Development of High-Temperature Superconducting Motor for Automobiles

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In recent years, electrification of automobiles is in progress. Following the advent of passenger electric vehicles, large size commercial vehicles with electric drive are also being developed. One of the problems in the development of large electric vehicles is the heavy weight which leads to short driving distances. Energy saving by the use of high-efficiency motors will be a solution. The authors have developed a prototype electric vehicle equipped with a high-temperature superconducting motor and a refrigerator. The test results showed that the motor has torque of 136 Nm and an output of 30 kW, and the prototype vehicle obtains the maximum speed of 80 km/h.

Keywords: superconductor, motor, electric vehicle

1. Introduction

In recent years, electrification of automobiles is in progress. As for passenger vehicles, hybrid electric vehicles have been popular, and some mass-production models of pure electric vehicles have appeared for consumer use. As for large size commercial vehicles, a numbers of experimental programs that use electric buses as public transportation have been done in some cities in Japan since 2010. In the near future, electric buses are to be utilized in cities that are environmental conscious and require new transportation systems based on the smart-city concept. The electric bus market is expected to grow.

One of the problems in the electrification of large size vehicles is the heavy weight of a vehicle and the load or passengers that the vehicle carries. In many cases, the space given for batteries is limited not to suppress the load space, thus the capacity of batteries eliminates driving ranges. Reduction in the energy consumption of batteries by the use of high-efficiency motors will be a good solution. In general, the permanent magnet synchronous motor (PMSM) is most efficient, and thus, passenger electric vehicles in the market commonly use the PMSM. Large size vehicles have also started using PMSMs or induction motors (IMs) on an experimental basis. The PMSMs and IMs have employed advanced technologies and it is not easy to increase the motor efficiency any further.

As an innovative material for electric power applications, researches are in progress on high-temperature superconducting (HTS) wire. HTS wire, whose electrical resistance is zero at liquid nitrogen temperature, has shown dramatic improvement in performance and been experimentally applied to electric power cable, ship propulsion and other applications (1)-(3).

In 2007 and 2008, the authors developed motors using bismuth superconducting wire and mounted it on electric vehicles to investigate the potentials and challenges of applying superconducting wire to automobiles (4). Conventional superconducting wires were simply cooled by liquid nitrogen, however, the current prototype has an on-vehicle refrigerator for investigation of a cooling system.

2. Environmental-Friendly Vehicle and Application of Superconducting Motor

To cope with the depletion of fossil fuels and global warming caused by CO_2 emissions and to realize sustainable motorization, significant improvements in energy efficiency and shift to petroleum alternative fuels are required. There are mainly three types of environmental-friendly vehicles under development by automakers and research institutes: Hybrid electric vehicles (HEVs), electric vehicles (EVs), and fuel cell vehicles (FCVs) (5), (6). HEVs have been mass-produced since 1997, spreading in the market much faster than EVs and FCVs. As HEVs use both a combination of a gasoline engine and an electric motor, the existing infrastructure for gasoline-driven vehicles can be utilized. EVs and FCVs, on the other hand, produce zero emissions during operation, making them the ultimate eco-cars. What these three types of environmental-friendly vehicles have in common is the use of electricity to deliver power from a motor. Realizing a high efficiency, high performance motor is the key to the development of electric vehicle systems. Thanks to recent improvements in the performance of HTS wire and in the adiabatic cooling technology, the feasibility of more efficient electric vehicle systems by applying superconducting motors is being actively investigated.

Figure 1 shows the features of a superconducting motor coil. A superconducting coil provides a high magnetic flux density, and therefore, delivers much higher torque than ordinary motors. Furthermore, a superconducting motor can be used without copper loss, and an air-core superconducting motor may be developed in the future to reduce iron loss and increase motor efficiency. Automobile motors need to respond to a wide range of operations from low speed driving to high speed driving and from low torque output for constant-speed cruising to high torque output for acceleration. While ordinary motors exhibit considerable copper loss and poor efficiency during high torque output, superconductive motors provide high efficiency over a wide range. The high torque feature leads to the development of a system in which the motor directly drives a shaft without variable-speed gears, and thus, results in the reduction of transmission loss caused by the gear system.

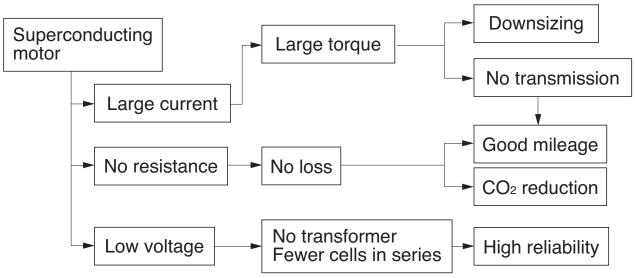

Fig. 1. Features of superconducting motor

The major challenge in applying a superconducting motor to an automobile is that the superconducting coil must be kept at a low temperature, below the critical temperature of the superconducting material. Cryogenic coolants, such as liquid nitrogen, are suitable for keeping materials in a superconducting condition, allowing simple motor designs with vessels. But in a long operation without the refilling of coolant, an on-vehicle refrigerating unit is required to keep the superconducting motor at a low temperature while the vehicle is running.

