Development of Simple Driver-friendly Electric 4WD System

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OVERVIEW: With their known superiority in stability and versatility under adverse driving conditions, 4WD (4-wheel-drive) systems are starting to be considered for application to ordinary passenger vehicles. However, mechanical 4WD vehicles have a number of drawbacks, most notably their relatively poor fuel economy and lack of cabin space and luggage room. Hitachi, Ltd. has now developed an electric 4WD system that satisfies all the performance advantages of 4WD yet is equivalent or even priced lower than mechanical 4WD systems. Hitachi's electric 4WD system has already been installed on Nissan Motor Co., Ltd.'s March and Cube models that came out in the fall of 2002 and on Mazda Motor Corporation's Demio that went on the market in the fall of 2003. The electric 4WD system consists of a water-cooled alternator, a DC (direct current) motor, a clutch and differential gear unit, and a 4WD control unit that manages the drive system. Being powered by electricity, the system provides a finer degree of control that is beneficial in a number of ways.

INTRODUCTION

HITACHI'S electric 4WD (4-wheel-drive) system has been well received by the vehicle manufacturers and was installed first on Nissan Motor Co., Ltd.'s March, then on Nissan's Cube, and most recently on Mazda Motor Corporation's Demio model.

Since power is transmitted to all four wheels in a 4WD vehicle, it provides superior traction compared with 2WD on slippery or snow-covered roads, and is practically indispensable in colder northern regions. The problem with mechanical 4WD systems is that they require a bulky propeller shaft and transfer case to supply power to the rear wheels which reduces cabin space and luggage room in the vehicle, and the increased mass and added friction in the drivetrain results in significantly lower fuel mileage compared to 2WD vehicles. To gain the benefits of 4WD without these drawbacks, Hitachi developed an electric 4WD system using an electric motor and an alternator (a synchronous generator).

In this article we review the design concept and the system and unit requirements that Hitachi had to address in the process of developing the electric 4WD system (see Fig. 1).

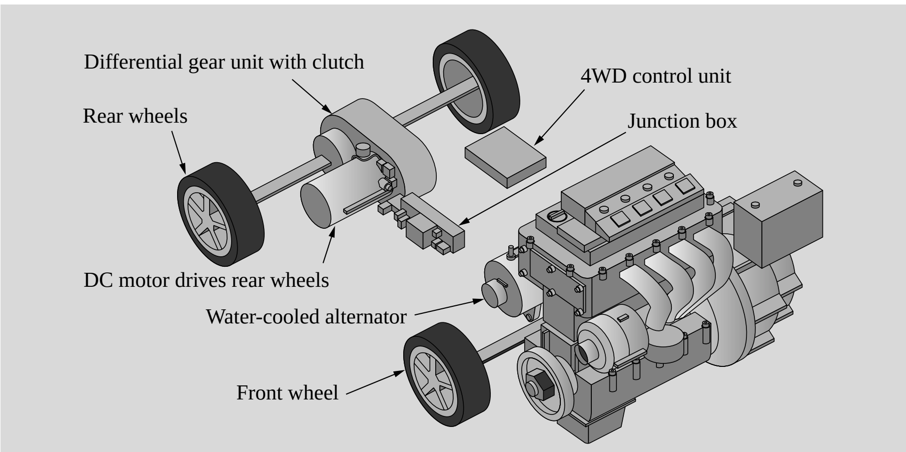

Fig. 1—Schematic of Electric 4WD System.
A water-cooled alternator is the main power source via the junction box for the DC motor that drives the rear wheels. The 4WD control unit controls power generation of the water-cooled alternator and motor shunt wiring control based on the driving conditions.

ELECTRIC 4WD SYSTEM REQUIREMENTS

Our initial objective in developing an electric 4WD system was to create an electric motor that would drive the rear wheels of an FWD (front-wheel drive) vehicle, and we commenced work on the project after settling on the March, an entry FWD vehicle developed by Nissan, as the vehicle platform. The March model was a good candidate for this project because it is a compact vehicle and has very exacting demands regarding cabin space and luggage room, and also requires relatively little power to drive the rear wheels because of the small mass of the March. We thought this would enable us to develop the various subsystem units configuring the electric 4WD system within a relatively short time frame.

Power for the system is provided solely by a water-cooled alternator driven by the engine. This approach has a number of advantages:
(1) there is no need for a dedicated battery, and
(2) because a DC (direct current) motor is used for the drive, the voltage and current from the alternator can be directly supplied to the motor. In addition,
(3) the floor is flat because there is no propeller shaft so the vehicle manufacturers can use the same platform as they use for 2WD vehicles, and
(4) drivers can be pleased with the fuel economy and peace of mind when driving on icy roads.

