

Development of High Power Density DC-DC Converter for IMA

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ABSTRACT

A smaller and more powerful 12V DC-DC converter has been developed for Honda's Integrated Motor Assist (IMA) system. Low breakdown voltage FETs and a beam lead diode module in combination with high-efficiency soft switching circuits have reduced energy loss to increase the efficiency of the unit. Heat dissipation simulations were employed to optimize the component layout for efficient cooling. The new unit employs a digital signal processor, and the reduction in component numbers enabled by digital control has resulted in a 40% reduction in the size of the circuit board of the control section. The application of these technologies has enabled the unit volume to be decreased by 17% while output current has been increased by 60% against the former model.

1. Introduction

The demand for higher fuel economy and lower emissions for automobiles has been increased in order to ameliorate the global environment and conserve fossil fuels. Honda has responded to this demand by offering the high fuel economy and clean hybrid vehicles employing a lightweight, compact Integrated Motor Assist (IMA) system. In 1999, Honda introduced the Insight⁽¹⁾, and in 2001, the CIVIC Hybrid⁽²⁾. In December 2004, the ACCORD fitted with an enhanced IMA system giving even higher performance was launched in the North American market. This paper introduces technologies used in the development of a compact DC-DC converter with high output for the IMA system installed in the ACCORD Hybrid.

The DC-DC converter is one part of the Power Control Unit (PCU), converting high voltage electricity to 12 V. As shown in Fig. 1, it is placed in the Integrated Power Unit (IPU) in the rear of the vehicle, together with the high voltage battery.

In an ordinary gasoline vehicle, electricity generated by the alternator, which is powered by the engine, is supplied to the 12 V electrical devices such as lights, audio system, and ECU. In contrast, an IMA system uses a DC-DC converter to reduce high voltage electricity to 12 V before supplying to the devices as shown in Fig. 2. When the vehicle decelerates, the Power

Drive Unit (PDU) converts the regenerated energy from the IMA motor to direct current (DC) at high voltage to recharge the batteries. In addition, it is possible to have electrical supply from the high voltage battery, even when the engine is off during idling stop.

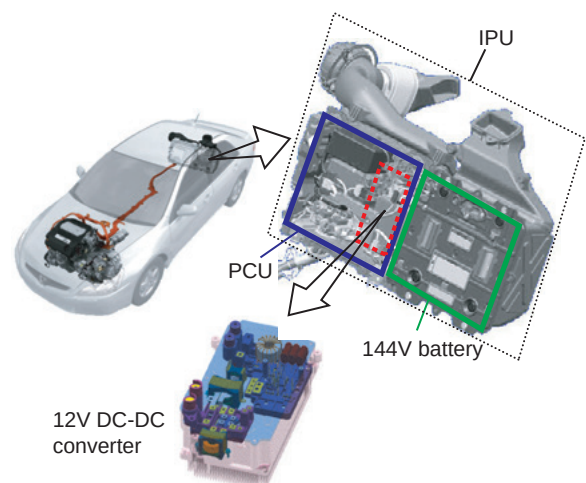


Fig. 1 Layout of DC-DC converter

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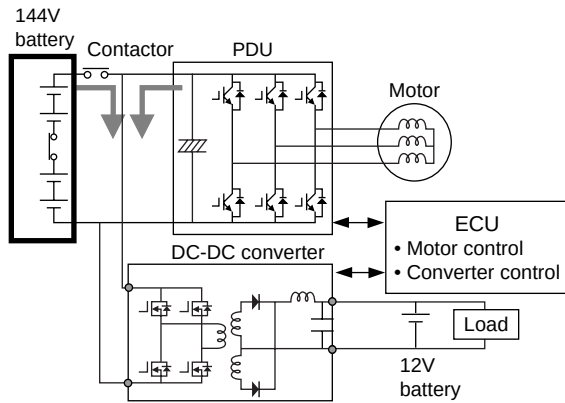


Fig. 2 IMA system

2. Development Goals and Means of Achievement

2.1. Development Goals

The DC-DC converter in the IMA system for the ACCORD Hybrid is required to provide greater output to enhance comfort features appropriate to the vehicle class, and electrical devices that contribute to fuel economy. It was also necessary to make the system more compact in order to fit it to the same body as the gasoline vehicle. Specifically, development goals were set as below based on the current DC-DC converter for the CIVIC Hybrid.

- (1) Output Current +60%
- (2) Volume -15%

2.2. Means of Achievement

In order to achieve a compact, high-output DC-DC converter, the following methods were studied.