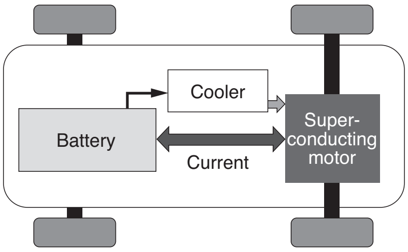

Fig. 2. System configuration with on vehicle refrigerator

3. Prototype Superconductive Motor

3-1 Principle and specifications of the motor

The specifications of the motor used in the test are shown in **Table 1**. In terms of the basic principle, it is a series-wound DC motor with a coil formed of polyimide film wrapped type-H superconducting wire to provide a constant magnetic field. The superconductive coil is immersed in liquid nitrogen for refrigeration, and a copper/stainless-steel cooling insulation vessel with a vacuum layer is used. The inner vessel is made of copper to transfer heat easily from the coil to the refrigerator. The iron core consists of four claw poles. The coil is a simple pancake coil formed of 186 turns of superconducting tape. The claw pole design was adopted to make the coil larger in winding radius and thus reduce the number of coils, and to simplify the design of the cooling apparatus and other elements. Because the motor has a long shaft, the coil is divided into two parts as shown in **Fig. 3**. The same armature rotor as one used in a commercial DC motor is used.

Table 1. Specifications

Wire	Wire type	Type H (polyimide film insulated)
	Dimensions	4.2 x 0.22 mm
	Critical current (Ic)	140 A
	Maximum tensile strength (77 K)	150 MPa
	Minimum bend radius (room temperature)	70 mm
Coil	Shape	Inner dia.: 216 mm, Outer dia.: 241 mm, Width: 35 mm
	Turns	186 turns / coil
Motor	Motor type	Series-wound DC (field superconductor)
	Coil refrigeration method	Liquid nitrogen immersion, with on-vehicle refrigerator
	Maximum voltage	144 V
	Maximum current	500 A
	Dimensions	307 (dia.) x 400 (axis len.)
	Weight	About 110 kg

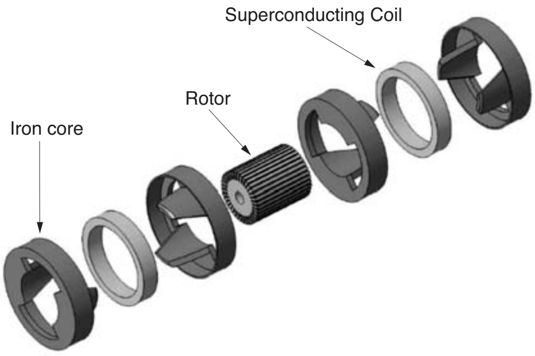

Fig. 3. Components of superconducting motor

3-2 Design

In designing an on-vehicle cooling system, the configuration of a copper inner vessel is determined by means of computer-aided thermal analysis. **Figure 4** is an analysis result, which shows the temperature of 74 K is obtained at the lower end of the coil, while the temperature of refrigerator is set to 65 K.

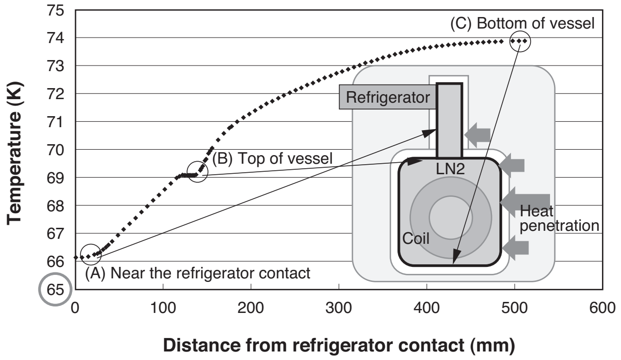

Fig. 4. Temperature of copper inner vessel

The wall of the copper inner vessel is directly connected to the cold tip of the refrigerator through the thick copper block to attain thermal conductivity. The refrigerator is divided into two components with a flexible tube connecting both of them, which provides flexible layouts in the engine compartment of the vehicle.

The height of the refrigerator is designed as short as possible to avoid the interference to the hood. The inertance tube of the refrigerator is directed upward and bent downward to set the large compliance tank in the lower place.

3-3 Configuration and appearance

Photo 1 shows an exterior view of the superconducting motor with a refrigerator. The superconducting coil is immersed in liquid nitrogen in the thermal insulation vessel. Liquid nitrogen reservoirs are placed on the top of the motor. In operation, liquid nitrogen is provided first for pre-cooling, and then the refrigerator starts to cool down liquid nitrogen. When the temperature of liquid nitrogen is cooled below the boiling point, the evaporation of liquid nitrogen stops. Therefore, liquid nitrogen does not need to be refilled during the refrigerator operation.

