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DEVELOPMENT OF INVERTER AND POWER CAPACITORS FOR MILD HYBRID VEHICLE (MHV) – TOYOTA "CROWN"

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ABSTRACT–The 42V Mild Hybrid System has been released into market by Toyota for the first time in the world in 2001. The set-up employs an inverter unit to control the motor/generator (MG) electronically. The driving system called such as Toyota Mild Hybrid System (TMHS) has additional new functions to conventional internal combustion engines. When stopping vehicle, the engine stops promptly. When starting vehicle, by releasing the brake pedal MG starts the vehicle at the same time (EV-driving mode). When stepping on the accelerator pedal, or after a given period of time the engine firing occurs and the engine-driving mode starts. When running by motor, the power is supplied to the motor from 36V battery through the inverter. High outputs and instant responses are required for Inverter. At the same time, the compact volume is required to fit into the limited space of the engine room. The compact size and high output are also required to Power Capacitor used for this inverter. The power capacitors has been newly developed, shaped in "flat" type, suitably for the inverter. The points of developments on inverter and power capacitor are described in this paper.

KEY WORDS : HEV (hybrid electric vehicle), Inverter, Powertrain

1. TOYOTA MILD HYBRID SYSTEM

This system is aimed at reducing exhaust gas emissions, fuel consumption and idling noise, by adding new functions – idle stop in particular – to conventional internal combustion engines.

When stopping vehicle: The engine stops promptly and smoothly while being controlled by the motor/ generator (MG). Upon request for activation of the air conditioner or power steering, the air conditioning compressor or power steering pump can be activated with the engine stopped.

When starting vehicle: The moment the brake pedal is released and MG starts the vehicle at the same time (EV-driving mode). When the driver steps on the accelerator pedal, or after a given period of time has passed, engine firing occurs and the engine-driving mode starts.

When running in ordinary condition: The vehicle runs powered by the engine, same as ordinary vehicles.

When decelerating: Upon braking, the wheels activate the MG for power regeneration, and some of the brake-deceleration energy is recovered and stored in the battery.

Due to the above functions, vehicles equipped with this system have increased the fuel economy by 15% (in 10~15 mode) in comparison with conventional vehicles.

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2. SYSTEM CONFIGURATION

Figure 1 shows the appearance of the system. Figure 2 shows the system configuration. Since extensive applicability was a prerequisite of the Mild Hybrid System, emphasis was put on the installation ease. And MG, expected to work as the prime mover of the system, is designed to minimize the engine modification. Specifically, it is installed at the location where the alternator used to be installed in the conventional system. The power is transmitted through the belt. The starter remains in the configuration, as it is necessary to start the engine in the configuration, as it is necessary to start the engine in the initial state (MG can be activated only after the engine is warmed up). The size of MG is minimized by suppressing the torque requirement. Aiming at a compact design, the inverter, DC/DC converter and the total system control unit are combined into a single structure so that the resulting unit can be accommodated in the space provided for the conventional battery.

An electromagnetic clutch is provided as a shut-off mechanism between the engine and the belt for the auxiliary equipment. Owing to this clutch, the driver can use two comfortable systems – air conditioner and power

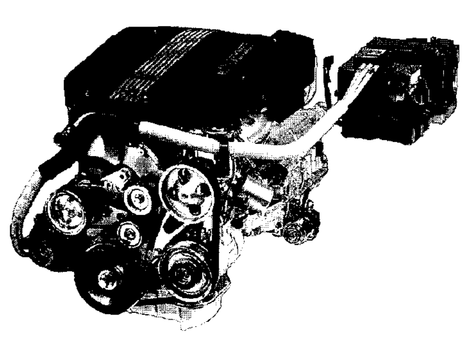

Figure 1. Appearance of the toyota mild hybrid system.

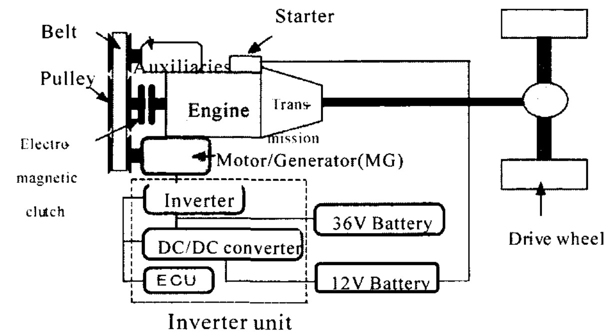

Figure 2. System configuration.

