

Development of a Motor Assist System for a Hybrid Car – INSIGHT

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ABSTRACT

A motor-assist system has been developed and employed for the ‘Insight’ hybrid car. The system consists of an internal combustion engine as a primary power source, and a motor placed around the engine crankshaft. This construction is highly compact and offers more flexibility for a power plant layout.

The system’s functions include absorption of braking energy, idling-stop, driving power assistance, and power supply for the 12V electrical system. A proper energy management method for various driving modes has been established by combining these functions and fuel economy is significantly improved as a result. Other control features include, an active motor vibration control, which compensates for idling vibration that is unique to 3-cylinder engine, and sophisticated transient torque control between assist and regenerating modes, which harmonizes the characteristics of the two power sources to ensure better driving comfort.

1. Introduction

Automotive emissions reduction as a means of reducing the greenhouse gas carbon dioxide (CO₂) is an important issue facing the automobile industry. One approach taken to achieve this goal is to improve fuel economy with hybrid power plants, which combine an engine with an electric motor. During braking, a conventional gasoline engine wastes the vehicle’s motion energy by converting it to heat energy via the brakes. Fuel economy is also lowered by fuel consumption during idling.

A hybrid system, in contrast, is capable of:

- Recovering braking energy
- Idle-stopping and restarting with the motor
- Highly efficient recharging and assistance

Various types of hybrid systems have been proposed, such as the series type, which, based on the electric automobile, uses the engine to generate electric power; the parallel type, which centers on the engine and uses a motor for auxiliary power; and, other designs that strive for an intermediate approach⁽¹⁾⁽²⁾.

2. The Goals of Development

Although capable of using energy effectively as stated above, a hybrid car can also have lower fuel economy due to increased system weight.

To achieve a proper balance between the effective use of energy and weight, the authors developed a hybrid system dubbed Integrated Motor Assist (IMA).

Other objectives are to ensure smooth driving by harmonizing the two driving power supplies, achieve a

superior idle-stopping feature that ensures smooth restarting, and constructing system control that makes maximum use of energy.

3. System Configuration

In developing the system, three major points were emphasized regarding system configuration, component layout, and component design.

First, because of body shape restrictions, a compact component layout and thorough system streamlining were needed to achieve the enhanced aerodynamic performance necessary to improve fuel economy.

Second, decreasing the weight of the components themselves was necessary to improve fuel economy.

Third, the high-voltage system necessitated measures that would assure safety (e.g., prevent electrocution) not only during normal use but also during maintenance and in the event of collision.

To meet these requirements by keeping wiring as short as possible and thereby assuring high-voltage safety, the Integrated Power control Unit (IPU), as shown in Figs.1 and 2 was placed outside of the crushable zone, concentrating the high-voltage components in the vehicle rear.

The cooling system chosen for inside the IPU employs a lightweight forced-air cooling system rather than water cooling, and features cooling passages that are designed to minimize passage resistance and to prevent the entry of water and such.

The motor developed is a thin motor designed to be placed around the crankshaft, between the engine and the transmission.

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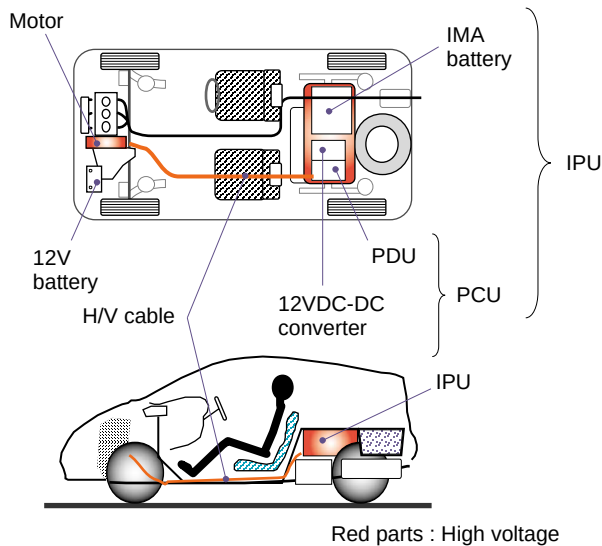


