

Development of Compact Transverse Flux Motor with 2 Coils and 3 Stators

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ABSTRACT

Honda has been conducting research to create a T.F. (Transverse Flux) motor with a new three-dimensional magnetic circuit in order to produce more versatile motors for HEVs. The effectiveness of magnetic circuits has been proven in principle, but there is also a clear need to improve the torque characteristics.

To improve torque characteristics, the magnetic saturation needs to be reduced by creating a more even flux path area and widening the gap between the teeth. Torque characteristics were improved by designing a new stator with sufficient flux path area and distance between teeth. The new T.F. motor also has a simple structure, consisting of two winding wires and three stators. This has improved torque density.

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INTRODUCTION

HEVs with electric power trains are one method of improving fuel consumption in cars and reducing CO₂ emissions. There is a demand to equip a wider range of vehicles with Honda's HEV system that is called IMA (Integrated Motor Assist) system [1], [2], [3] in which the motor is mounted between a CVT and an internal combustion engine (depicted in Fig.1). To do this, the axial length needs to be shortened.

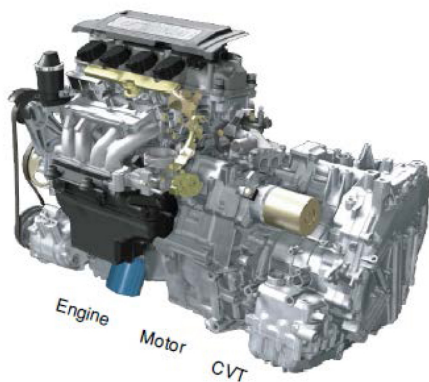


Figure 1. IMA power train

An effective way to shorten axial length is to shorten the coil end, as the coil end does not contribute to torque generation. A salient-pole concentrated winding stator has been adopted to realize short coil ends, as shown in Fig.2. However, as can be seen in Fig. 3, the coil end still accounts for over 20% of the axial length even in salient-pole concentrated winding motors. It is preferable to shorten the coil end length further.

A transverse flux motor (henceforth "T.F. motor") containing a new magnetic circuit with no coil end was proposed. It was proven that the T.F. motor's magnetic circuit could work well as a motor [4], but the increase in phase current reduced the torque increase rate. In this paper the methods to improve torque characteristics will be considered.

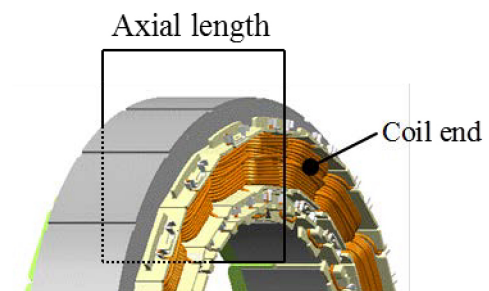


Figure 2. Salient-pole concentrated winding stator

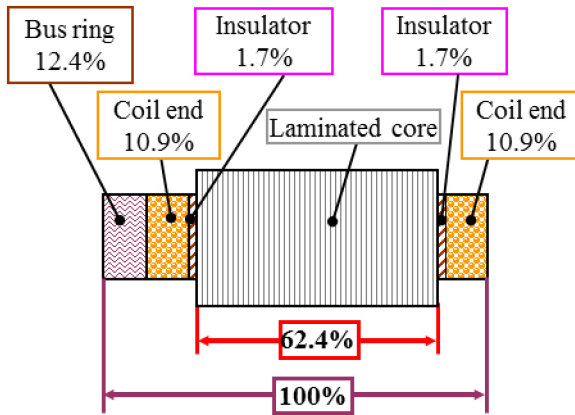


Figure 3. Breakdown of axial length of salient-pole concentrated winding motor

PRINCIPLES OF T.F. MOTOR

Figure 4 shows the structure of the T.F. motor proposed in the previous report [4]. As can be seen in the picture, the motor consists of a three-dimensional flux path stator made from soft magnetic composites (SMC) and ring-shaped winding wires. The principle of the T.F. motor magnetic circuit configuration is explained as follows.