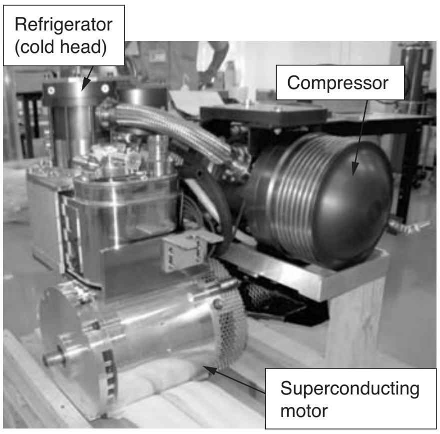

Photo 1. Superconducting motor

4. Prototype Vehicle with Superconducting Motor

The authors developed two prototype superconducting electric vehicles in 2007 and 2008. In the present study, a superconducting motor with a refrigerator is mounted on a converted vehicle (a Toyota Crown Athlete) to verify its feasibility in a vehicle environment. The drive system of the vehicle is diagrammed in **Fig. 5**.

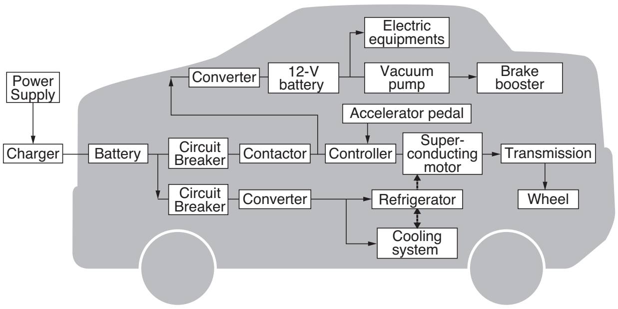

Fig. 5. Configuration of superconducting vehicle

The power source of the motor is twelve 12-V lead-acid batteries connected in series (144 V). The rotation angle on the accelerator pedal is converted to electric resistance with a potentiometer, and a commercial current controller is used for supplying the corresponding amounts of current to the motor. Torque from the motor is conveyed to the wheels as drive force by the original vehicle's FR transmission. Batteries are charged by the contact-type method, using a cord running from an external charger to a socket in the place where a fuel tank lid used to be. Since the original gas engine was removed, the negative pressure for the brake booster needs to be generated by other method. Therefore, a commercial vacuum pump designed for electric vehicles is applied. A DC-DC converter is installed in order to supply power to the 12-V electrical equipment. The weight of the prototype vehicle is about 2,000 kg.

Photo 2 shows an engine compartment with a super-

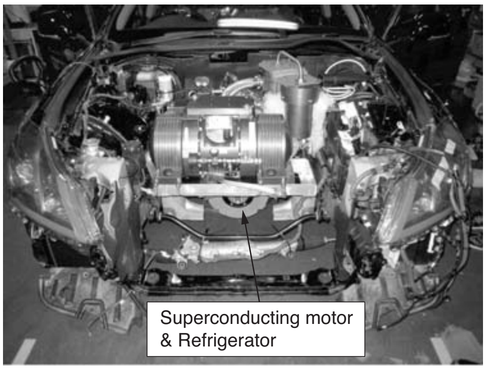

Photo 2. Superconducting motor mounted on vehicle

Photo 3. Test drive

Table 2. Vehicle performance

Items		Performance
Vehicle performance	Maximum torque (1,540 rpm)	136 Nm
	Maximum output (2,200 rpm)	30 kW
	Maximum speed (4th gear)	About 80 km/hr

conducting motor, refrigerator, and current controller installed. The lead-acid batteries are installed in the luggage room on the rear side of the vehicle.

The results of the vehicle performance test are shown in **Table 2**. The maximum speed was 80 km/hr, which is suitable for use in normal driving. As for the refrigerator cooling test result, the lowest temperature of 73 K was obtained in the superconducting coil even though in a transition condition.

5. Conclusion

The authors have developed a prototype passenger EV which consists of a motor using HTS wire and devices to supply power to the motor. In the driving test held from December 2011 to May 2012, the vehicle operated smoothly without problems. As for the on-vehicle cooling system, components, such as a refrigerator, power supplier, water cooling pump and radiator, operated properly to keep the temperature under 77 K, the boiling point of nitrogen. The authors will continue compiling test-driving records to verify the reliability of the superconducting motor.

Furthermore, the authors will move forward with research on further advanced superconducting motor systems, with the aim of developing superconductor-applied products with excellent commercial advantages. A superconducting motor system for electric buses is one example. Since the operation rate of the bus motor system is higher than that of the passenger vehicle's motor system, energy required for cooling the motor in the out-of-service state is relatively small, and thus the total energy efficiency of the system increases.

Also, in a heavy vehicle that requires a high output, the output of the cooling mechanism has less impact on the increase of the motor efficiency and the decrease of transmission loss. Furthermore, as heavy vehicles require high output for acceleration and deceleration regeneration, a superconducting motor would be suitable for buses and other mass-transit vehicles that are subject to frequent stop-and-go operations.

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