- (1) Higher output through reduction of element loss
Reduction of element loss decreases junction operating temperature for the same current. This decrease in temperature increases maximum forward current, enabling higher power to be output.
- (2) Reducing size by enhancing cooling performance
Enhancement of the cooling performance of the heat sink that disperses the heat from the element allows the converter to have a layout that concentrates the heat generating parts, enabling the converter to be made smaller.
- (3) Reducing size by reducing the number of parts and by having a higher density package
Change of the control circuit method and radio noise restraint method reduces the number of parts, and at the same time, raises actual element installation density, enabling the converter to be made smaller.

3. Technologies for Making a Compact Converter with Higher Output

3.1. Higher Output through Reduction of Element Loss

3.1.1. FET for switching

A Field Effect Transistor (FET) was adopted in the switching circuit. The switching circuit consists of an H bridge that is connected in parallel to the high voltage battery and PDU. With this FET, the lower the breakdown voltage, the smaller the on

resistance, so it is possible to reduce loss. However, if the FET breakdown voltage is reduced, there is the possibility that when the electromotive force generated by the motor is raised, the voltage applied to the FET would exceed the element breakdown voltage. To address this, the over-voltage protection circuit was accelerated.

Figure 3 gives the DC-DC converter input voltage waveform, and the FET switching waveform. When the input voltage rises to the operating voltage of the over-voltage protection circuit and after a finite circuit response time passes, FET switching stops.

With the over-voltage protection circuit, the circuit board was designed to enhance toughness against switching noise, and revisions were made to the filter constant, shortening response time. As a result, switching voltage rise was controlled, making it possible to use low breakdown voltage elements having low loss features. FET on resistance, as shown in Fig. 4, is 47% less than the previous unit, and the reduction in loss is proportional to this.

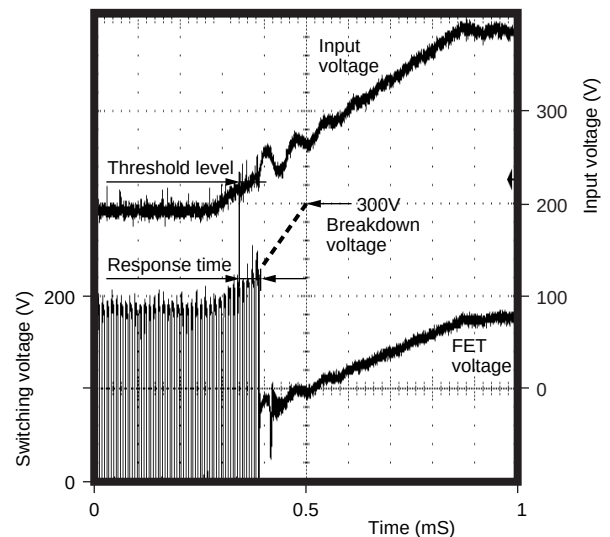


Fig. 3 Waveform of FET showing operation of voltage protection

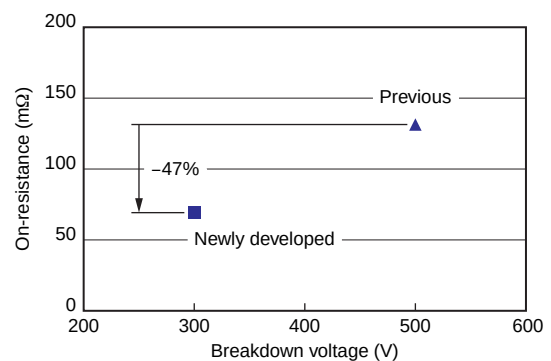


Fig. 4 Reduction of on-resistance

3.1.2. Output rectifying diode

By enlarging the output diode chip size to the limits where it can fit in the module, it is possible to reduce current density. Through these technologies, forward threshold voltage can be reduced from the 0.95 V of conventional products at the same current, to 0.85 V. As shown in Fig. 5, diode module loss is reduced by 11%. Because diode loss is expressed as the product of forward threshold voltage and output current, reducing the forward threshold voltage makes it possible to reduce element heat generation, making a smaller module possible.

Furthermore, the diode module package was given a beam-lead structure, as shown in Fig. 6. The connection between the diode chip anode and the anode terminal was changed from wire bonding to a beam-lead method. This allows large current to flow evenly through a thin copper sheet, enabling the height of the chip in the vertical direction to be minimized in comparison with the wire type.

