Dynamic Motor Control System for Enhancing Energy Efficiency and Safety of EVs

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OVERVIEW: Hitachi researches and develops control technologies and systems for electric vehicle motors that provide better energy efficiency and safety. This has included using an EV test vehicle to demonstrate the use of the electric motor in traction control and antilock braking, utilizing the rapid changes in torque made possible by the superior torque response of electric motors to maintain vehicle traction even on slippery road surfaces. G-vectoring control and electric yaw-moment control are techniques that will be used with electric drive control in the future. Hitachi has proposed these together with methods for analyzing heat and energy consumption in the motor and other components under near-real-world conditions.

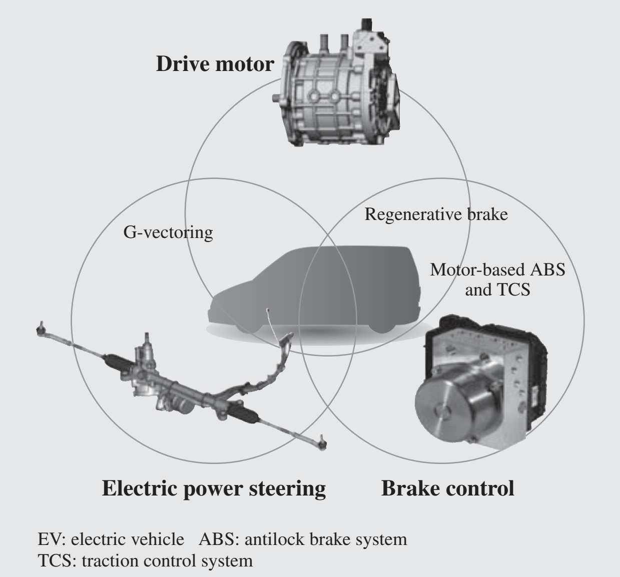
INTRODUCTION

HYBRID electric vehicles (HEVs) and other types of electric vehicles (EVs) have some features that are beneficial to environmentally conscious energy efficiency. Also, it has become possible for such vehicles to be used for energy storage as part of social infrastructure(1) and their superior acceleration and deceleration performance can enhance driving performance. Mobility will take on many different forms in the future, with experiments and demonstrations being conducted around the world. Hitachi takes a user's perspective to designing future vehicles and conducts research into the components and systems that they will require.

In anticipation of future work on control systems capable of delivering both energy efficiency and improvements in driving performance in dangerous driving situations, this article describes the results of simulation and trials using a test vehicle.

CONCEPT BEHIND NEXT-GENERATION EVs

The use of devices such as stereo cameras to improve visibility and techniques that compensate for errors of judgment is an effective way to prevent accidents. The improvement of driving performance in dangerous situations can also be used to prevent accidents that are about to happen. The drive motors used in EVs have a fast response to requested changes in torque (approximately 1 ms), meaning they are suitable for instantaneous control of the vehicle in ways that take account of factors such as road friction and wheel slip. Meanwhile, increasing use is being made of electric drive in the steering and brakes that respectively steer and slow down the vehicle, with electric power steering already in widespread use. If electric motors are to be used to improve driving performance in dangerous situations, then it is necessary that the steering, brakes, and other systems be controlled in tandem. Examples include regenerative braking, in which the electric motor and brakes interoperate during deceleration and braking, and G-vectoring control, which uses the electric motor and brakes to compensate for lateral acceleration that results from steering operation(2), (3). It is anticipated that future use of motor-based traction control systems (TCSs) and antilock brake systems (ABSs) will feature interoperation between the electric motor and brakes (see Fig. 1).



EV: electric vehicle ABS: antilock brake system
TCS: traction control system

Fig. 1—EV Control.
The motor not only powers the vehicle, but also interoperates with the steering and brakes to assist with cornering and stopping.