We intended to mass produce this electric 4WD system and make it available at the same cost or lower than mechanical 4WD systems.

FEATURES OF EACH UNIT

In this section we will consider the basic technologies, areas where we focused most of our R&D (research and development) efforts, and solutions we adopted in developing each subsystem unit of the electric 4WD system.

DC Motor

(1) The DC motor was essentially designed as a separately excited DC motor capable of field control with proven performance in vehicles, and the same approach was applied for the armature, poles, yoke material, production equipment, etc.
(2) The region around the brushes and commutator has been redesigned. First, based on assumptions as to how 4WD vehicles are used, we sought to make the system virtually maintenance-free for the life of the vehicle by optimizing the brush materials and dimensions to enhance durability. We also redesigned some of the peripheral parts to improve the heat dissipation effect. For example, we relocated the brushes and brush-related parts to the side coupled to the differential gear unit (i.e. the output shaft side of the motor). This allows the heat generated by the brushes to escape into the differential gear unit which has ample heat capacity.
(3) Because the motor is mounted near the rear axle of the vehicle, it serves as a sealing structure that assures waterproofness and also provides a structure for ventilating internal air via a breathing pipe. In addition, sensors have been installed to detect elevated brush temperature so the 4WD controller can constantly monitor the temperature of the brushes. If the brush temperature gets too hot, the output is gradually constricted to bring the temperature down, a scheme that significantly extends the life and durability of the motor (see Fig. 2).

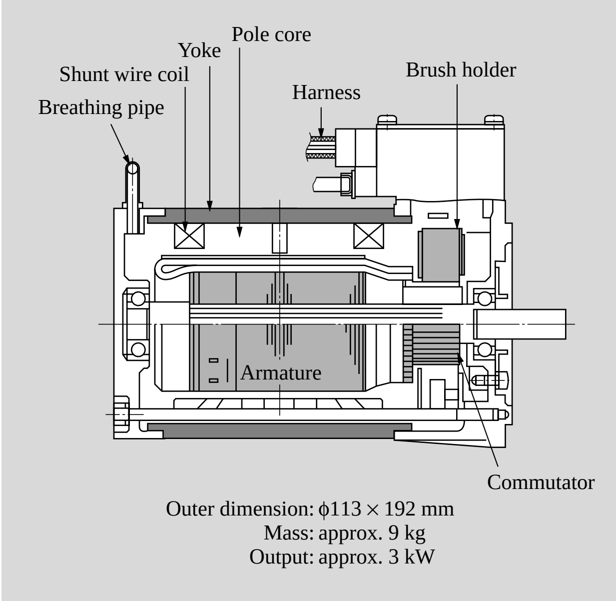

Fig. 2—Structure of DC Motor for Rear-wheel Drive.
Employing a separately excited DC motor permits shunt wiring control and enables high-speed rotation output.

Water-cooled Alternator

(1) Hitachi's water-cooled alternator for 14-V applications offers a number of advanced features.

(a) A claw pole type rotor with permanent magnet inserted between the poles was adopted which significantly improves output in the low-rotation domain.

(b) To maximize output from such a compact implementation, a configuration was adopted in which molded resin stator coil, diodes, and control broad are water cooled (see Fig. 3).

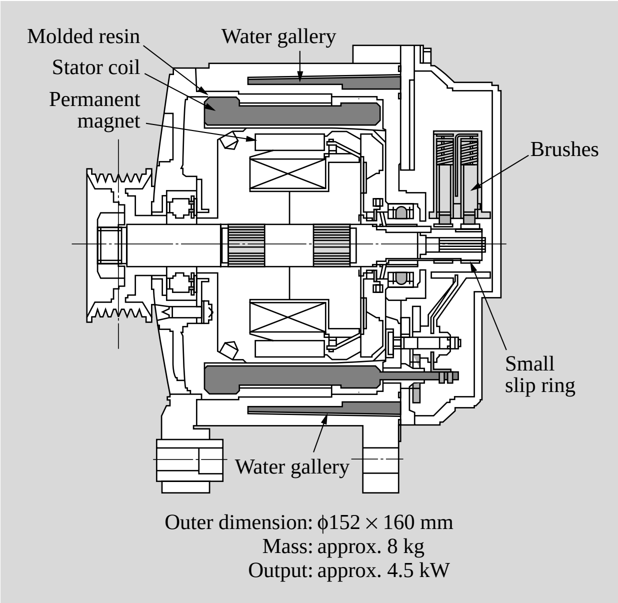

Fig. 3—Structure of Alternator for Generating Electrical Power.
The water-cooled alternator is implemented compactly and supplies stable output of energy.