As noted above, loss is reduced with the adoption of a low breakdown voltage FET and enlarged diode chip size, thereby minimizing heat generation while increasing output current. Combined with the benefits of a beam-lead structure, it is possible to increase output current from 75 A to 120 A while keeping the size of the module the same as the conventional module.

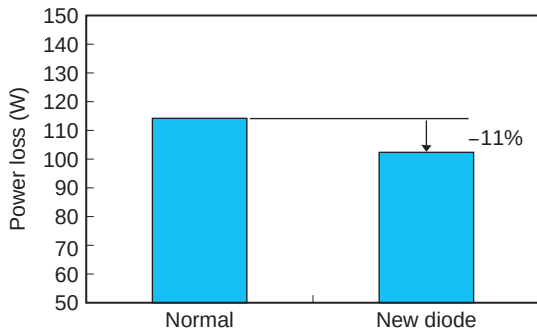


Fig. 5 Power loss characteristics of diode

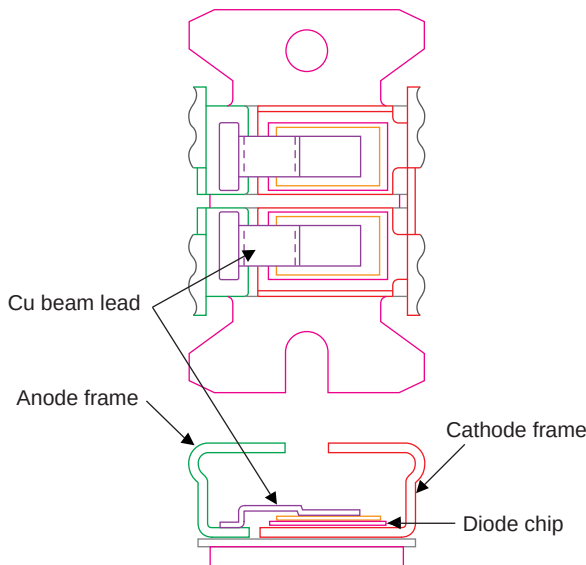


Fig. 6 Structure of diode module

3.2. Enhanced Cooling Performance

Studies were carried out of the layout of heating elements and of the heat sink shape in order to enhance cooling performance.

3.2.1. Layout of heating elements

The devices that require cooling are the FET (switching element), resonance choke necessary for partial resonance control, main transformer that forms the current path, output diode, and output choke. A simulation was carried out to determine the effect of the layout of these parts, the thickness of the heat sink, the length of the fins, and the pitch of the fins on heat radiation and the reduction of heat resistance.

Figure 7 shows temperature distribution when looking at the DC-DC converter from above. The FET has its four elements laid out so that there is no heat interference between them, minimizing temperature rise. The output diode is placed on the windward side to effectively utilize the fins. For the output diode, in order to disperse the heat, the heat spread plate is placed on the bottom of the module, raising heat radiating capability.

3.2.2. Heat sink shape

The heat sink is formed through die-casting. To realize increased heat radiating performance, the surface area of the heat radiating fins was enlarged 30% over the previous unit. In addition, the case and the fins were integrated to counter the radio noise and to reduce

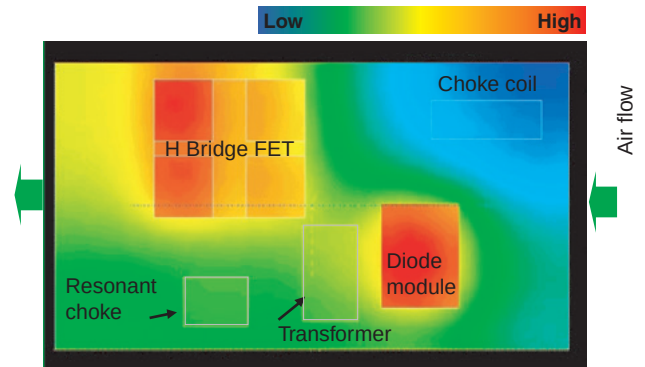


Fig. 7 Simulation of temperature distribution

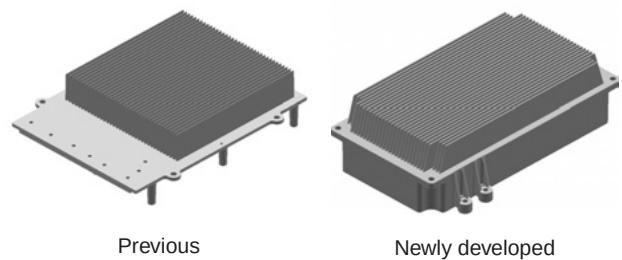


Fig. 8 Case design

the number of assembly processes. As a result, as shown in Fig. 8, the heat sink mold depth is at least twice what it was, and occurrence of air bubbles during forming was expected.