Fig.1 IMA package

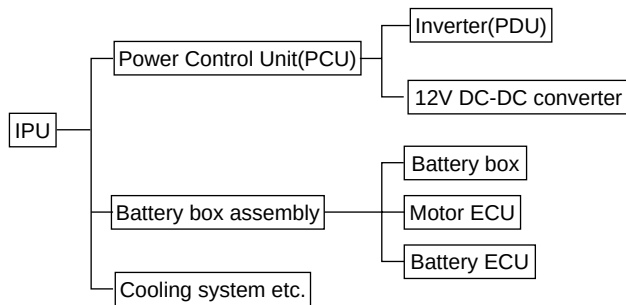


Fig.2 IPU component

1000 rpm and maximum power of 10 kW at 3000 rpm (Table 1). To fit inside the engine room, the engine was made more compact, while the motor was equipped with high-thermal-resistance neodymium magnets to fit in the 60-mm-wide space between the engine and transmission - highly severe thermal conditions. Natural air cooling is used.

Table 1 IMA specifications

Engine specifications	
Construction	Liquid-cooled 3-cylinder in-line
Valve train	Chain-driven SOHC 2intake/2 exhaust valves
Capacity (cc)	995
Bore x Stroke (mm)	72.0 × 81.5
Compression ratio	10.8
Max. power (PS/rpm)	70/6700
Max. torque (kgm/rpm)	9.4/4800
Motor specifications	
Electric current	AC
Rated voltage (V)	144
Max. power (kW/rpm)	10.0/3000 (MT)
	9.2/2000 (CVT)
Max. torque (Nm/rpm)	49.0/1000

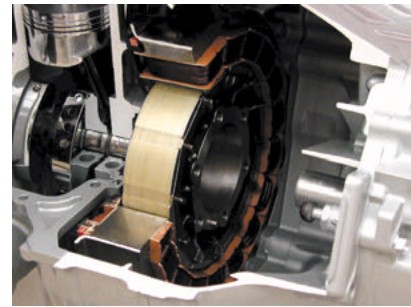


Fig.3 IMA motor

3.1. The Engine

As the primary power source, the engine incorporates numerous new technologies designed to improve fuel economy⁽³⁾.

This lean-burn engine has a 1.0-liter displacement. A 3-cylinder design was chosen in order to reduce mechanical loss and such. To improve combustion efficiency, existing VTEC lean-burn technology was given a further evolved combustion chamber shape.

Other weight reducing technologies adopted include a magnesium oil pan, the use of resin in such parts as the intake manifold and headlight cover, and an aluminum exhaust manifold integrated with the cylinder heads.

3.2. The Motor

An alternating current synchronous (DC brushless) motor was chosen for its superior efficiency. Bearings were eliminated from the design to reduce mechanical loss, and the motor was placed around the engine crankshaft to ensure compactness.

To achieve power performance comparable to that of a 1.5-liter gasoline engine-equipped automobile, motor output in the assist mode provides a maximum torque of 49 Nm at

3.3 The Battery

The battery used is a custom Ni-MH battery for hybrid vehicles (Table 2 and Fig.4). It is designed for use under various conditions, and was provided with the optimum battery capacity for the electric energy of motor assistance and regeneration.

The fan motor used to cool and warm up the battery is a brushless type that assures maintainability and reduces onboard noise levels. This switchable motor has two speeds: high and low.

Mounted atop the battery box is an Electronic Control Unit (ECU) that controls the motor and monitors remaining battery capacity.

Table 2 Battery specifications

Type	Nickel metal hydride (Ni-MH)
Cell voltage (V)	1.2
Quantity (cells)	120 (6cells × 20modules)
Connecting method	In series
Capacity (Ah)	6.5 (3-hour discharge rate)

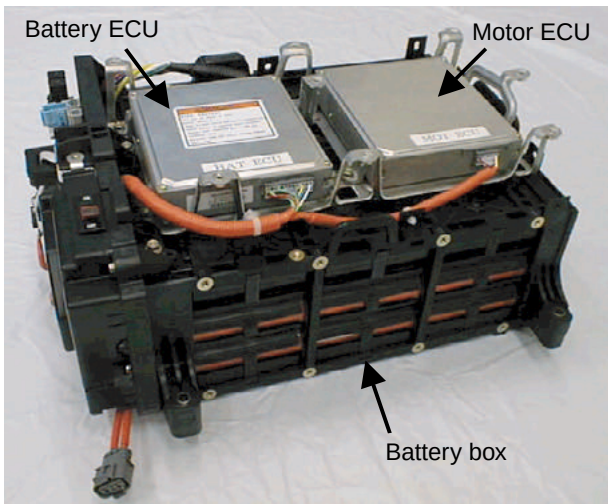


Fig.4 Battery box assembly

3.4 The Power Control Unit

The power control unit comprises a high-efficiency drive and regeneration Power Drive Unit (PDU) and a DC-DC step-down converter for 12V power supply generation, both located on either side of the cooling heat sink case (Fig.5). This forced air cooled structure enables a compact design and high-efficiency cooling.

