic Full-Cabin Sedan, which is founded in Honda's philosophy of Man Maximum and Mecha Minimum (M/M), the FCX Clarity adopted a short-nosed design with a compact motor room. The components inside the motor room had to be made more compact than in the 2005 model year FCX in order to realize this design. Limiting the height of the hood, in particular, was a crucial point on which the possibility of

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this design depended.

Therefore, the PDU for the FCX Clarity was developed with its size, together with the driving motor in the motor room reduced in the vertical dimension, in order to conform to the body design concept.

3. Integrated PDU and Driving Motor

The volume occupied by components in the motor room was reduced by adopting a structure that integrates the PDU with the driving motor and connects the three-phase power lines internally. The components were made compact and a high-density layout was adopted in order to reduce the size of the PDU itself. The purpose of this was to limit the increase in the space necessary to help prevent interference when wobbling occurs due to the integration of both components. These measures enabled the size of the combined PDU plus driving motor in the FCX Clarity to be reduced, as shown in Fig. 1, by 240 mm in the vertical dimension relative to the 2005 model year FCX. This contributed to realization of the short nose style.

Adoption of an integrated PDU and motor structure is effective as a method for achieving greater compactness. In order to realize this structure, however, measures had to be taken to address the following kinds of technical issues in the PDU:

- (1) Limiting deformation of the PDU case due to wobbling and absorbing the relative displacement of the PDU case from the motor case
- (2) Assuring the vibration durability of the PDU with respect to vibration originating in the motor
- (3) Limiting the rise of temperature inside the PDU due to heat transfer from the motor side
- (4) Enhancing the noise resistance of control systems with respect to the high-density layout of the internal components and the greater electrical coupling with noise sources

The technologies used to address these technical issues are introduced in the following.

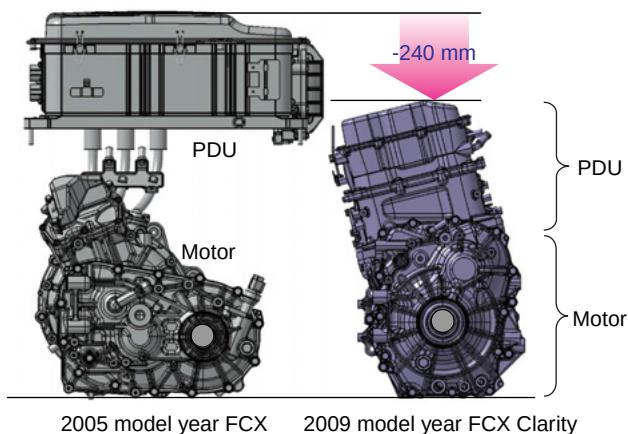


Fig. 1 Comparison of size (PDU and driving motor)

3.1. Measures to Counter Wobbling

The structure of the PDU integrated with the driving motor has the PDU and motor cases joined directly to each other with an O-ring sealing the join. The three-phase power lines are wired inside the cases. These measures enable the greater compactness. When the motor produces wobbling, a large moment is generated at the PDU case and the surfaces joined by the seal are deformed so that gaps open up. The PDU case is therefore made rigid in order to help prevent loss of the seal function.

The PDU and motor cases are further fastened together with bolts to form an integrated structure. The motor case and PDU case cannot, strictly speaking, be viewed as a single rigid body, and the connecting member for the three-phase power lines that link the two cases calls for a structure to absorb the relative displacement resulting from wobbling of the motor and PDU.

3.1.1. Rigid case design

The operating conditions under which the seal area of the PDU case undergoes maximum deformation when the PDU case is mounted in an actual vehicle were determined. An FEM analysis of strength and vibration was then carried out, as shown in Fig. 2, to help ensure that the size of the gap that opens up at the seal comes within the amount by which the O-ring is compressed even under those conditions. The figures obtained in the FEM analysis were used in deciding the position of the ribs on the case and the mounting boss, the thickness of the walls, and the location of the fastening, thus achieving increased rigidity in the case while limiting the increase in its weight.