Figure 9 shows the results of the molten flow simulation. Before countermeasures, the metal flow concentrates along the walls, so the flow path becomes long and the molten material does not reach all areas of the fin, creating air pockets. In comparison, with the change to the gate shape and establishing a slope on both ends of the fin, the molten material flow is enhanced.

3.3. Reducing the Size by Digital Control

The highly efficient soft switching method⁽³⁾ that has traditionally been adopted was digitalized⁽⁴⁾ using a Digital Signal Processor (DSP) to make a smaller control board.

3.3.1. Phase shift control

As shown in Fig. 10, the DC-DC converter has constant voltage control from light load to rated output of 120 A. In the over electric current zone of 120 A and higher, voltage drooping characteristic control is carried out in order to reduce output voltage. Based on commands from the ECU, each voltage control determines the target output voltage, and the FET's are switched (from Q1 to Q4) by the PID control so that the target voltage is reached. The control circuit

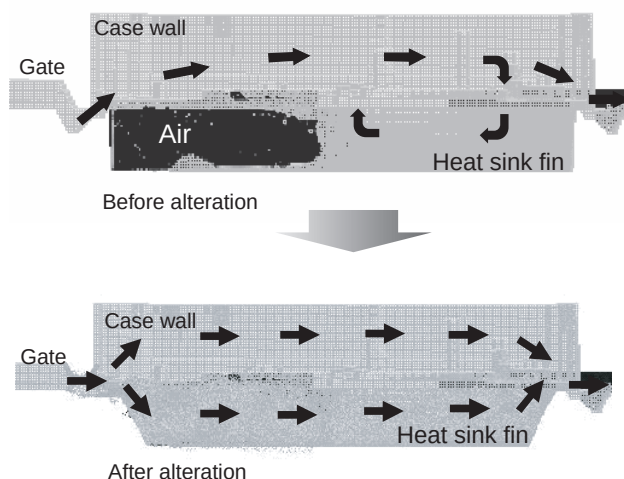


Fig. 9 Flow simulation of molten model

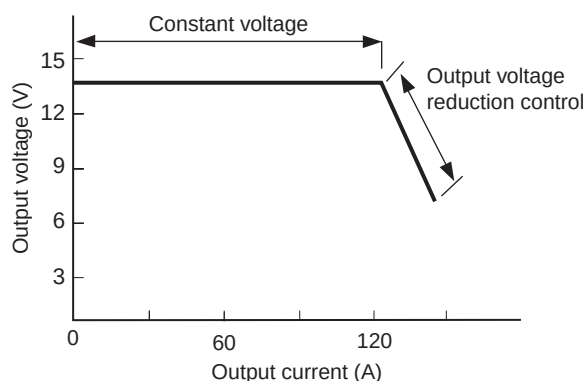


Fig. 10 Output characteristics

is composed, as shown in Fig. 11, of four FET in an H bridge circuit. By shifting Q4 phase with Q1 phase as the reference^{(5),(6)}, the current flows from Q1 to Q4 through the transformer. Q2 and Q3 also operate according to the timings shown in Fig. 12, generating voltage in the transformer. Through full-wave rectification of this voltage by the output diode, direct current output is obtained. Understanding of the output voltage and current state in this way enables voltage control and current control to be carried out.

3.3.2. Digitalization

If these controls are composed of general-purpose analog phase shift control IC's, there are issues in their use for the vehicle, such as not recovering from a stationary state due to latch operation when self-protection happens to operate. In this case, a latch release circuit has to be added as another external part. Therefore, it was necessary to produce a special customized IC. When carrying out phase shift control using a DSP, output voltage and current are input from the AD converter, and FET phase is digitally controlled so that it is at the target output voltage.