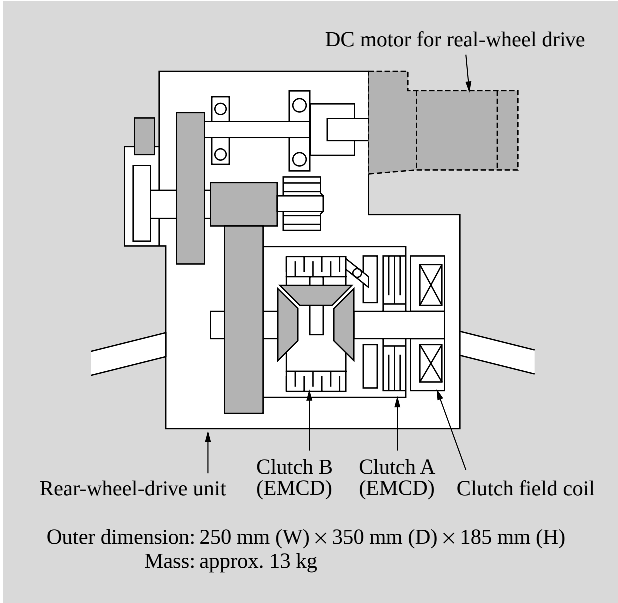

Fig. 4—Structure of Differential Gear Unit.
The number of mechanical parts required at the same time when switching to 2WD is reduced by installing the clutch in the last stage of the reduction gear.

(2) Magnetic circuitry was optimized to supply the current and voltage needed by the DC motor. In addition, a new control broad was developed that controls the field current of the alternator, thus enabling 0- to 50-V variable voltage to be controlled by the controller.
(3) Based on earlier implementations of high-output water-cooled alternators for 14-V applications developed by Hitachi, we were able to share components and production equipment.

Differential Gear Unit with Built-in Clutch

(1) For the clutch we adopted the same EMCD (electromagnetic control device) that is used in the mechanical 4WD center differential gear unit. Proven products were also used for the differential gear unit.
(2) The clutch was modified for use in the electric 4WD system. It was reduced in size and weight so the entire unit could be mounted in an FWD vehicle.
(3) The clutch is installed in the last stage of the reduction gear. Using a product developed by Tochigi Fuji Sangyo K.K., we were able to reduce the number of mechanical parts used at the same time when switching to 2WD and also minimize fuel losses due to friction (see Fig. 4).

Control System Overview

The ECU (engine control unit), the AT (automatic transmission) control unit, and the ABS (anti-lock brake system) control unit output the accelerator stroke, speed of each wheel, and so on via the CAN (controller area network). The 4WD control unit calculates the amount of slip based on the various output signals, then determines the target motor torque required by the vehicle. Next, the target armature current and motor shunt wiring current needed to output the motor torque are calculated, and commands executing armature current feedback control and motor shunt wiring feedback control are issued. Regarding the motor shunt wiring current, weak shunt wiring control is used to suppress the induced electromotive force when the motor is rotating at high speed. Under low-speed high-torque conditions that are used relatively frequently, a constant force that is not sufficient to cause magnetic saturation generates the maximum torque with the least armature current. Consequently, the electric motor torque is practically proportional with the armature current (see Fig. 5).

SYSTEM FEATURES AND DEVELOPMENT ACHIEVEMENTS

System Features

By applying electricity to an electric motor that drives the rear wheels, an electric 4WD system delivers power directly to the rear wheels with minimal response delay when starting. And because engine