3.1.2. Relative displacement absorbing structure of three-phase power lines

When wobbling occurs, differences in modes of

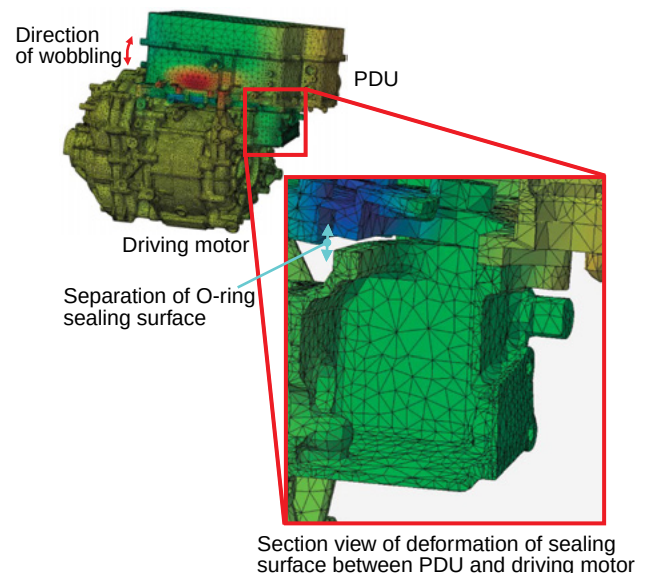


Fig. 2 Evaluation of deformation of PDU case

deformation and phase lag of response result in relative displacement, however slight, between the PDU and motor. Consequently, the three-phase power lines that form the connection between the power module mounted on the PDU and the windings affixed to the motor should have a mechanism to absorb the relative displacement between these systems produced by wobbling.

A structure as shown in Fig. 3 was adopted, therefore, in which terminals are used to fasten the bus bar from the power module to the PDU case and to fasten the motor windings to the motor case, respectively. These terminals are then joined to each other by a short high-voltage cable. This structure enables the relative displacement between the PDU and motor to be absorbed without causing the bus bar and motor windings to undergo deformation stress from wobbling.

The integration of the PDU with the motor brings the terminals on the motor and PDU sides closer together. As a result, the cables connecting the two components need to be configured into a space-saving layout. With the conventional cable structure, however, the cable has a larger diameter because of the limits on the cable's heat resistance temperature, and so a larger layout space is necessary. The following measures were therefore taken to reduce the amount of temperature increase in the cable and to raise the heat resistance temperature of the cable so that the wire diameter could be reduced and a space-saving layout realized.

- (1) Active cooling structure on the PDU terminal and motor terminal
- (2) Active cooling structure for the bus bar inside the power module
- (3) Increased cable heat resistance (heat resistance temperature raised from 120° C to 150° C)

3.2. Measures to Counter Motor Vibration

When the PDU is to be mounted on the vehicle body, as it was in the 2005 model year FCX, the frequency band

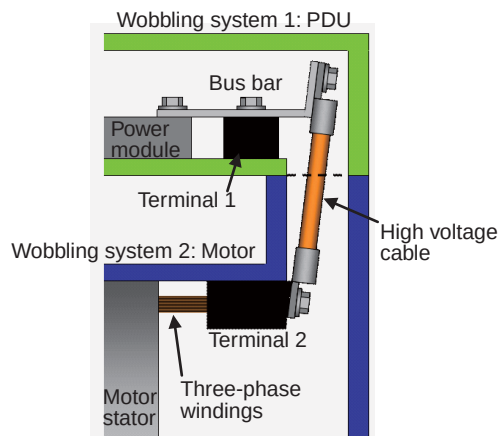


Fig. 3 Configuration of three-phase power line connection

of the vibration applied to the PDU is the same as for ordinary vehicle components. The vibration durability can be verified by the same methods used for those components.