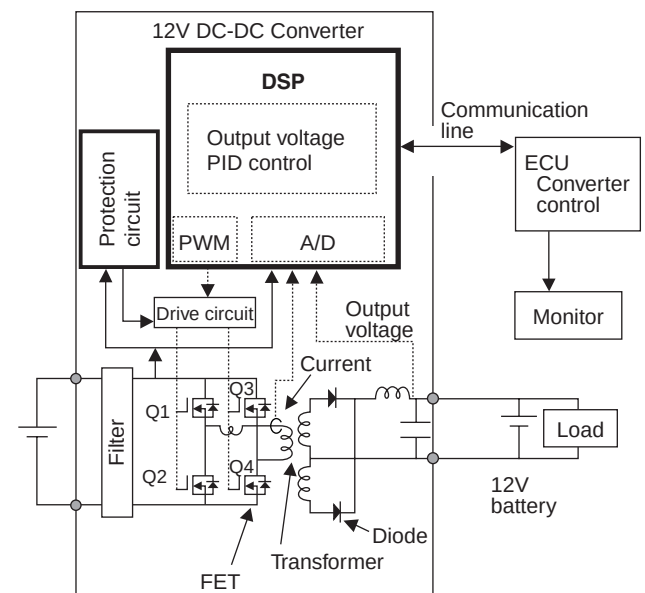


Fig. 11 Control block

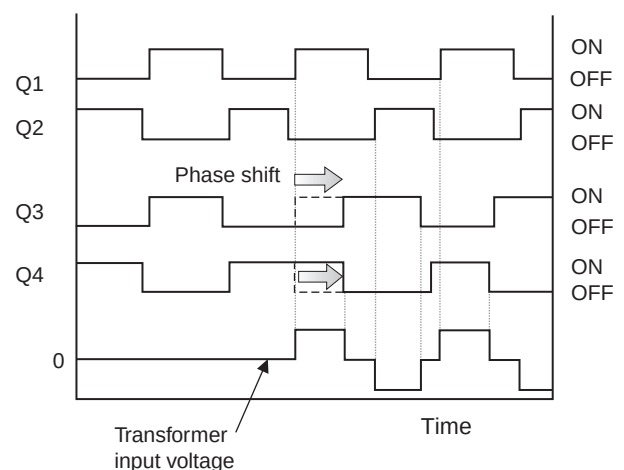


Fig. 12 FET switching pattern of phase shift control

Additionally, using DSP programs, it is possible to carry out operations such as information transmission as well as protection operations. These operations include sequencing operations based on commands from the vehicle ECU, cooling requirements to the ECU, requirements for warning lights, etc., for which it was necessary to have external parts when using analog circuits.

Furthermore, it is now possible to freely set the current change rate and the voltage change rate when the DC-DC converter is activated or stopped. Adjustable settings are also possible that match the vehicle high voltage battery management. Figure 13 shows the soft start and soft stop current waveform.

When the analog circuit has the configuration of operations necessary as a vehicle power supply system, the scale of the circuits becomes larger due to consideration of circuit part constant variations and temperature characteristics. In comparison with the use of analog circuits, digital controls can actualize diverse operations with high accuracy, using simple circuits. When comparing the same control specification, a digital circuit requires approximately 300 parts, while an analog circuit requires approximately 500 parts. Due to this reduction in the number of parts, it is possible to reduce the size of the circuit board as shown in Fig. 14.