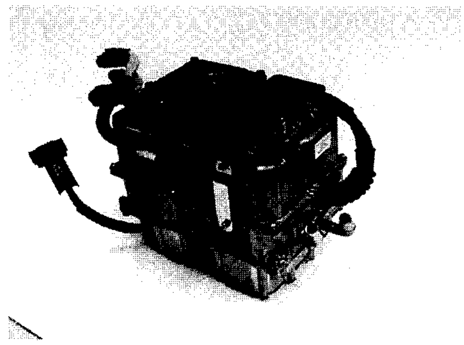

Figure 3. Appearance of an inverter unit.

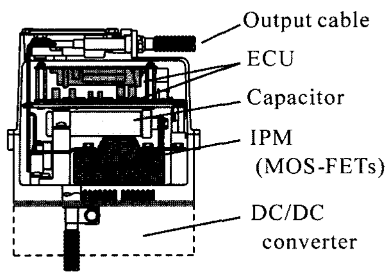

Figure 4. Inner structure of the inverter unit.

steering – easily even if the engine is stopped.

Two power supply systems of 42V and 14V are installed. One is for MG, and the other for the conventional power supply. The MG through the inverter charges the 36V battery, while the DC/DC converter charges the 12V battery. As the main power supply is the 42V system, it should be able to cope with the power requirements of the next generation 42V vehicles.

3. INVERTER UNIT

The inverter unit is a control unit built into a single module incorporating three parts – the inverter itself, DC/DC converter and MHV-ECU, with a coolant conduit situated among them. The size of the unit as a whole, is reduced by incorporating the MHV-ECU, resulting in, not only cost reduction of the entire system, but also enhancement of reliability. Moreover, both the installation ease and high production efficiency are established, while improving wire harness design.

Figure 3 shows the appearance of the inverter developed under this study, and Figure 4 shows the inner structure. The size reduction is accomplished by using the newly developed compact 6 (arms) in 1 (module) Intelligent Power MOS-FET Module (IPM), and a Flat type aluminum electrolytic capacitor (Power Capacitor). Furthermore, the cost reduction of the entire system is achieved by incorporating the Mild Hybrid System and the DC/DC converter on opposite sides, and sharing the water-cooling system between them. In order to facilitate the installation on vehicle, the three-phase output unit and the harness connector are set on the top of inverter to enable easy connection.

The power capacitor has been newly developed, and has a high heat discharge rate. The details of the development are described below.

4. DEVELOPMENT OF POWER CAPACITOR

The inverter requires high outputs and instant responses. At the same time, the compact volume is necessary for fitting into the limited space of the engine room. The volume of the inverter is 6 liters.

For this application, the compact size and high output are also required for power capacitor. The power capacitors have been newly developed, shaped in "Flat-type" suitably designed for the inverter.

4.1. Performances of Power Capacitor

In order to reduce the size of power capacitor, the reduction of element temperature should be reduced. There are two approaches for that purpose – one is to reduce the electrical loss by lowering the impedance of

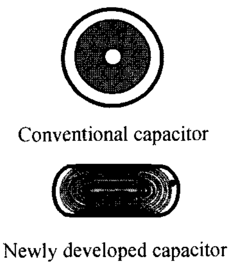

Figure 5. The shape of the capacitor (horizontal cross-section).

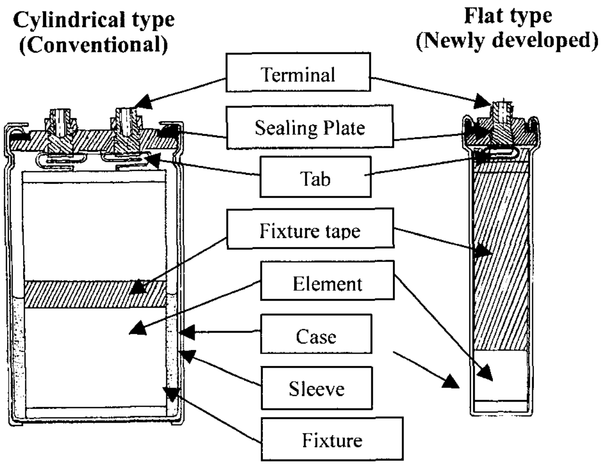

Figure 6. The construction of the capacitor (vertical cross-section).

the element, and another is to increase the heat discharge performances. The author *et al.* have taken the both approaches in a joint study. And the achievement has been made as size reduction by 40% compared with the conventional capacitor.