The PDU for the FCX Clarity, however, is rigidly mounted on the driving motor. Consequently, the vibration generated by the rotation of the motor is applied directly to the PDU by means of the connecting member.

3.2.1. Motor vibration characteristics

In the case of the FCX Clarity driving motor, the most conspicuous source of motor vibration occurs when the stator deforms due to magnetic excitation of the windings. There are pluralities of modes (revolution orders) in stator deformation, depending on the slot shape and the number of electrode pairs. These states are always generated simultaneously at frequencies that are in proportion to the motor speed, so that the motor vibration can be measured as their compositional vibration.

The vibration acceleration of each mode is in proportion to the product of the vibromotive force (the magnitude of stator deformation produced by magnetic excitation) and the vibration response gain of the motor structure in the excitation frequency. Therefore, the characteristics of motor vibration, which are the sum of the vibration modes, vary in a complex manner with the changes in the motor speed and generated torque.

Figure 4 shows the results of tracking analysis of vibration characteristics in the FCX Clarity driving motor at maximum generated torque.

This graph suggests the following:

- (1) There is a specific frequency band in which the motor vibration reaches higher levels.
- (2) There is a specific range of motor speeds in which the motor vibration reaches higher levels.
- (3) When a specific mode (revolution order) line impinges on the above range, the magnitude of motor vibration becomes conspicuous.

The PDU was designed in light of these characteristics relating to motor vibration.

3.2.2. Vibration-proofing design

The design was created taking into account the

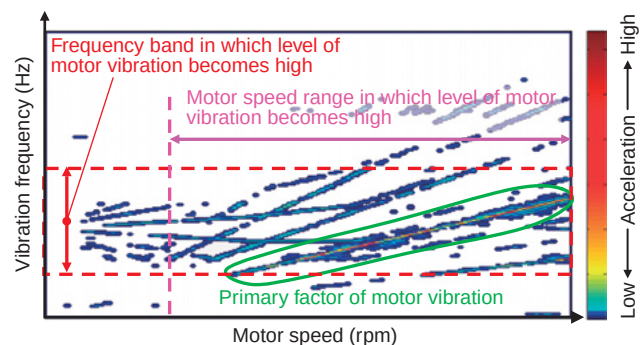


Fig. 4 Result of tracking analysis of motor vibration

methods used to constrain the various components and the configurations defining their resonance characteristics. The purpose was to help prevent any major increase in the relative displacement of the component parts due to vibration in the frequency band where motor vibration reaches a high level, based on the results from the analysis of motor vibration.

- (1) Limit relative displacement by regulating resonance frequencies: Determine the shapes of components and select the materials used in them so as to remove resonance frequencies from the frequency band at which motor vibration reaches a high level.
- (2) Fix in place with multipoint constraints: The interval between fastening points is made small for components that have a large surface area, such as circuit boards, in order to limit displacement of the component.
- (3) Vibration isolation using rubber mounts: Use rubber mounts for components for which the measures in items (1) and (2) are insufficient, in order to isolate them from motor vibration.

Figure 5 shows the distribution of resonance frequencies for the PDU parts. These frequencies were determined for every part by examining the resonance points of those parts for which vibration acceleration can be measured directly, and by calculating them from the materials and shape of other, smaller parts.

As this graph indicates, chips and other such small parts are at the high range of resonance frequencies and so are not directly affected by motor vibration. The resonance points on other parts were successfully kept out of the frequency band at which motor vibration reaches high levels.

3.2.3. Verification of vibration durability

Although the vibromotive force is small, there are components that are affected by vibratory excitation at resonance points on the order lines with the changes in the motor speed. The vibrational durability of these components was therefore verified using the procedure shown in Fig. 6.