The main function of the drive motor during deceleration is energy regeneration. This means using the motor to generate electric power from the kinetic energy of the vehicle. An issue for these vehicles will be the extent to which energy efficiency achieved through the use of regeneration can be combined with the improvement of driving performance. Regarding this issue, Hitachi has conducted trials using an EV test vehicle.

Fig. 2 shows Hitachi's roadmap for EV control. Hitachi envisions moving toward autonomous driving in the future through a fusion of environmental technologies (electric motors and electric drive control) with both safety technology and information technology.

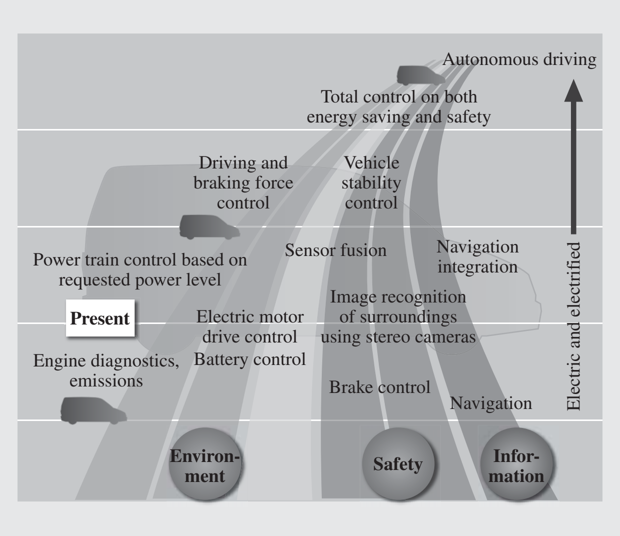


Fig. 2—Roadmap for EV Control.
Hitachi is working toward autonomous driving by fusing environmental technologies (electric motors and electric drive control) with safety and information technologies.

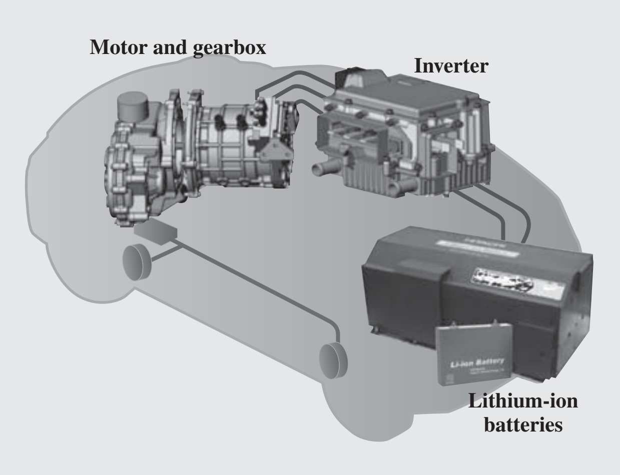


Fig. 3—Structure of EV Test Vehicle.
Hitachi built an EV test vehicle by fitting an electric motor, inverter, and lithium-ion batteries that it had developed in a commercially available vehicle.

EV TEST VEHICLE DEMONSTRATIONS

Hitachi built an EV test vehicle by fitting an electric motor, inverter, and lithium-ion batteries that it had developed in a commercially available vehicle, and used this vehicle to trial electric drive control (see Fig. 3). Table 1 lists the main specifications of the EV test vehicle and its components.

The functions tested for use in EV control were a motor-based TCS and ABS in which rapid changes in torque were used to maintain traction on a slippery road surface. Conventional TCSs and ABSs use dedicated components and are implemented as controllers of the brakes and engine. The demonstration was conducted under conditions of low road friction, and a control system was studied that detected changes in speed when the wheels were on the verge of spinning out and controlled the drive motor torque to minimize slip (see Fig. 4).

TABLE 1. Specifications of EV Test Vehicle
The motor and gearbox and the battery were both specially designed for the EV test vehicle.