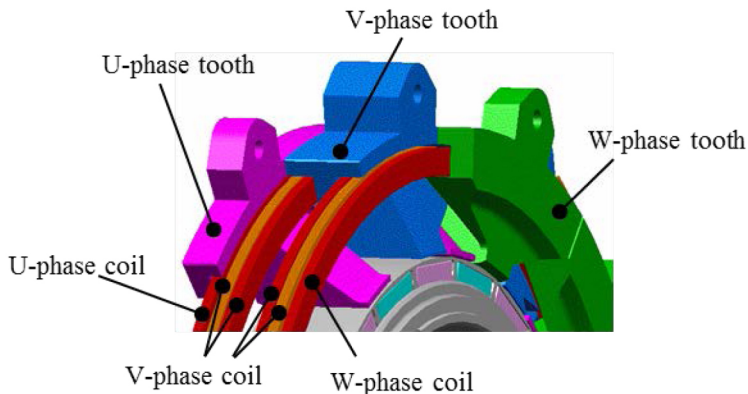


Figure 4. Structure of the motor

First, Fig. 5 shows a conventional salient-pole concentrated winding motor and Fig. 6 shows its magnetic equivalent circuit. If Φ_a is the magnetic flux between teeth WU, Φ_b is the magnetic flux between UV and Φ_c is the magnetic flux between VW, then Ψ_u , Ψ_v and Ψ_w are assigned to the interlinkage magnetic flux of the winding wires at teeth U, V and W as shown in equation (1).

$$\Psi_u = \Phi_a - \Phi_b$$

$$\Psi_v = \Phi_b - \Phi_c$$

$$\Psi_w = \Phi_c - \Phi_a$$

(1)

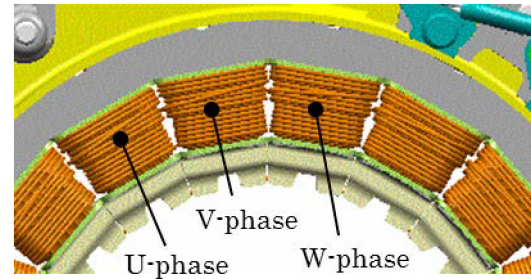


Figure 5. Conventional salient-pole concentrated winding motor

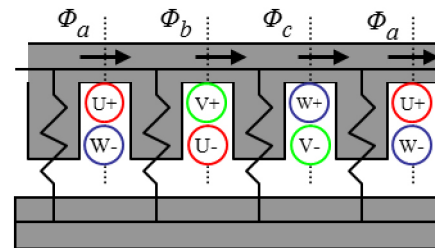


Figure 6. Magnetic equivalent circuit of salient-pole concentrated winding motor

Figure 7 shows the T.F. motor and Fig. 8 shows its magnetic equivalent circuit. In the T.F. motor, teeth U, V and W are axially aligned, with Φ_a , the magnetic flux between WU passing through the same path as Φ_b , the magnetic flux between UV and Φ_c , the magnetic flux between VW. The interlinkage magnetic flux between the teeth is as shown in Equation (2). Equations (1) and (2) show that the interlinkage magnetic flux is the same in both salient-pole concentrated winding motors and the T.F. motor. This means that even without a coil end, the T.F. motor utilizes all rotor magnetic flux effectively.

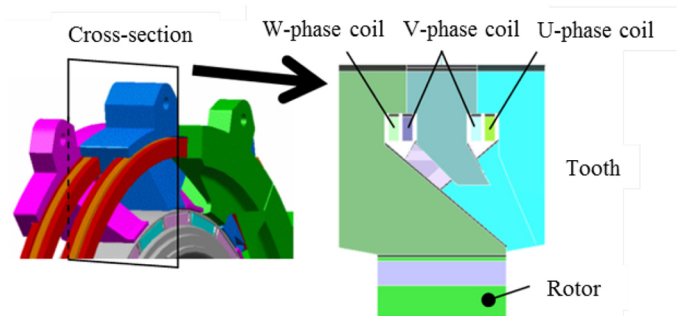


Figure 7. Cross-section of T.F. motor

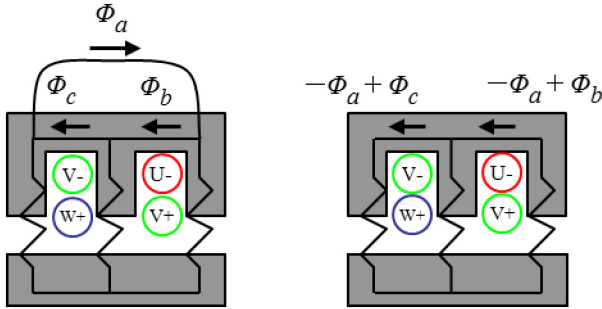


Figure 8. Magnetic equivalent circuit of T.F. motor

$$\Psi_u = \Phi_a - \Phi_b$$

$$\begin{aligned}\Psi_v &= -\Phi_a + \Phi_b - (-\Phi_a + \Phi_c) \\ &= \Phi_b - \Phi_c\end{aligned}$$

$$\Psi_w = \Phi_c - \Phi_a$$

(2)