(1) Vibration characteristics: A frequency sweep was performed on the reference sine wave input vibration and the vibration response characteristics of the PDU

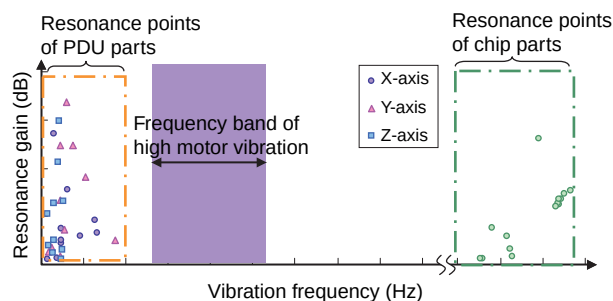


Fig. 5 Distribution of resonance frequencies of PDU parts

components were measured. The resonance frequencies for each component as well as the resonance amplification were thus identified. Further frequency analysis of the measurement results was conducted to determine the transfer function of vibration (the frequency characteristics of gain and phase) from the point of application of the vibration to the PDU to each component.

(2) Allowable level of relative displacement: The vibration characteristics for each component determined in (1) were used to conduct vibration durability tests at a high level of input vibration to determine the allowable level of relative displacement⁽⁵⁾ at which the component would not be damaged. In order to selectively excite the object component, the test frequency was set at the resonance frequency of that component, but the allowable level of relative displacement is not dependent on the frequency (Fig. 7).

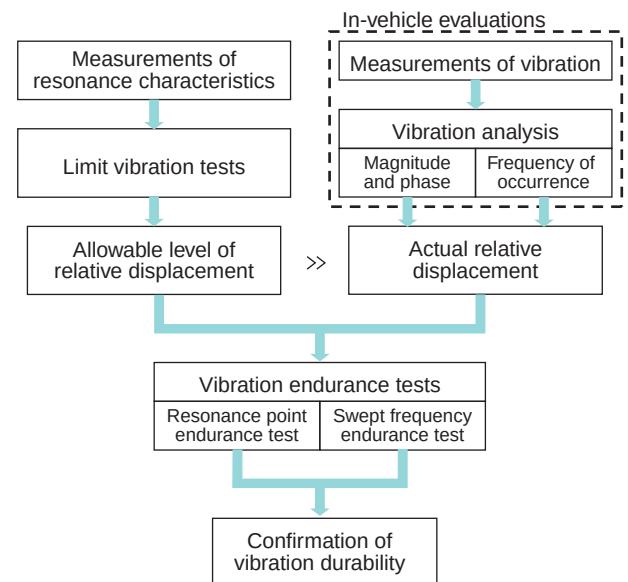


Fig. 6 Procedure for confirmation of vibration durability

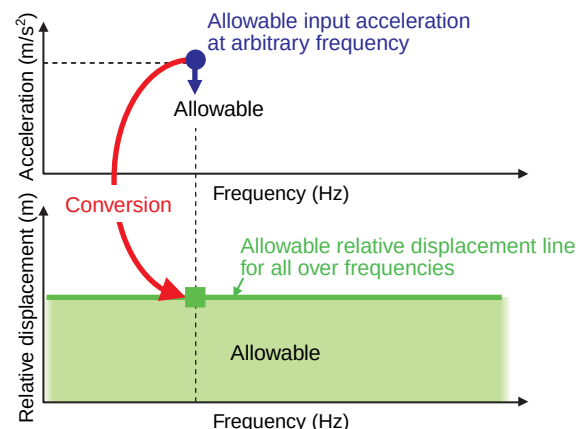


Fig. 7 Allowable relative displacement

The fact that the relative displacement of a component is at or below the allowable level means that the component is being used at a range of stress that is lower than the fatigue limit of the component material.

(3) Vibration when vehicle is in motion: Frequency analysis was conducted of the motor vibration that is applied to the PDU when a completed vehicle is in motion. This was done to confirm the vibrational state of each component (the magnitude of vibration acceleration and the frequency of occurrence for each frequency) by the vibration input in a completed vehicle, as well as the conditions of vibration under which relative displacement rises to its maximum in connected components. In this way, it was confirmed that the obtained levels were lower than the allowable level of relative displacement determined in item (2). Figure 8 shows examples of the confirmation results.