The PDU is also made even more compact and lightweight by integrating six motor power switching elements into a single module.

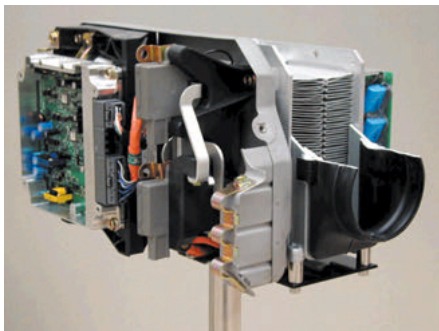


Fig.5 PCU (Power Control Unit)

3.5. ECUs

Enhancements such as a magnesium frame make the motor ECU and battery ECU approximately 50% lighter than an ECU with an aluminum frame.

Together, this compact component layout, decreased weight component enhancements, and cooling system streamlining make possible the package shown in Figs.6 and 7. This package helps lower the weight of the entire IMA system to less than 80 kg, or under 10% of vehicle weight. Further, concentrating the IPU package in the rear creates a structure that assures high-voltage safety, even in the event of collision.



Fig.6 IMA power unit



Fig.7 Rear layout of IMA system

4. Control System

4.1. Required Functions

The basic functions required by this system are energy absorption during deceleration, idle-stopping, motor assist to supplement engine output during acceleration, and generation of a 12-volt system's load.

Other requirements include motor operation that seems natural to the driver, and the ability to disengage the system to permit driving on engine power alone in the event of failure, for instance.

The minimum system configuration needed to achieve these functions is shown in Fig.8.

The functions of each ECU are listed below.

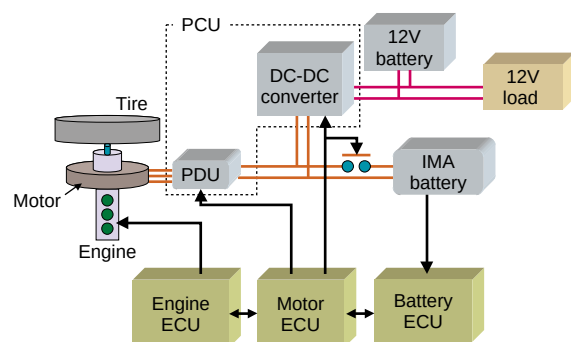


Fig.8 IMA System block diagram

1) Engine ECU

Engine control, control mode determination, assist/regeneration level calculation, idle-stopping determination, failure detection, etc.

2) Motor ECU

Motor control (assist/regeneration, engine starting), control mode determination, high-voltage power distribution control, battery protection control, idling vibration damping control, control status indication.

PDU cooling, DC-DC converter cooling, failure detection, etc.

3) Battery ECU

State Of Charge (SOC, i.e., charge level) calculation, battery protection requirement output, temperature control, failure detection, etc.

4.2. Driving Conditions and the Flow of Energy

The IMA system determines the IMA control mode and the motor's assist or regeneration level according to engine speed, vehicle speed, throttle opening, gear position, SOC and other vehicle information.

The flow of energy in the IMA system comprises a total of six directions (Fig.9).

- 1) Motor assist
- 2) IMA battery charging
- 3) 12V load generation
- 4) Supplying the 12V load from the IMA battery
- 5) Supplying the 12V power with the DC-DC converter

6) Supplying the 12V power from the 12V battery

These six directions of energy flow correspond to six energy patterns, according to driving mode and SOC.

The list below explains which energy pattern corresponds to which energy flows.

Pattern 1: Driving the motor with the IMA battery, e.g., assist during acceleration and engine starting after idle-stopping.

..... Energy flows (1), (4), (5)

Pattern 2: Absorption of deceleration energy and charging during cruising and idling.

..... Energy flows (2), (3), (5)

Pattern 3: Supplying only the DC-DC converter power (12V system load) when charging of the IMA battery is unnecessary (e.g., at maximum SOC).

..... Energy flows (3), (5)

Pattern 4: Supplying the 12V system load with the IMA battery during idle-stopping.