Figure 9 shows the results of back EMF voltage waveform measurement in the prototype. Back EMF voltage was confirmed for the three phases, and it was proven that the magnetic circuit in the T.F. motor functioned sufficiently as a motor. Table 1 shows the target characteristics of the T.F. motor. Calculated torque constant K_t from the back EMF voltage is of 0.525 Nm/Arms. The target torque is 105 Nm at 200 Arms, the maximum phase current in the power control unit of the IMA system.

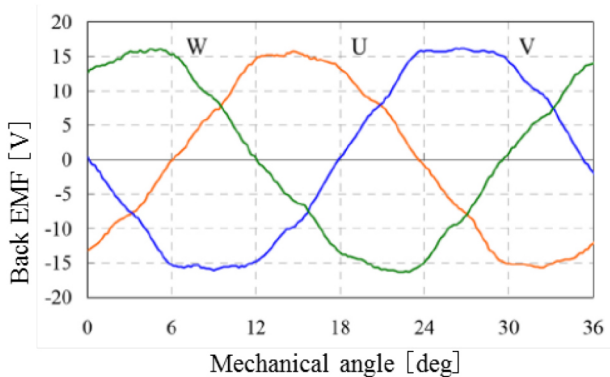


Figure 9. Back EMF voltage waveform (600 r/min)

Table 1. Motor characteristics

Maximum target torque	105 Nm
DC voltage	144 V
Maximum current	200 Arms
Maximum speed	6000 r/min

Figure 10 shows the relationship between phase current and torque of the prototype motor. Torque generation was

confirmed, but the generated torque when current was applied was less than the torque predicted from the back EMF voltage. As the torque increase rate decreases as the phase current increases, magnetic saturation is presumed to be the reason for the torque reduction. It is therefore necessary to find a way to alleviate magnetic saturation.

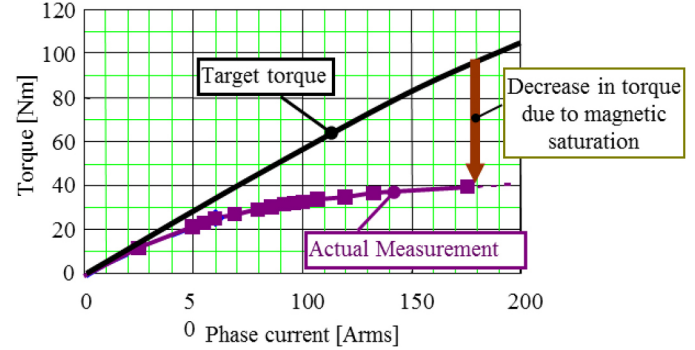


Figure 10. Phase current - torque characteristic

COUNTERMEASURES AGAINST MAGNETIC SATURATION

As can be seen in Fig. 10, the torque increase rate decreases as the phase current increases. It is therefore predicted that magnetic saturation is occurring in the flux path due to insufficient flux path area in places and too much magnetic flux flows through those areas when a current is applied. Below are methods for creating a more even flux path area and reducing the volume of magnetic flux that occurs when a current is applied.

CREATING A MORE EVEN FLUX PATH

Figure 11 shows the flux paths in the prototype motor. The magnetic flux of the rotor magnet passes across tooth surface A and then surface B, two surface Cs and the three surface Ds, before moving on to other teeth. The comparison of flux path areas in Table 2 shows that the surfaces at the base of the tooth (B and 2C + D) have a smaller flux path area than surface A.

Figure 12 shows the results of CAE analysis of magnetic flux density in each area at no load. A higher flux density can be seen at the base of the tooth than other parts of the tooth. As can be seen in Fig. 13, the maximum flux density for the SMC being used is 1.5 T. The CAE results show that the density at the base of the tooth is higher than 1.5 T. It is clear that magnetic saturation is occurring at the base of the tooth.

