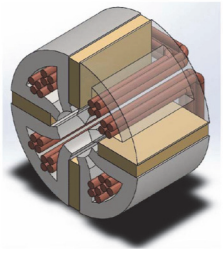
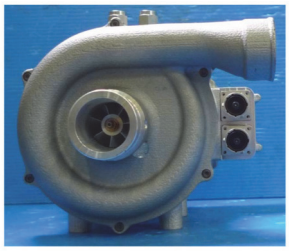
Development of High-speed Single-phase Motor for Automotive Turbocharger





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Mitsubishi Heavy Industries, Ltd. (MHI) has been making efforts in the development of power electronics (motors and inverters), which can provide high performance at a low cost and suit the character of each product. Among such efforts, together with Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (MHIET), MHI is now developing a high-speed electric supercharger and has successfully developed and tested the prototype of the single-phase flux switching motor with a simple configuration, which realizes a high response boost pressure.

1. Introduction

Due to environmental and resource problems, CO2 emissions regulations around the world have become increasingly strict, and will continue to do so. To cope with such regulations, the number of electrified vehicles such as Hybrid Electric Vehicle (HEV), Electric Vehicle (EV) and Fuel Cell Vehicle (FCV) is increasing; but most such vehicles still use combustion engines. Therefore the need to improve fuel economy continues to exist. Engine downsizing and downspeeding have been widely used as techniques to reduce fuel consumption, and from now Miller cycle combustion and lean burn, etc., will also be used, which will lead to the need for high response boost pressure control.

The migration of automotive systems from 12V to 48V that has already begun in Europe allows components to operate with lower current. It is due to this fact that electric superchargers, which can meet the aforementioned requirement, are already equipped in some high-class vehicles.

In this report, we will introduce MHI's development of power electronics (motors and inverters) that can cope with the challenges for turbocharging application at a low cost.

2. 48V Electric Supercharger Development Specifications

The specifications of MHI's 48V electric supercharger are listed in **Table 1** and **Figure 1**. The boost response for acceleration is 0.3s, and the maximum power is 7kW, after which 30s of 5kW and continuous 3kW operation are also possible. Water cooling is used, and ball bearings are used for the lubrication oil path.

Table1 MHI development specifications for electric supercharger

Item		Specification
Input voltage		48V
Max speed		80,000rpm
Output	Instantaneous	7kW (0.3s)
	Short period	5kW (30s)
	Continuous	3kW
Response		0.3s (0→80,000rpm)
Cooling		Water cooling
Bearing		Grease packed ball bearing

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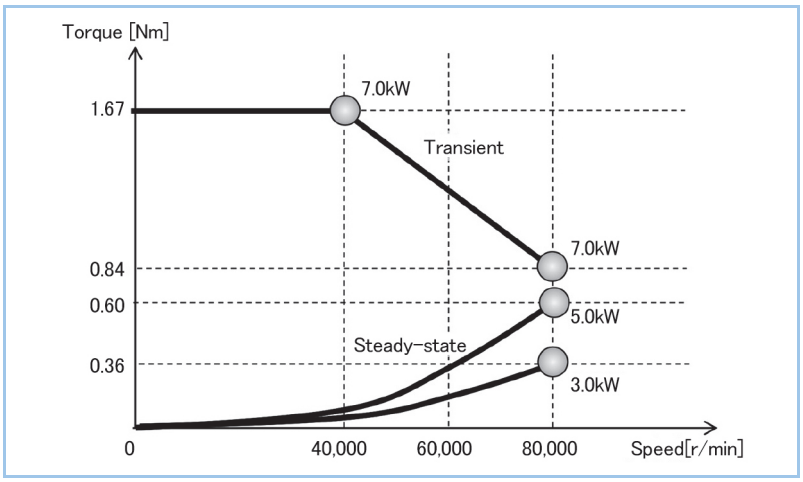


Figure 1 MHI development specifications for electric supercharger

3. High-speed single-phase flux switching motor

In HEV and EV, permanent magnet motors are widely used, but the high cost and inability to operate well at high temperatures, etc., are challenges of rare-earth magnets.

Accordingly, MHI and MHIET have chosen to develop a new flux switching motor, which does not use a rare-earth magnet, and has a simple structure which will result in a low cost. The details are presented below.

3.1 Characteristics

MHI's flux switching motor for electric superchargers is described below. The motor categorization is shown in **Figure 2**, and a comparison with other types of motors is given in **Table 2**.