Motor	Maximum torque: 180 Nm Maximum speed: 12,000 min^{-1} Output: 90 kW, permanent magnet, water cooled
Inverter	600 V, 400 A (max.) IGBT module with double-surface direct water cooling
Lithium-ion batteries	Voltage: 350 V (@50% SOC) Capacity: 8.34 kWh, Range per charge: 80 km*
Vehicle weight	1,151 kg
Maximum speed	140 km/h

* Calculated from actual results on test track
IGBT: insulated gate bipolar transistor SOC: state of charge

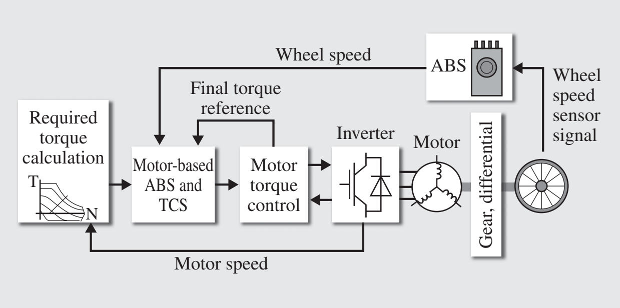


Fig. 4—Motor-based TCS and ABS Control.
In circumstances where ABS or TCS are activated, the control system detects the change in speed when the wheels are about to spin out and controls the electric motor torque to minimize slip.

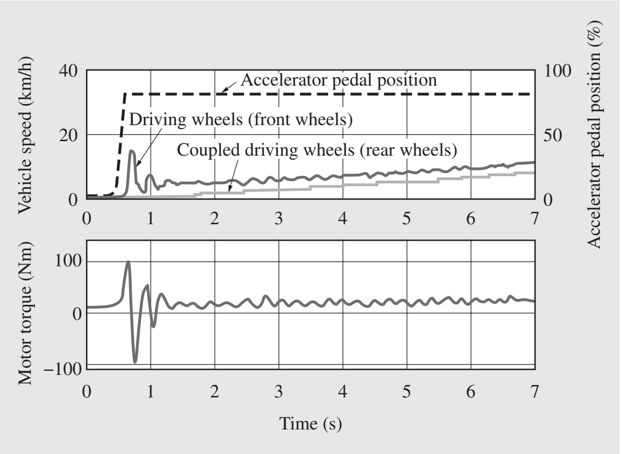


Fig. 5—Demonstration Results for Motor-based TCS.
The vehicle was able to accelerate from a halt on a frozen road without slip by applying rapid changes in the torque to the driving wheels (front wheels).

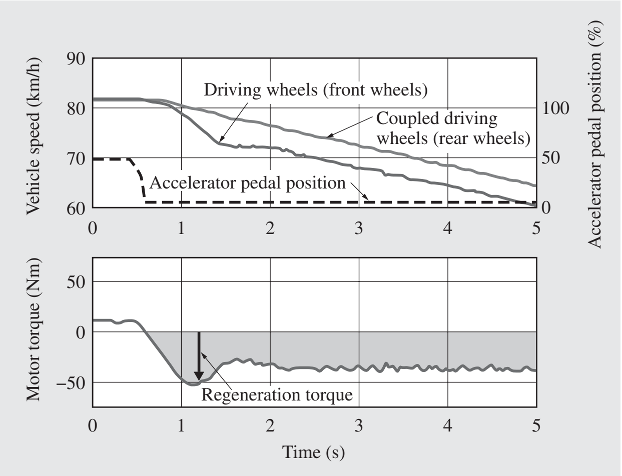


Fig. 6—Demonstration Results for Motor-based ABS.
Slip was prevented and regeneration maintained by detecting the speed difference between the driving wheels and coupled driving wheels and varying the motor torque accordingly.

Fig. 5 shows the effect of using motor-based TCS when the EV test vehicle accelerated from a halt on a frozen road. Rapid changes in the torque applied to the driving wheels allowed the vehicle to accelerate without wheel slip.