The conditions under which relative displacement reaches its maximum level are determined from the frequency characteristics of gain and phase for the vibration of each component (response) with respect to the motor vibration (input). The vibration of a given component in a certain direction can be viewed, when simplified, as a single-degree-of-freedom forced vibration by displacement such as shown in Fig. 9.

When the base (the component that is the source of excitation) vibrates in a vertical direction such that the relative displacement with respect to the base is $x(t)$, then

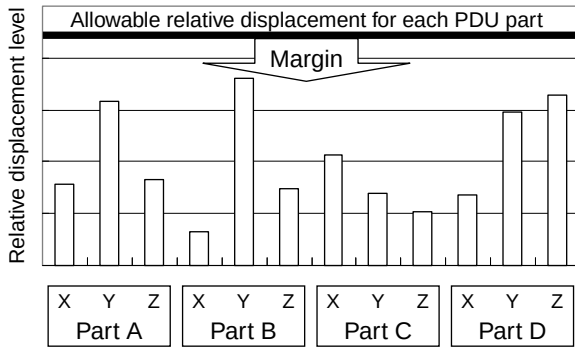


Fig. 8 Maximum relative displacement levels of PDU parts measured in vehicle

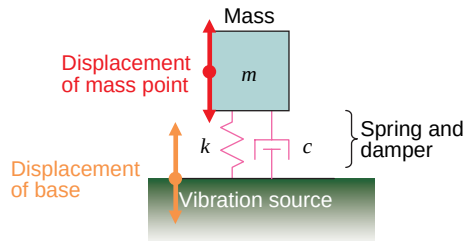


Fig. 9 Single-degree-of-freedom vibration by displacement

the equation of motion for the mass point (the component that is subject to vibration) will be (1) below, where m is the mass of the mass point, a is the amplitude of displacement of the vibration source (the component that is the source of excitation), k is the spring constant, c is the attenuation factor, and ω is the angular velocity:

$$m\ddot{x} + c\dot{x} + kx = ma\omega^2 \sin\omega t \quad (1)$$

The steady-state vibration can be expressed by:

$$x = x_{\max} \sin(\omega t - \gamma) \quad (2)$$

In this case, the magnification of the relative displacement of the vibration source and mass point and the phase lag angle can be expressed by the following equations:

$$\frac{x_{\max}}{a} = \frac{(\omega/\omega_0)^2}{\sqrt{\{1-(\omega/\omega_0)^2\}^2 + (2\xi \cdot \omega/\omega_0)^2}} \quad (3)$$

$$\gamma = \tan^{-1} \frac{2\xi \cdot \omega/\omega_0}{1-(\omega/\omega_0)^2} \quad 0 \leq \gamma \leq \pi \quad (4)$$

Figure 10 shows examples of the frequency characteristics of relative displacement and phase lag angle derived from Eqs. (3) and (4) when the attenuation ratio $\xi = 0.015^{(6), (7)}$.

The magnification of the relative displacement with respect to the input displacement reaches a maximum at the resonance condition of the component. The magnitude of the relative displacement is determined by the response gain, the phase difference, and the magnitude of the input vibration. When a large input vibration is generated at a frequency other than the resonance frequency, therefore, the conditions under which the relative displacement reaches its maximum will not necessarily coincide with the resonance conditions. As shown by the example in

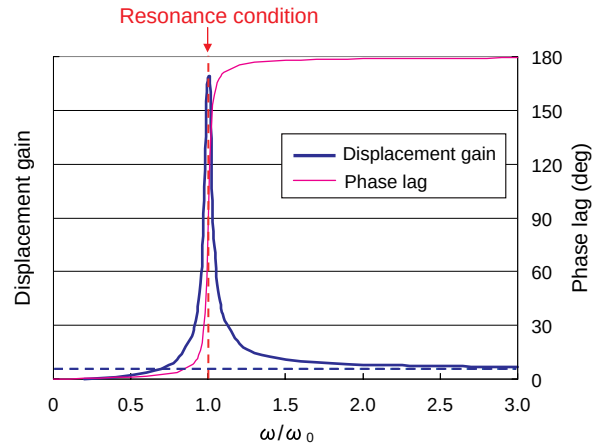


Fig. 10 Example of frequency characteristics of displacement gain and phase lag

Fig. 11, the results from measurement of relative displacement made with this PDU indicate that these conditions do coincide with the resonance conditions of the components that undergo excitation by motor vibration.