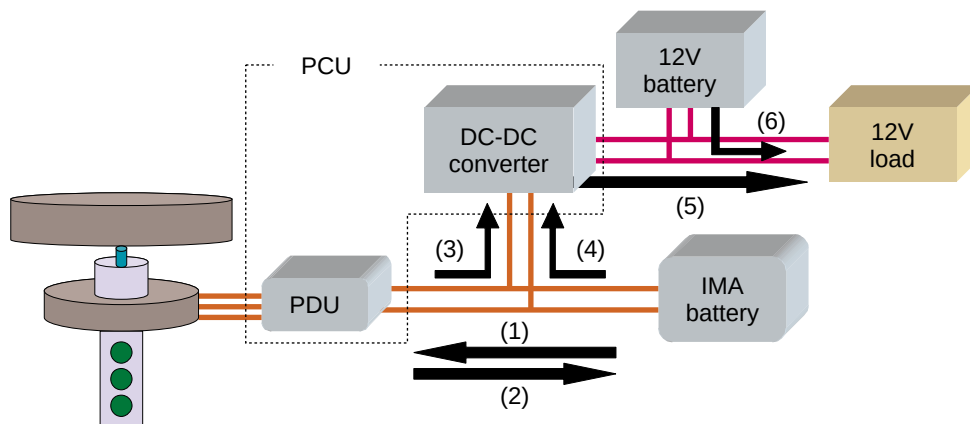
..... Energy flows (4), (5)

Pattern 5: Supplying the 12V load with the 12V battery when starting the engine with the IMA motor.

..... Energy flows (1), (6)

Pattern 6: Starting the engine with the starter (as in an ordinary gasoline engine-equipped vehicle) in cases where starting with the IMA motor is not possible, e.g., at extremely low temperatures.

..... Energy flow (6)



IMA mode	Condition	(1) Assist	(2) IMA battery Charging	(3) 12V from Motor	(4) 12V from IMA battery	(5) 12V from DC-DC	(6) 12V from 12v Battery	Energy pattern
1. Assist	Normal	●			●	●		Pattern 1
	Low SOC			●		●		Pattern 3
2. Decelerate	Normal		●	●		●		Pattern 2
	High SOC			●		●		Pattern 3
3. Cruise	Normal		●	●		●		Pattern 2
	High SOC			●		●		Pattern 3
4. Idling	Normal		●	●		●		Pattern 2
	High SOC			●		●		Pattern 3
5. Idling stop					●	●		Pattern 4
6. Engine start	Ignition ON	●					●	Pattern 5
	Idling stop	●			●	●		Pattern 1
	Starter						●	Pattern 6

Fig.9 Energy flow of the IMA system

The energy flow as determined by the driving condition is displayed on the IMA meter (Fig.10).

The SOC meter displays the battery's SOC with a 20-segment display, and the assist/charge meter communicates the IMA's operational status to the driver by displaying the assist or charging power in real time.

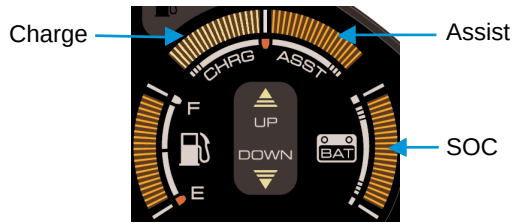


Fig.10 Hybrid meter

4.3. Energy Management

A hybrid car's SOC must be maintained within a certain range in order for motor driving and regeneration to function. To this end, energy management based on driving conditions is incorporated as described below to maintain the proper balance between SOC and driving power/regeneration power control.

1) Assist/deceleration modes

In the assist and deceleration modes, in which the vehicle's driving and braking power is emphasized, power is provided exactly as requested by the PDU's DC unit, regardless of the 12V load level.

2) Cruising/idling modes

In the cruising and idling modes, the battery power balance is more important than motor output. Because SOC variation must be kept to a minimum, the battery input element's DC power is controlled. This minimizes battery charge/discharge loss so that the motor's regenerated power can be used for the vehicle system's 12V load. In the example in Fig.11, the charging requirement is 2 kW and DC-DC converter consumption is 0.5 kW. In this case, feedback is provided so as to maintain the battery side's power at 2 kW, effectively enabling the motor to generate 2.5 kW of power and thereby providing the power consumed by the DC-DC converter.