- There is no permanent magnet in the rotor, so there is no need to protect the permanent magnet from centrifugal force and cooling is simpler.
- The existence of a field allows the use of magnet torque, so compared to a switched reluctance motor (SR), less EM vibration and noise can be expected.
- Stator winding does not require a rotating magnetic field, so there is no need for a 3-phase configuration like in PMSM. This leads to fewer switching devices resulting in a lower cost.

Table 2 Motor feature comparison

Type of rotor	Flux Switching Motor (FSM)	Switched Reluctance Motor (SRM)	Permanent Magnet Synch-Motor (PMSM)
Cost	**Low** - No rare-earth magnet (Ferrite magnet or field winding) - Small number of FETs	**Medium** - No magnet - High-spec controller	**High** - Rare-earth magnet - Magnet holding structure
System efficiency	**Medium (<=90%)** - Copper loss: Medium (Weak field or field winding)	**Low (<=88%)** - Copper loss: Large (No field)	**High (>=90%)** - Copper loss: Small (Magnet field) - Magnet eddy current loss
Vibration and noise	**Quiet** - Pulse current, but supported by field magnetic flux (magnet torque)	**Noisy** - Pulse current, only utilizing reluctance torque	**Most quiet** - Smooth drive with sine-wave current
Drive circuit	Single phase inverter	Single phase inverter x pulse number	3-phase inverter

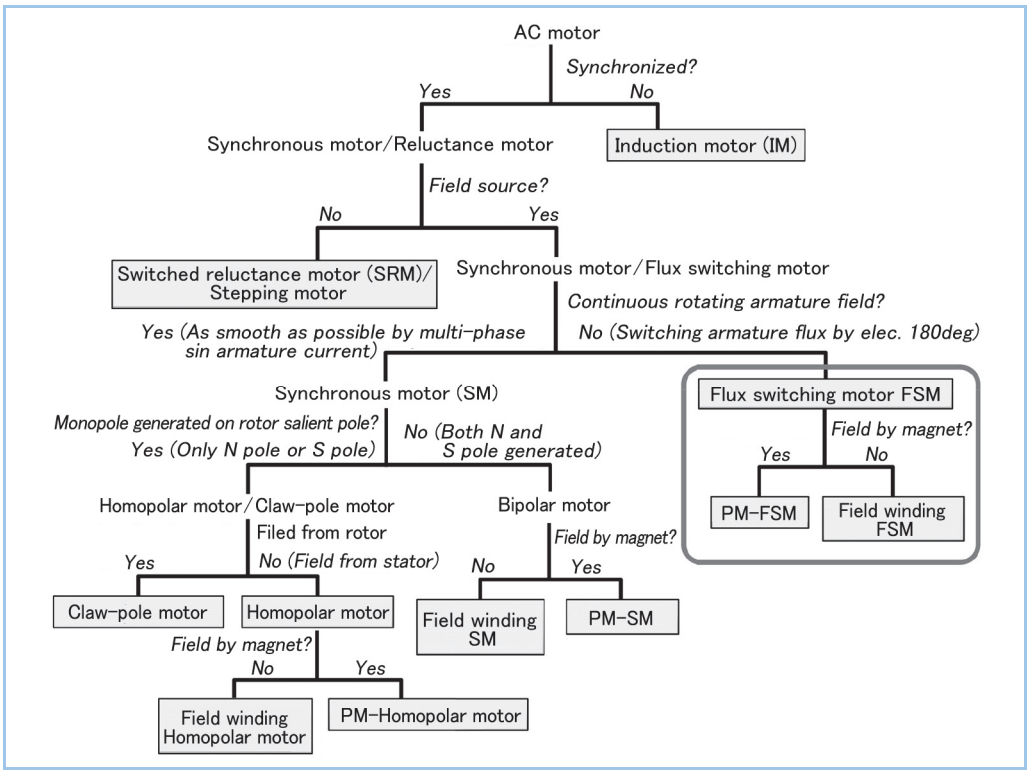


Figure 2 Flux Switching Motor categorization

3.2 Structure

(1) Motor

Figure 3 presents the flux linkage for every 45 mechanical degrees of the rotor, for FSM with 2 poles using a magnet for the field. This figure illustrates the flux when the coil is not conductive (no-load condition). If the coil winding direction is as can be seen in the figure, when the rotor is at 0 degrees and 90 degrees, total flux will be zero. At 45 degrees and 135 degrees, we will have maximum flux, but the direction will be opposite. If we assume that the flux changes (increasing/decreasing) linearly, the induced voltage is as presented in **Figure 4**. If we assume the current as given in Figure 4, which current and induced voltage has the exact same shape, constant torque can be achieved.