(4)Durability testing: In order to demonstrate the vibration durability of each component, the following durability testing was performed, thereby confirming that the components were undamaged:

(a) Resonance endurance test

The relative displacement of every part was analyzed from the vibration acceleration that occurred with a completed vehicle in motion and vibration conditions (the frequency and acceleration of vibration input to the resonance point) under which the relative displacement with respect to connected components reaches a maximum were identified. Resonance endurance testing was performed for every part based on the results of the above, and it was confirmed that no damage occurs.

(b) Sweep vibration endurance test

An analysis was made of the frequency of occurrence of vibration when a completed vehicle was driven in various modes. The results were used to configure a sweep vibration test profile that simulates operating life in terms of the kind of frequency, acceleration, and duration of excitation for each component shown in Fig. 12. A vibration testing device was used to conduct sweep

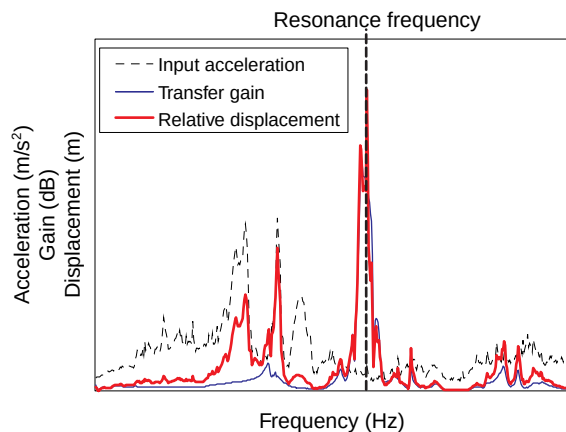


Fig. 11 Example of relative displacement characteristic

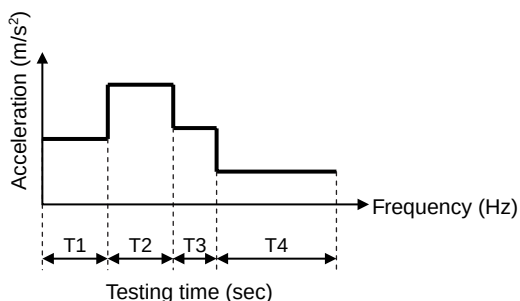


Fig. 12 Vibration profile for sweep vibration endurance test

vibration endurance tests accordingly, and it was confirmed that the components were not damaged.

3.3. Measures to Counter Heat Transfer

The three-phase windings in the driving motor reach higher temperatures than the internal components of the PDU. When the PDU and the driving motor were separate structures, the heat in the windings was released into the outside air while being conducted through the power cable connecting the two structures. Consequently, there was little impact on the PDU from heat receiving. When the PDU and the motor are integrated in a single structure, however, the three-phase power lines are housed inside the case and the wiring is reduced to the shortest length. With this layout, the heat of the windings flows into the PDU side so that the temperature of internal PDU components rises. The FCX Clarity is designed to reduce this transfer of heat from the windings while also reducing the cables to a smaller diameter, as explained earlier, by the installation in the PDU of a junction terminal incorporating a heat transfer structure as shown in Fig. 13.

The heat coming from the three-phase power lines is passed through the insulating resin and aluminum block and released on the heat sink side. As a result, the temperature rise in the block portion of the terminal due to heat receiving from the windings could be reduced by approximately 11°C, as shown in Fig. 14.