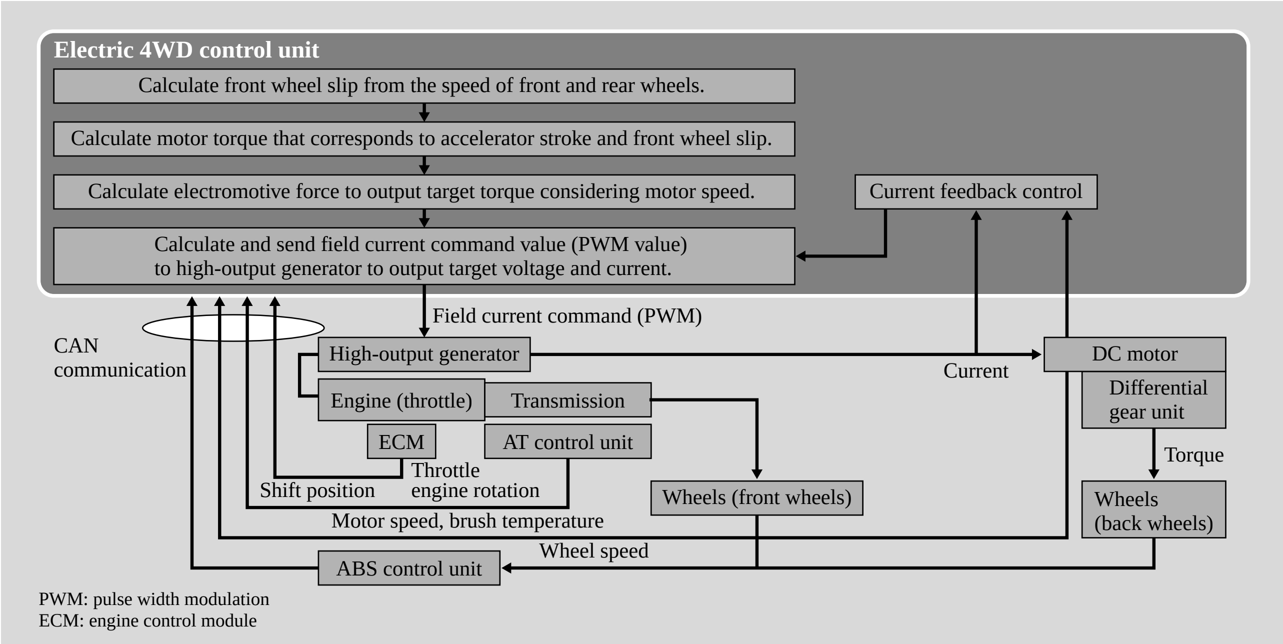

Fig. 5—Control System Configuration.
Motor is controlled by adjusting the generator field coil current to achieve the calculated target torque value.

torque is distributed to the rear wheels via a high-output alternator, it has the effect of suppressing front wheel spin. Since the vehicle is also equipped with a traction control system that also helps suppress front wheel spin, the vehicle has more than sufficient traction even with rough acceleration to operate safely on icy, slick low-friction roads. By separating the rear wheels from the engine, torque control can be applied to the electric motor even as the driver is accelerating, so traction control can be applied to the rear wheels independently of the engine that drives the front wheels.

System Development Achievements

Having successfully addressed all the performance criteria demanded of 4WD vehicles under everyday driving conditions, we have now realized the world’s first battery-less electric 4WD system that has the following advantages:
(1) Start performance on low-friction roads that is equivalent to conventional mechanical 4WD vehicles.
(2) Electric 4WD vehicles are easier to operate on icy inclines than mechanical 4WD vehicles (electric 4WD vehicles are more stable when starting and climbing hills where friction $\mu = 0.1$ and the degree of slope ranges from 0 to 10%).
(3) Fuel mileage of electric 4WD vehicles is 5% better than that of mechanical 4WD vehicles.
(4) The electric 4WD vehicle is about 15% lighter than mechanical 4WD vehicles, but the height of the trunk compartment is reduced by about 40 mm.
(5) The number of new parts that must be developed for 4WD vehicles by the vehicle manufacturers is reduced by 60%.

Usually when a new product is introduced on the world stage it incorporates a massive amount of complex advanced new technologies, but this is not the case with the electric 4WD system described here. The electric 4WD system is assembled from simple and clearly defined units whose functions can be readily grasped by anyone, and it gives drivers peace of mind, especially under adverse road conditions.

CONCLUSIONS

This paper outlined the design concept and system and unit needs that were addressed in the process of developing the world’s first battery-less electric 4WD system.

Although the electric 4WD system was developed only very recently, it is already apparent that the new electric 4WD system has enormous potential. For example, it has long been known through R&D on studless tires that hills which are impossible to navigate due to adverse conditions can be driven to the top if the vehicle’s drive power is carefully controlled and traction assured. Certainly there is room for improvement extending the upper limit of the 4WD operating speed range, improving the maximum drive torque specs, and improving the ability to mount each unit in the vehicle. However considering the close integration between the electric 4WD system and the brake and steering and other systems, we have come up with a very driver-friendly system with enormous potential. Based on our belief "Development is the Ultimate Service," Hitachi remains committed to meeting the diverse needs of consumers and the auto industry, and will continue to pursue R&D contributing to a safe and enjoyable driving experience.

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