In reality, however, there is some nonlinearity caused by coil inductance, stator iron saturation, etc., so it is difficult to obtain constant torque, and in some cases the torque will momentarily become negative. Qualitatively, by switching current direction every 90 mechanical degrees of rotation, the direction of the composition of the field and armature will change, and single-direction torque will occur. For a rotor with 2 poles ($2p$), at N rpm, $f=2pxN/60=pN/30$ Hz of current direction switching frequency is required to control the motor. At a lower switching frequency, the necessary calculation speed is also reduced, and the iron loss is also smaller. Accordingly, a 2-pole rotor structure might seem more suitable, but due to the reason below, we have chosen to use a 4-pole type.

Figure 5 presents various variations of FSM with different magnet and coil shapes. In (a), to increase the field flux, the width of the magnet is increased. In (b), opposite direction coils in (a) are skipped and full-pitch winding is used. In this case, copper loss is reduced which results in better efficiency. In (c) there is no winding across the slots and toroidal winding is used. The end-winding length can be reduced and the motor length in the axial direction can be decreased, but the coil will stick out in the radial direction at the same time. To reduce the size of motor in both the axial and redial directions, MHI has decided to use a 4-pole structure. By using a 4-pole structure, the end-winding length of the full pitch winding can be reduced. **Figure 6** is the final structure of our motor, with **Figure 7** illustrating only the coil part. By using wave winding instead of lap winding, the end-winding length can be reduced even further.

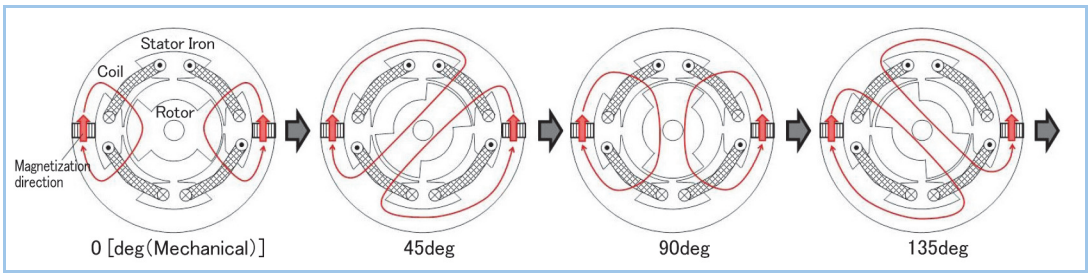


Figure 3 Flux linkage under no-load condition (Coil not conductive)

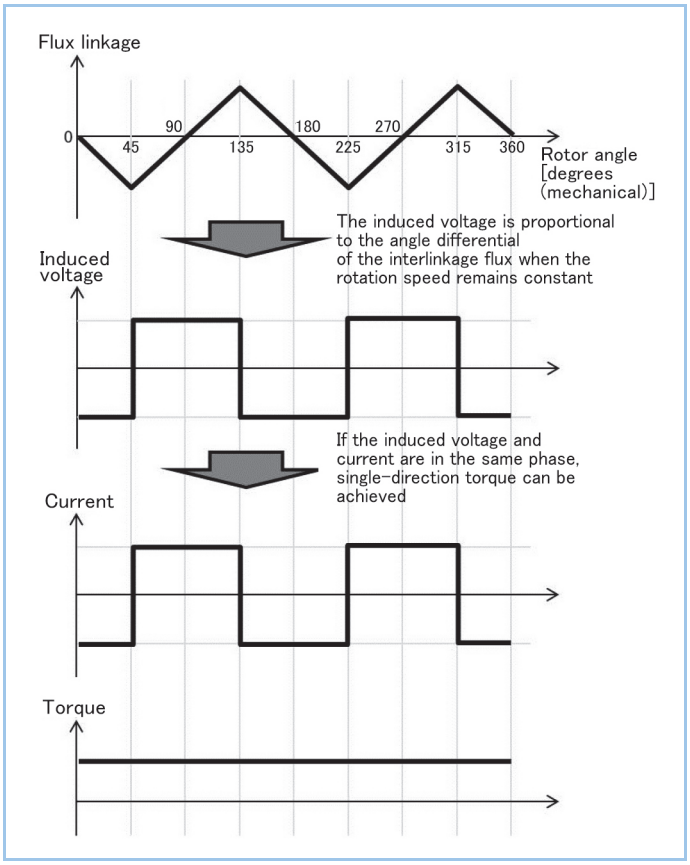


Figure 4 Torque waveform with flux linkage increases/decreases linearly and induced voltage and current are in exactly the same phase