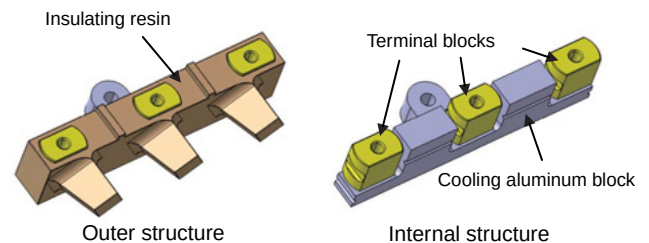


Fig. 13 Structure of cooling terminal for PDU

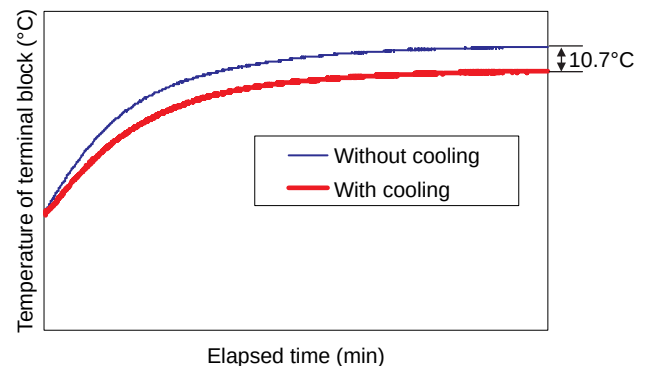


Fig. 14 Effect of cooling terminal for PDU

As shown in Fig. 15, the bus bar inside the power module and the terminal on the motor side also have cooling devices built in. This reduces the heat transfer from the power elements and motor.

3.4. Measures to Counter Noise

Electrically floating configuration is used to isolate the high-voltage power lines in the FCX Clarity from the body, and the interface between the PDU and outside circuits is entirely a low-voltage system, with the exception of the high-voltage power cables. The PDU consists of a power circuit section, which performs high-power switching using semiconductors, and a control circuit section, which functions as an interface between the inverter switching control and external devices. These are located inside the same metal case (Fig. 16).

In order to help prevent malfunctions of the inverter circuits and control circuits due to noise and to strengthen tolerance against EMI, the high- and low-voltage circuits inside the same case should be kept separated as far as possible. This goal, however, is incompatible with the use of a high-density layout. Consequently, the geometry of the high-voltage wiring assembly, its distance to the control board, and its location were optimized in order to limit the effects on the PDU control board produced by conductive and radiation noise from the high-voltage wiring, as well as to enhance the high-density layout. This

achieved a balance between the use of a high-density layout and the measures against noise.

In the motor, a stray impedance is present between the motor windings and housing, and, for structural reasons, a flow of noise currents is generated during inverter switching. These currents conduct noise throughout the entire vehicle and may sometimes affect the quality of the vehicle as a commodity because of radio noise, malfunctions in other components, and the like. Optimization was therefore performed with a line bypass capacitor used inside the PDU to feed back the noise currents and limit the influence of noise on the vehicle.

Another consideration is that when these feedback currents travel through the PDU case, they may sometimes cause malfunctions in the control boards through stray capacitance between the frame around the printed circuit board (PCB) that serves as the control board inside the PDU case and the copper foil patterns in the PCB's inner layers. One example of the means used to address this issue, as shown in Fig. 17, is to maintain the distance between the wiring patterns inside the circuit board and the rim of the metal frame that holds the board by keeping the two from overlapping. This structure keeps the stray capacitance between the two at or below a certain level, and thereby optimizes the noise level.

These measures succeeded in reducing noise levels. Figure 18 shows the results.