Similarly, Fig. 6 shows the test results for motor-based ABS on a frozen road. Torque control of the driving wheels (front wheels) based on the difference in speed between the driving wheels and coupled driving wheels provided the vehicle with good grip and prevented slip. The electric motor could thus, be used for regeneration during this situation; the demonstration showed that energy efficiency can be combined with the improvement of driving performance.

ANALYSIS TECHNIQUES FOR HEAT AND ENERGY

Because EV drive motors typically operate continuously with variable output, keeping their internal temperature within the permitted range is a concern. While many studies have been published on the thermal analysis of electric motors, the challenge is to devise a method for estimating the internal thermal resistance and heat capacity parameters. Accordingly, Hitachi has investigated a method that applies recursive correction to an analytical model based on experimental results (a model of the motor as a thermal network of thermal resistances and heat capacities) (see Fig. 7). A similar method for estimating the temperature of the magnets embedded in the motor rotor has also been studied(4).

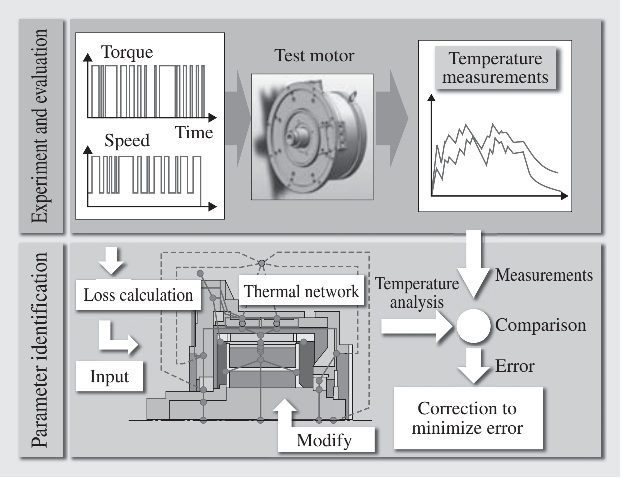


Fig. 7—Method of Identification for Motor Thermal Design Parameters.
A feature of the method is that it uses recursive correction to converge on the thermal network model parameters (thermal resistances and heat capacities), with reference to experimental results.

Thermal analysis uses the estimated losses in the motor and inverter, with losses being calculated by considering both the fundamental waveform and harmonic components based on an initial analysis of the motor current. The analysis can also include battery energy consumption based on the vehicle's driving pattern and estimated losses in each component. Fig. 8 shows a comparison of the measured values (the coil temperature in the motor and the battery state of charge) with the calculated values based on the driving pattern of the EV test vehicle. It is believed that the error in the motor temperature is largely due to errors in boundary conditions such as case temperature. Further work aimed at improving accuracy is planned.

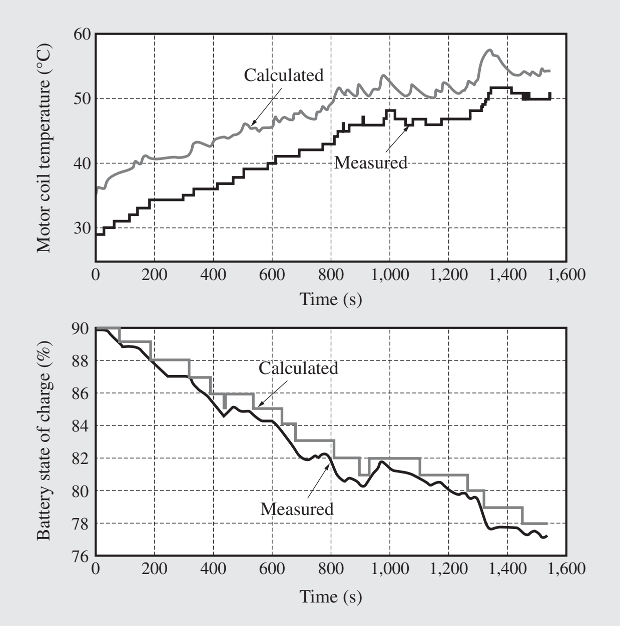


Fig. 8—Simulation of Motor Coil Temperature and Battery State of Charge.
The simulation performs an analysis to obtain the temperature of the coil in the motor and the state of charge of the battery for an input driving pattern of the test EV.