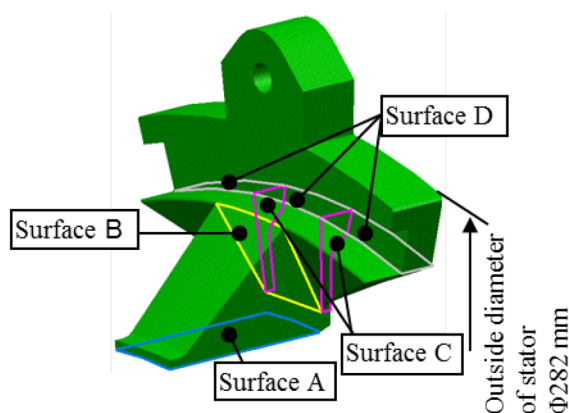


Figure 11. Flux path area (10Poles)

Table 2. Comparison of flux path area (10Poles)

Surface	Area [mm ²]	Ratio to A
A	678	1.00
B	469	0.69
2C+D	375	0.55
3D	650	0.96

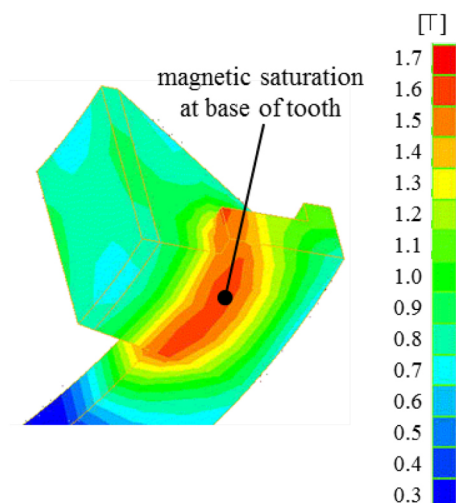


Figure 12. Contour map of magnetic flux density (tooth U, 0 Arms)

In order to increase surfaces B and C and create a more even flux path area, the outside diameter of the stator needs to be increased. However, there are restrictions on the outside diameter of the stator, meaning that the winding wire space must be decreased instead. Decreasing the winding wire space increases copper loss, leading to a decrease in efficiency. In order to create a more even flux path without decreasing the winding wire space, it seems to be effective to increase the pole pair number. By increasing pole pair

numbers, the magnetic flux passing through the tooth will decrease and the tooth width can be reduced.

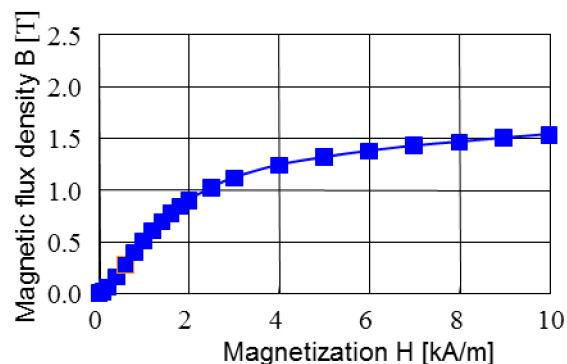


Figure 13. SMC magnetization characteristics

Figure 14 shows the shape of a tooth with the increased pole numbers from 10 poles to 20, and Table 3 shows the flux path area of each surface. The comparison of area shows that the each surface has almost uniform flux path area. This is an effective way to reduce magnetic saturation.

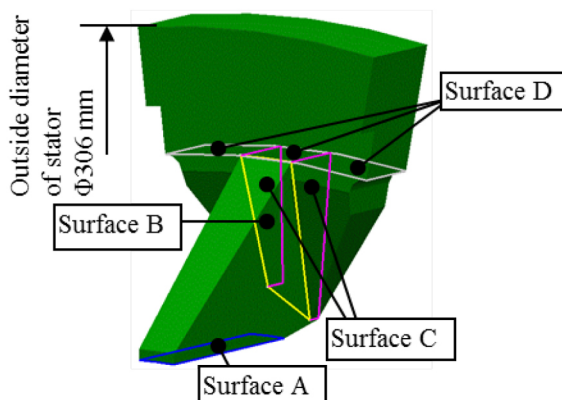


Figure 14. Flux path area (20 Poles)

Table 3. Comparison of flux path area (20 Poles)

Surface	Area [mm ²]	Ratio to A
A	259	1.00
B	252	0.97
2C+D	278	1.07
3D	373	1.44

A prototype T.F. motor was made with 20 poles. Figure 15 shows the torque characteristics measured in this motor. The torque was 58 Nm at 160 A, 45% higher than the 40 Nm measured in the 10-pole motor. Creating a more even flux path was therefore effective.