3) Idle-stopping mode

While the vehicle is stopped, unnecessary fuel consumption is avoided by stopping the engine rather than idling. In this idle-stopping mode, the IMA battery provides the power needs for the 12V load through the DC-DC converter.

4) Engine starting mode

In this mode, the engine is started by the IMA motor

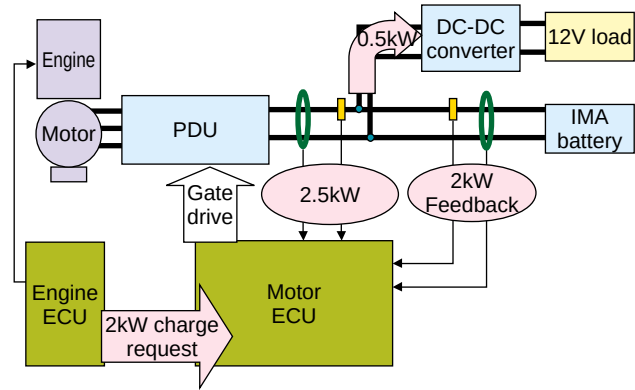


Fig.11 Energy flow for conventional electric load

using the regeneration energy that is generated during deceleration. More durable than the starter motor, the IMA motor assures faster starting and lower levels of noise and vibration. The torque pattern in Fig.12 was adopted to enable the engine to quickly achieve idling speed. Figs.13 and 14, which show how engine speed rises after a cold start with

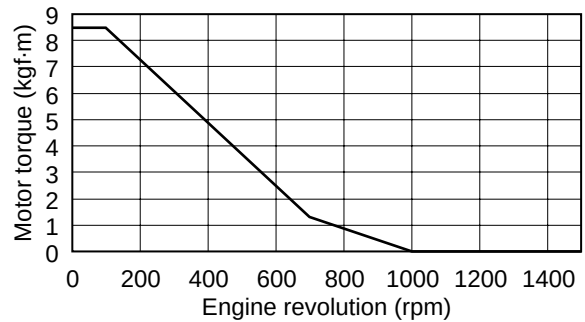


Fig.12 IMA motor torque at engine start

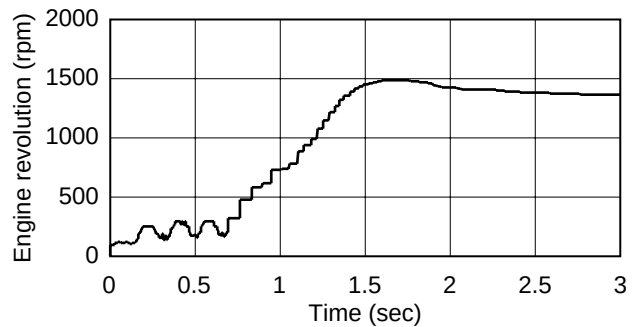


Fig.13 Engine revolution chart (starter motor)

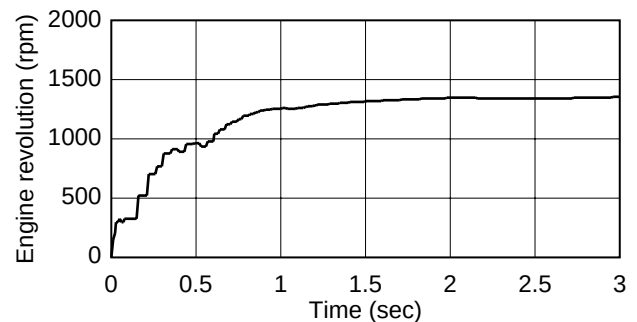


Fig.14 Engine revolution chart (IMA motor)

the starter motor and IMA motor, demonstrate how the IMA motor is capable of smooth engine restart after idle-stopping.

4.4. Motor Output Control

Improving the controllability of vehicle movement requires sufficient responsiveness and stability in motor output control. Although required output depends on such factors as vehicle speed, engine speed, and SOC, the actual command value is calculated by switching between open control and feedback control, taking into account the fidelity of the motor's actual output.

As Fig.15 shows, when the difference between current actual output and required output is large, open control is initiated to provide a larger change in torque per unit time. This is continued until the predetermined differential is reached, after which power feedback control, which also includes the DC-DC converter, is carried out until the target value is achieved.