FUTURE TECHNOLOGIES FOR ELECTRIC DRIVE CONTROL

Hitachi has devised G-vectoring control as a means of improving stability and ride comfort during cornering by applying driving and braking force to the vehicle in proportion to the rate of change of lateral acceleration(2). Although the technology was first developed on the assumption that this accelerating or braking would be provided by the electronically controlled friction brake and engine, an electric motor can also be used to provide the required acceleration or braking control. Use of energy regeneration means that employing an electric motor for G-vectoring control is more energy efficient than employing the friction brake.

The fuel savings due to electric G-vectoring can be obtained analytically for a given road that includes corners. Assuming a 10-km stretch of road contains three pairs of curves that have radii of curvature of 30 m, 50 m, and 100 m, for example, a saving in electric power consumption of approximately 5% can be achieved compared to using the friction brake for G-vectoring control(3).

In-wheel electric motors are widely recognized as being capable of improving vehicle driving performance. Because in-wheel motors can provide drive or braking independently to the left and right wheels, they can be used for active control of vehicle cornering trajectory by generating a yaw moment in the vehicle. However, a characteristic of this approach is that the available difference between left and right motor torque diminishes for the faster motor speeds that accompany high-speed driving. In response, Hitachi has developed a new actuator called a “motorized yaw-moment mechanism”(5) (see Fig. 9). The mechanism consists of two rows of planetary gears that link the left and right wheels. By applying motor torque to one of the planetary gears, a single motor can generate opposite torque at the left and right wheels. The motor rotates at a speed proportional to the speed difference between the left and right wheels during cornering, but remains idle when the vehicle is driving in a straight line. As there is no loss of torque due to the vehicle accelerating, a relatively small motor (rated output in the 1 to 3 kW range) can generate adequate torque across the entire vehicle speed range. Because this mechanism can control small amounts of yaw moment with high precision, it is also suitable for use in preventive safety systems such as lane-keeping support systems.

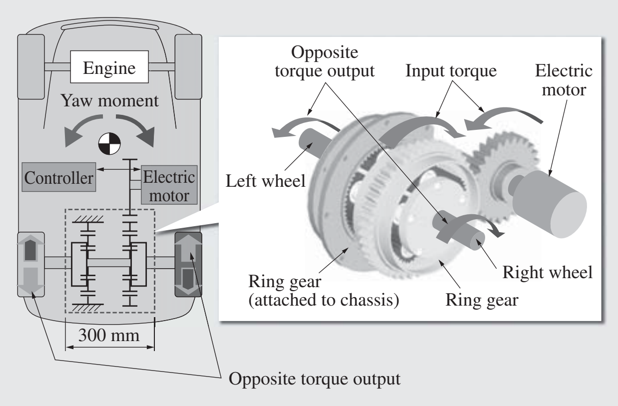


Fig. 9—Motorized Yaw Moment Control.
The control system controls yaw moment by using a single motor to apply opposite torque to the left and right wheels.

CONCLUSIONS

With EVs steadily gaining acceptance in the marketplace, Hitachi is conducting research into EV control techniques that utilize the electric motor, anticipating that this will become an important aspect of vehicle appeal in the future. Whereas the indicators of electric motor performance in the past have been high output, small size, and high efficiency, future demand will be for highly responsive characteristics combined with quiet operation, including control. The use of electric drive throughout the vehicle cannot be assessed simply by the conventional practice of evaluating motors on test beds. Instead, Hitachi believes that it is becoming increasingly important to perform experimental testing under near-real-world conditions, including practices such as the use of test vehicles and simulations of different driving scenarios.

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