Figure 5 shows the shapes of the conventional capacitor and the newly developed capacitor. Figure 6 shows the vertical cross-section of the conventional and newly developed capacitors. In case of the conventional one, a space is provided over the entire circumference between the element and the case to suppress the rise of inner pressure. This accounts for the deterioration of heat discharge rate. The volume is also large due to its cylindrical shape. In case of the newly developed capacitor, the case is flattened with both sides of the element adhered to the case. Also, the cathode box is touching the bottom of the case, for increasing the heat discharge rate.

4.2. Improvement of Space Factor

The flat type capacitor has superior features compared with the cylindrical type capacitor in space effectiveness.

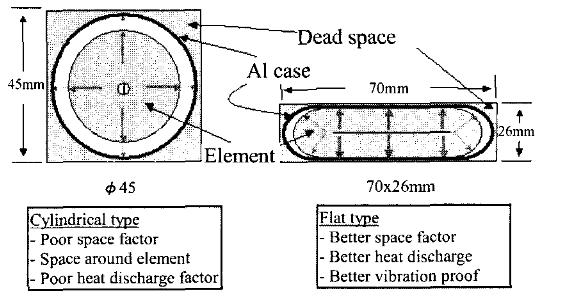

Figure 7. Improvement of heat discharge by space factor.

Figure 7 shows the space effectiveness between the flat type with 70×26 mm and the cylindrical type with ϕ45 mm, which has the equivalent mounting area. When actually required area has been compared, the occupied area by the cylindrical type capacitor is about 80%, while the area is about 90% by the flat type capacitor.

4.3. Higher Ripple by Improvement of Heat Discharge Factor

The temperature at the core of capacitor element shows the highest temperature by the nature of capacitor structure, when a ripple current is superimposed. The temperature

Comparison of performance

Rating	100WV-7500 μF
Flat type	70×26×100 mm
Cylindrical type	ϕ45×100 mm
Ripple heat result	Ref. Fig. 8

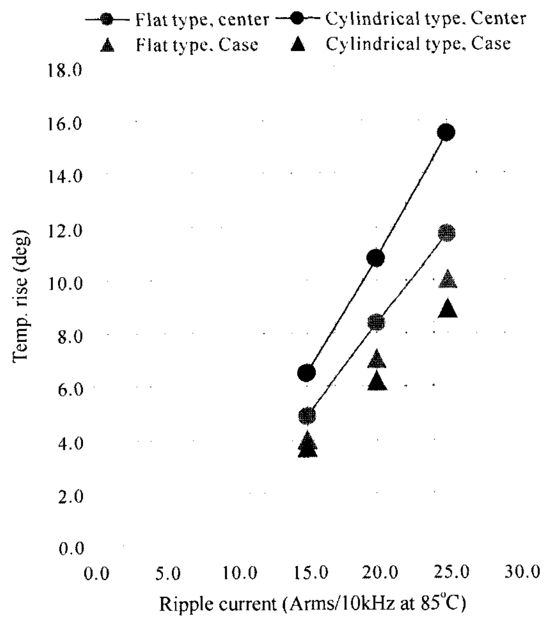

Figure 8. Test results of ripple heat rise.

Table 1. Comparison at ripple of 20 Arms/10 kHz superimposed.

Item	Flat type (70×26×100L)	Cylindrical type (ϕ 45×100L)
ΔT : Heat rise at element center	8.4 deg	10.8 deg
P : Joule heat	1.08 W	1.04 W
βA : Heat discharge (βA=P/ΔT)	0.127 (132%)	0.096 (100%)
Permissible ripple current ratio	1.15	1.00
Occupied volume with dead space	159 cc	202 cc
Ratio of permissible ripple current per volume	1.46	1.00

rise is lowering toward the surface of capacitor. Thus, as the distance between the core of element and the surface of capacitor is shorter, the temperature rise is lowered.

In case of flat-type capacitor, the distance between the core of element and the surface of capacitor is shorter compared to the cylindrical-type. It has superior with heat discharge performance.

Furthermore, the element of cylindrical type capacitor is fixed by putting additional fixture material such as atactic polypropylene family. As this fixture material has poor heat conductivity, the thermal resistance is increased between the surface of element and the outer case by the Joule heat occurred inside the capacitor element, when superimposing a ripple current.