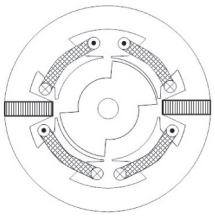
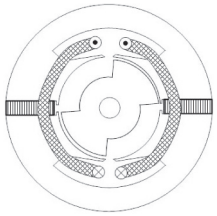
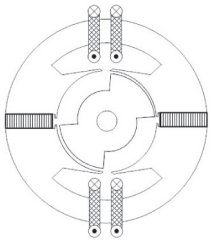
(a) Larger magnet type	(b) Full pitch winding type	(c) Toroidal winding type
		
Increase magnet width to increase field flux	Skipping the slot with opposite direction coil (full pitch winding) to reduce copper loss	Can reduce the length of end-winding, but will make the radial dimension larger

Figure 5 Examples of various types of FSM with different magnet and coil shapes

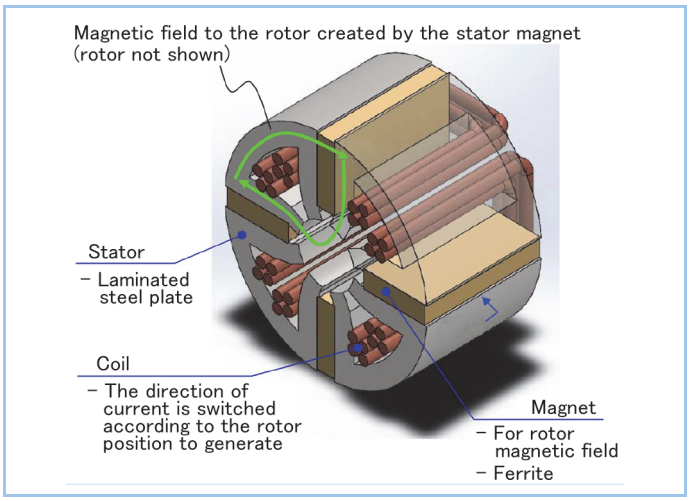


Figure 6 Structure of magnetic-field flux switching motor

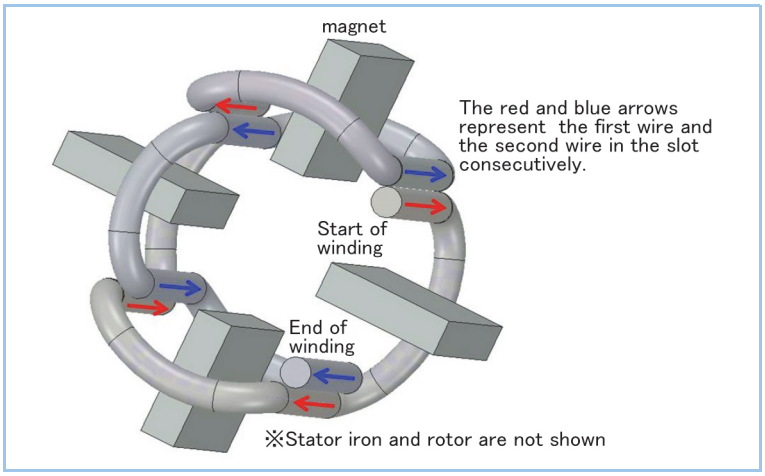


Figure7 Structure of wave winding coil

(2) Inverter

Figure 8 is a basic circuit diagram of FSM and explains about the conductive modes. By using these 3 conductive modes, the current can be controlled in the winding. For the type of FSM shown in Figure 6, there are 4 poles, therefore the direction of current is switched every time the rotor has rotated 45 mechanical degrees. For 80000 rpm, the switching frequency will reach 5.3 kHz. The switching frequency for FSM is twice that of a permanent magnet motor, but this motor does not require complex control such as vector control, therefore a commercially available microprocessor can be used. **Figure 9** presents the integrated version of motor and inverter.

(3) Overall structure

Figure 10 depicts the exterior of an electric supercharger which is equipped with the aforementioned motor and inverter.