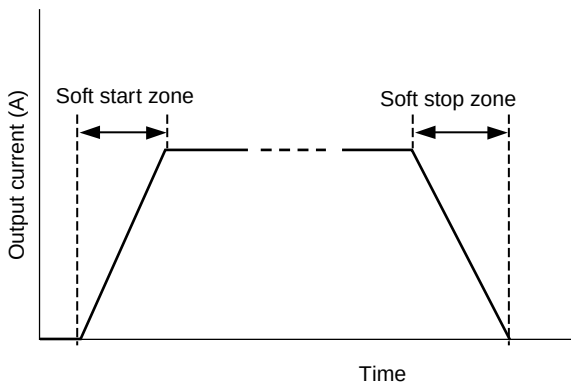


Fig. 13 Start-stop characteristics

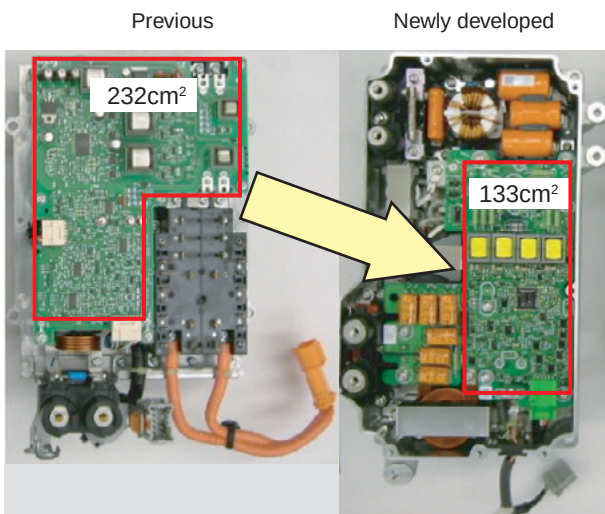


Fig. 14 Reduction of circuit board size

3.4. Reducing the Size of the Filter Preventing Radio Noise

The switching noise harmonics were matched with the AM radio broadcast carrier wave so that the effect of DC-DC converter switching noise on the in-vehicle radio is minimized and the noise filters can be reduced. The switching frequency was matched with overseas and domestic broadcast carrier waves. Figure 15 shows a schematic diagram of the alignment between broadcast carrier waves and interference waves. If the noise frequency is the same as that of the broadcast wave's carrier, the radio does not detect noise, and there is no mixing of noise in the voice signal. In addition, the switching frequency is derived by dividing down the DSP clock frequency of 36 MHz, so it is highly accurate. Therefore, the effect on radio audio due to departing from the broadcast carrier waves is eliminated. Through the means outlined above, it is possible to reduce the reliance on filters, and to reduce the large noise filter parts.

4. The Effects of Being Compact and Having High Output

The results of making the DC-DC converter with smaller size and higher output are shown in Table 1. In addition to the output current being increased 60%, there was a reduction in volume of 17%. As shown in Fig. 16, efficiency was raised by 1.5% in the normal operation range in comparison with the previous model.

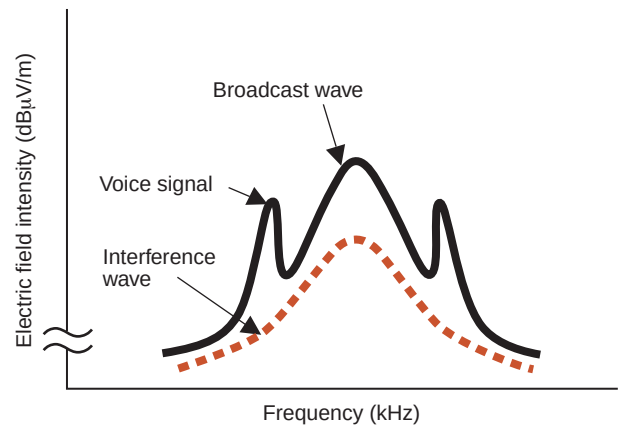


Fig. 15 Interference wave characteristics

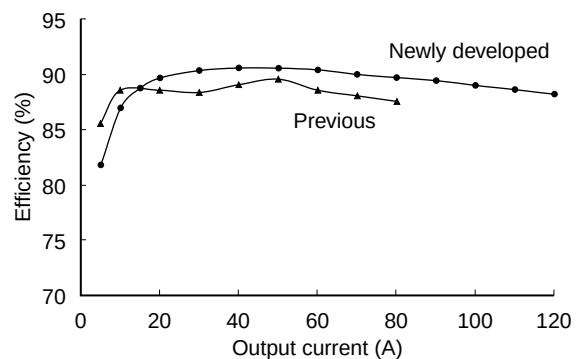


Fig. 16 12V DC-DC converter efficiency

Table 1 Specifications of DC-DC converter

	Previous	Newly developed
Output current (A)	75	120
Dimensions (mm)	178 × 60 × 235	150 × 50 × 250
Volume (cm ³)	2510	2100
Current density (mA/cm ³)	30	57

5. Conclusion

The following measures have been taken to develop the smaller DC-DC converter with higher output for the ACCORD Hybrid's IMA system.

- (1) A low breakdown voltage FET and a diode module having a beam-lead structure were employed to increase converter efficiency.
- (2) A heat dissipation simulation was carried out to develop a part layout that provides efficient cooling.
- (3) Digital controls using DSP were employed to reduce the number of parts, enabling the control circuit board to be made 40% smaller.
- (4) Switching noise harmonics were matched with AM radio carrier waves, minimizing the effect on audio signals. This reduced the number of filter parts.

As a result, in comparison with the previous DC-DC converter, output current is increased by 60% while volume is reduced 17%.

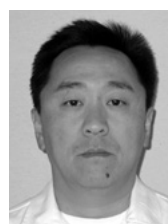
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