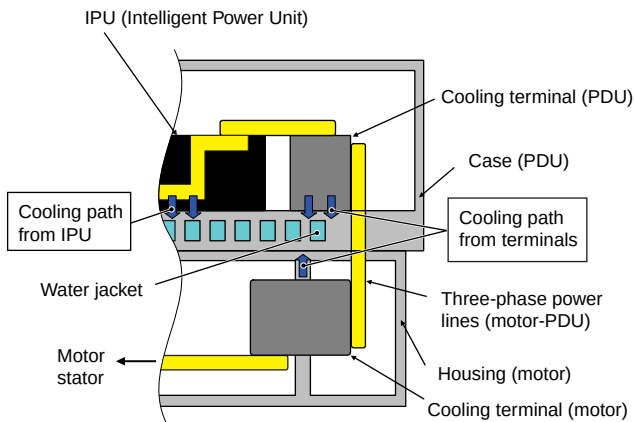


Fig. 15 Structure of cooling system for three-phase power line

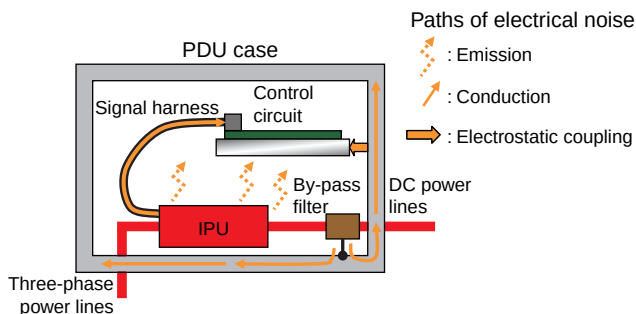


Fig. 16 Noise environment of PDU

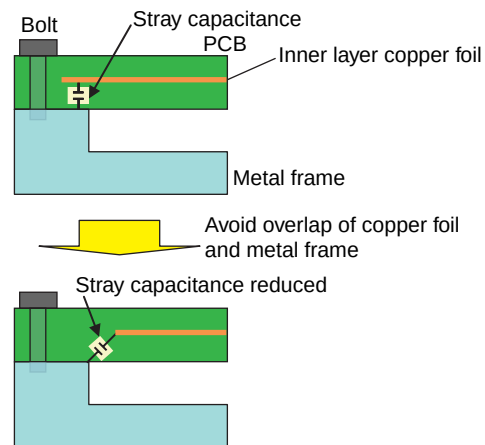


Fig. 17 Reduction of stray capacitance between inner layer copper foil and metal frame

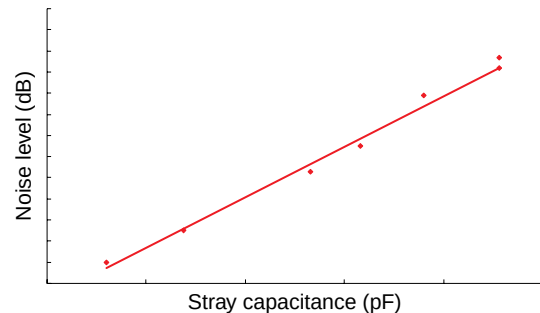


Fig. 18 Effect of reduction of stray capacitance

4. Conclusion

A PDU integrated with the driving motor was developed in order to limit the size of the integrated structure in the vertical direction inside the motor room.

- (1) The high-voltage cables are laid out to make the shortest possible connections inside the PDU case, thereby realizing a compact connecting structure for the three-phase power lines that also includes a mechanism to absorb the relative displacement between the motor and PDU when wobbling occurs.
- (2) Vibration-proofing design was carried out according to the results from analysis of motor vibration characteristics, thereby assuring the durability of the PDU against motor vibration.
- (3) Terminals incorporating a cooling structure enable heat from the three-phase power lines to escape to the heat sink side, thereby reducing the increase in temperature by components inside the PDU due to heat receiving from the motor windings.
- (4) The geometry of the high-voltage wiring assembly, its installed position, the position of the control board, the capacity of the line bypass capacitor, and the stray capacitance between the pattern wiring of the control circuit PCB and the frame, were optimized. These measures limited the effects on the control board and vehicle body from noise due to conduction, radiation, and electrostatic coupling, thereby enabling realization of a high-density component layout.

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