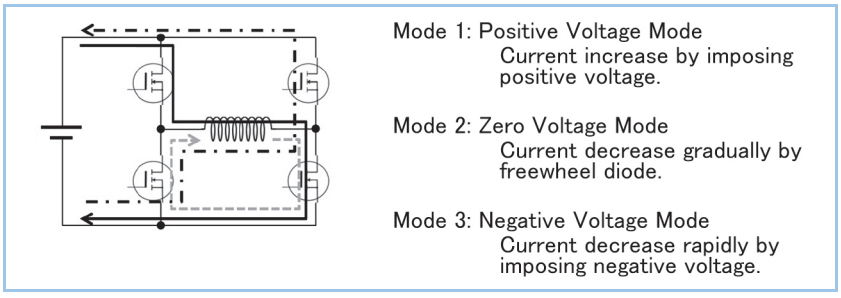


Figure 8 Structure of inverter to drive the single-phase FSM

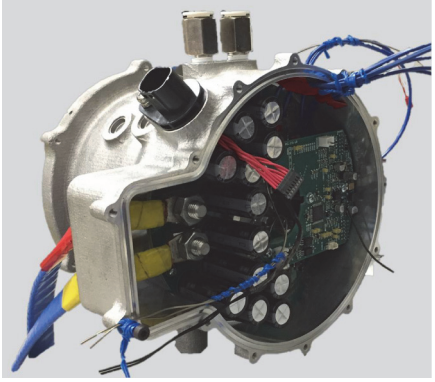


Figure 9 Exterior of integrated version of motor and inverter

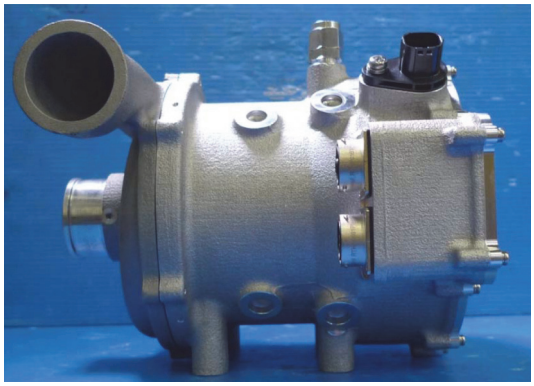


Figure 10 Exterior of electric supercharger equipped with FSM

3.3 Test results

Figure 11 presents one of the performance test results during controller tuning. This motor has already achieved the specifications listed in Table 1 and Figure 1, and MHI will continue to make the motor more compact and lower in cost. The application of this motor in a 2-stage electric supercharger will be introduced in an MHI technical review to be released in the near future.

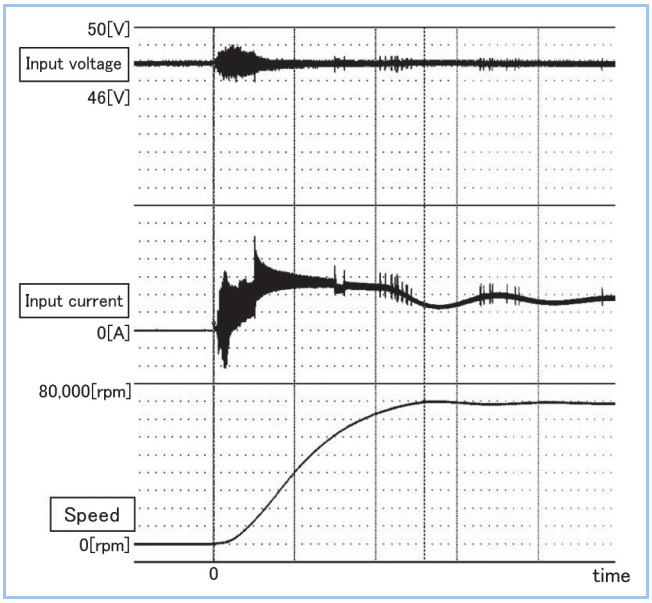


Figure 11 High-speed response test results

4. Conclusion

This report introduced a flux switching motor, which is a single-phase motor currently under development featuring the high speed unique to turbocharger products at a low cost, using the MHIET electric supercharger for automobiles as an example. High speed or low speed high torque specifications and the ability to operate under special environments – something that cannot be realized by motors or generators currently on the market – are sometimes required for products of the MHI Group, including those of our company. We will respond to the needs of customers by actively and constantly incorporating advanced technologies from both inside and outside the group, as well as Japan.

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