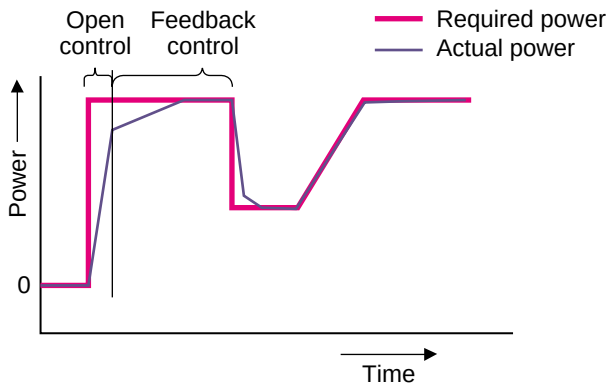


Fig.15 Method of torque feedback

In feedback control, feedback gain is also changed according to the degree of change in the requested output. A large change is interpreted as a transient state, and feedback gain is increased to improve responsiveness.

In times other than when the transient state has been identified, feedback processing functions to adjust feedback gain according to the control mode (e.g., deceleration, assist, cruising, idle) as shown in Table 3, thus stabilizing vehicle movement.

Table 3 Feedback gain of control mode

Control mode	Deceleration	Assist	Cruise	Idling
Gain				
Gain of proportional control	Kp1	Kp2	Kp3	Kp4
Gain of integral control	Ki1	Ki2	Ki3	Ki4
	High		Middle	Low

5. Using Motor Control to Damp Idling Vibration

The Insight's 3-cylinder engine generates vibration of n th order $\times 1\frac{1}{2}$ of engine speed. Therefore, the IMA system, taking advantage of the fact that the motor is placed around the engine crankshaft, counters this 1.5-order vibration, which is the primary component of vibration, by applying a torque whose phase is reversed relative to this torque, thereby damping vehicle vibration during idling (Fig.16). This process is referred to as damping control.

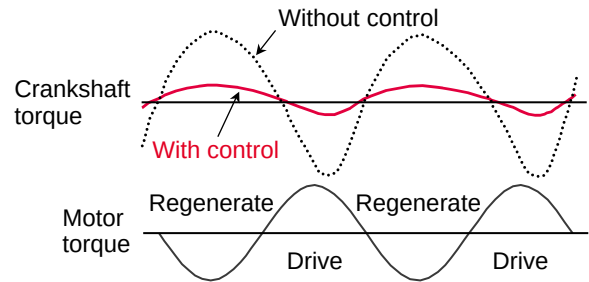


Fig.16 Principle of damping control

The example in Fig.17 gives actual engine torque, its 1.5-order component, and the torque to apply during damping control. This demonstrates how it is possible to use motor torque to cancel out 1.5-order vibration, which is the primary component of 3-cylinder engine vibration.

Damping control determines torque phase according to the parameters of engine load and speed, using the engine's top dead point signal as a benchmark. The amplitude of the torque to apply is similarly determined according to the parameters of engine load and speed.

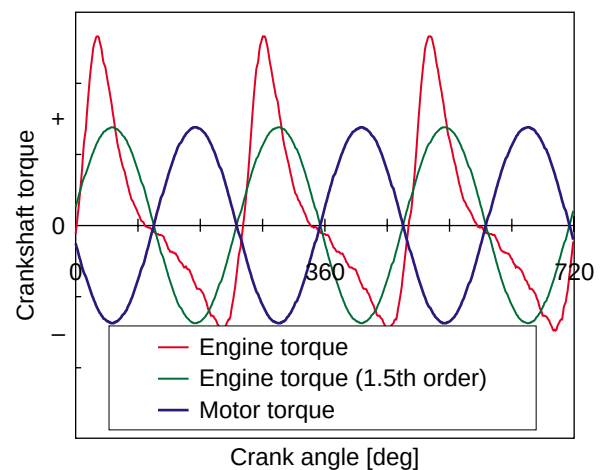


Fig.17 Example of engine and motor torque

Generating the waveform of the torque to apply requires crankshaft angle information, which is obtained from the top dead point signal.

The torque used in damping control and the regeneration torque used for battery charging are superimposed when they are output. This relationship is shown in Fig.18; the effects of damping control, in Table 4.