However, flat type capacitor is not required to use any fixture material, as the element is cohered to the surface of aluminum case. The thermal resistance between element and aluminum case is decreased, the performance of any heat discharge is improved much as you see Figure 7.

Figure 8 shows the ripple heat rise results under 20 Arms/10 kHz ripple superimposed.

Heat discharge characteristics, occupied volume with dead space, and ratio of permissible ripple current per volume, etc. are summarized in Table 1.

Calculation formula for ripple current

$$\beta A=\frac{P}{\Delta T}=\frac{Ir^2\times ESR}{\Delta T} \qquad Ir=\sqrt{\frac{\Delta T\times\beta A}{ESR}}$$

Table 2. Comparison at 22 Arms/10 kHz ripple superimposed.

Item	Flat type	Cylindrical type
Rating	100V-7500 μF	100V-9000 μF
Case size	70×26×100L	ϕ 45×115L
ESR/10 KHz, 85°C	2.40 mΩ	2.10 mΩ
BA: Radiation (βA=P/ΔT)	0.127	0.11
ΔT (22Arms)	9.2 deg	9.2 deg

Based on the test results shown in Figure 8, the flat type capacitor shows about 32% superior heat discharge performance compared to the cylindrical type. As converted into permissible ripple current, its ratio show about 15% higher value as summarized in Table 1. And the ratio of permissible ripple current per volume shows about 50% better for flat type capacitor, compared to cylindrical type capacitor.

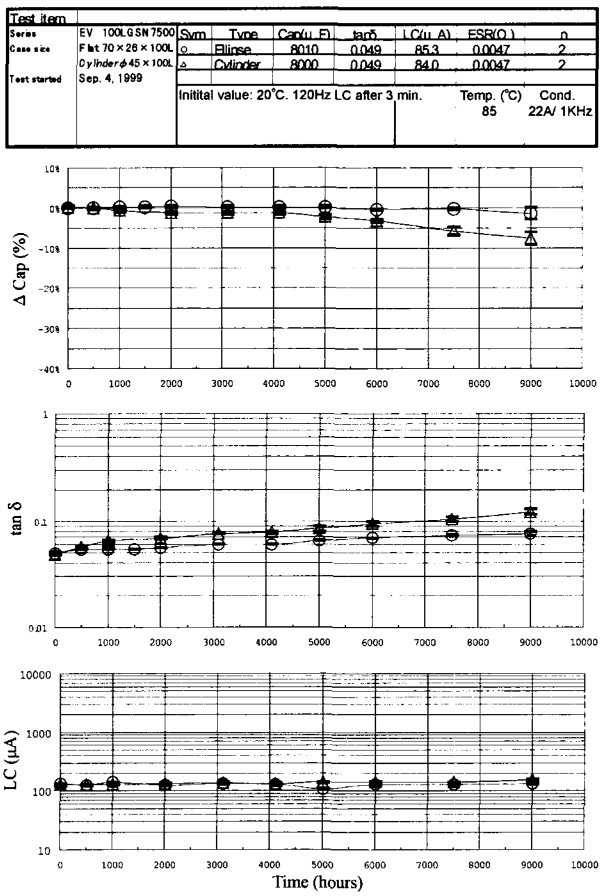

Figure 9. Life test performance for 7500 μF capacitors.

4.4. Equivalent Ripple Current Performance

The case size and the nominal capacitance of a cylindrical type, that can allow the same ripple current, have been calculated. Its case size becomes ϕ45×115L and its capacitance becomes 9000 μF. Its volume has been increased by about 15%, when comparing the case size of 7500 μF.

4.5. Results of Life Time Performances

For the same rating of 100V-7500 μF, both flat type and cylindrical type capacitors have been tested for comparing the life performances. The results are shown in Figure 9.

5. CONCLUSION

The easy-to-install 42V power control system for Mild Hybrid Vehicle was developed and introduced into market for the first time in the world. For MHV application, an inverter with highly compact and high performance has been developed by adopting a flat type capacitor newly developed.

(1) The inverter unit uses the newly developed flat type Power Capacitor (Aluminum Electrolytic Capacitor), and the size is reduced by integrating the ECU for the whole Mild Hybrid System control. Also, the reduction in both size and power loss is achieved by employing the newly developed MOS-FET module for power modulation.

(2) The shape of Power Capacitor is flat, which improves the space efficiency by about 40%, comparing the conventional type.

(3) By the flat shape of Power Capacitor, the heat radiation is improved by about 15%, realizing the higher ripple current flow and contributing to make the compact inverter unit.

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