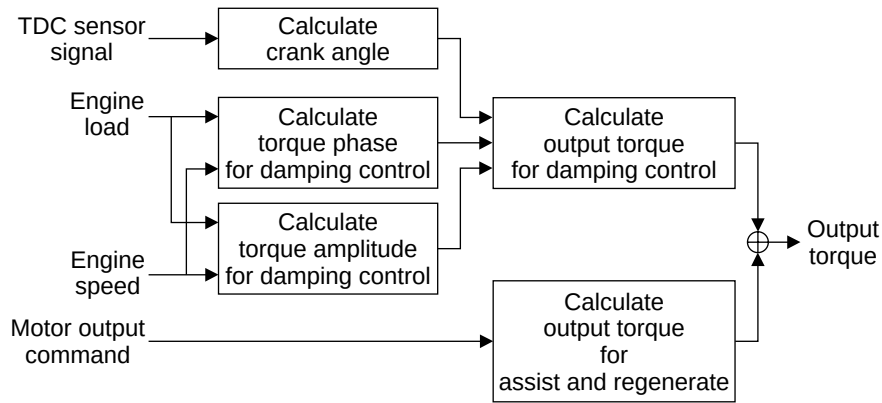


Fig.18 Block diagram of damping control

Table 4 Effect of damping control

Measuring point	Effect of damping control
Vibration of steering wheel	-3dB
Vibration of seat	-5dB
Sound pressure of vehicle compartment	-5dB

6. Ensuring Battery Longevity

A battery's SOC, voltage, and temperature must be maintained within their predetermined limits during actual use in order to ensure battery longevity.

The IMA system uses current sensors, battery voltage sensors, and battery box internal temperature sensors to:

- 1) Keep the SOC within the appropriate range
- 2) Keep input and output power within the upper and lower limits for battery voltage (voltage power save feature)
- 3) Restrict input and output power according to battery temperature (temperature power save feature)

6.1. Voltage Power Save

When the battery voltage exceeds the upper or lower voltage thresholds, which are determined by battery current and battery temperature, the IMA system reduces the motor's current output command value gradually, so that vehicle motion does not change abruptly. Once battery voltage returns to within the predetermined range, the restricted output is gradually returned to its original level. Fig.19 gives a block diagram of this.

6.2. Temperature Power Save

To prevent overheating and assure sufficient accuracy in SOC determination at extreme temperatures, motor output limits are controlled according to battery temperature to keep battery power below its predetermined upper limit (this is the batter temperature power save feature). With the settings shown in Fig.20, output control makes it possible to keep battery temperature within an appropriate range.

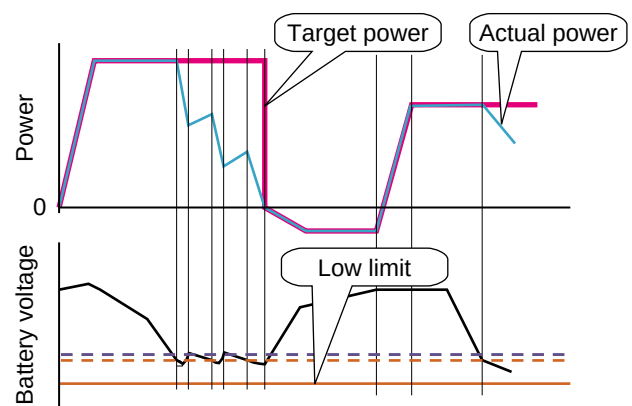


Fig.19 Power save control by battery voltage

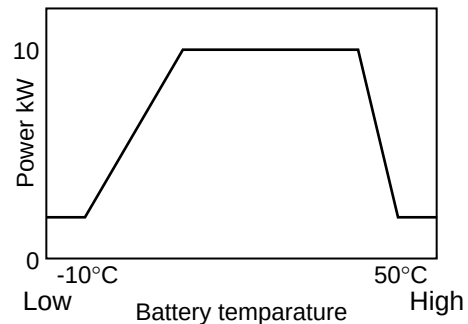


Fig.20 Power save action by battery temperature

7. Conclusion

The following achievements were made with a hybrid system whose motor is designed to function especially for engine assistance during acceleration and regeneration braking during deceleration:

- Energy management based on driving conditions and battery SOC helped improve fuel economy.
- A compact packaging designed for high-voltage safety and superior mountability was achieved.
- An assist/regeneration system that harmonizes engine

driving power with motor driving power was achieved.

- Motor-based damping control of idling vibration was shown to damp vibrations of -3 dB to -5 dB.
- The motor assist system was shown to be capable of smooth restarting after idle-stopping.

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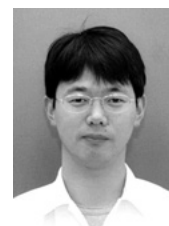
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