Experimental study on cogging-torque reduction of transverse-flux motor with skewed armature cores

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Abstract

Transverse-flux motors are suitable for getting high torque density by increasing their number of poles owing to the independent coil design from the number of poles. However, these kinds of motors typically have a large amount of permanent magnets with increasing the number of poles. We have designed a transverse-flux motor with a consequent-pole rotor having almost half amount of magnets compared with conventional surface-mounted magnet rotors. Although this motor can generate comparably large average torque to the conventional motors, it has larger cogging torque. And, conventional skew structures, often applied to axially uniform motors, are generally effective for reducing the cogging torque by offsetting dominant harmonic components but cannot be applied to transverse-flux motors including our motor due to their axially non-uniform structure. This paper describes radially skewed armature cores, compatible to basic configuration of general transverse-flux motors, for the cogging torque reduction of our motor. Results of FEM magnetic analysis and its spectral analysis indicate that the most dominant harmonic component of the cogging torque reduces by 96%, and consequently, peak-to-peak value of the three-phase cogging torque reduces by 87%. These analysis results are almost agreed with experimental result, in which the most dominant harmonic component reduces by 86% and peak-to-peak value of the cogging torque can be approximately estimated to decrease by 82%. Therefore, the radial skew structure could be verified to effectively suppress the cogging torque of the transverse-flux motor.

Key words: Cogging torque reduction, Radially skewed cores, Transverse flux motor, Consequent pole rotor, Experimental study, FFT spectral analysis, FEM magnetic analysis

1. Introduction

Electromagnetically driven motors have been applied to a wide variety of fields, and most of them are required to have higher torque density from the viewpoint of saving their installation space. The electromagnetic torque is basically proportional to the flux content due to the magnets, armature current, and number of the poles of the motors. However, design approach with increasing the flux content and armature current has limit due to scarcity of the rare-earth magnet materials and magnetic saturation of the iron cores, respectively for improving the torque density. Most of conventional motors, having armature coils put in the slots and wound around the teeth, are difficult to have a large number of the poles from the viewpoint of inserting the coils into the narrow slots, the space of which is approximately inversely proportional to the number of the poles.

Transverse-flux motors have an advantage over them in generating larger torque with increasing number of the poles because of their simple armature-coil structures independent on the number of the poles (Weh and May, 1986). The armature, which is typically on the stator, comprises of ring coils around the axial direction and circumferentially distributed iron cores surrounding them. The iron cores are mostly U-shaped, and sandwich a single coil with their two teeth. Some prior motor has E-shaped cores sandwiching two ring coils with their three teeth in each phase for generating large magneto-motive force (Weh, 1995). All the armature iron cores in each phase are equally magnetized with the coil excitation. Thus, these motors have unipolar magneto-motive distribution for the circumferential direction.
in contrast to the conventional motors mentioned above. And, some other prior motors for obtaining bipolar magneto-motive distribution has circumferentially deformed U-shaped cores (Mitcham, 1997), claw-pole cores (Maddison, et al., 1998), intermediate poles (Arshad, et al., 2002), return-path cores (Henneberger and Bork, 1997), and double-sided structures (Mitcham, 1997) (Muljadi, et al., 1999) (Weh and May, 1986) in their armature. In terms of field magnets, which are typically on the rotors, most of prior motors have surface-mounted arrangements (Arshad, et al., 2002) (Henneberger and Bork, 1997) (Maddison, et al., 1998) (Muljadi, et al., 1999) (Weh and May, 1986) or flux-concentrated arrangements (Maddison, et al., 1998) (Mitcham, 1997). Some has a cylindrical magnet between axially separated two toothed cores and biasing them (Kastinger, 2002). However, in any motors comprising of these armature and field magnet structures, the field magnets are located in the flux path resulting from the coil excitation. Therefore, permeance for magneto-motive force due to the armature current is often low and this kind of motor has a potential for improving the torque density with magnetic design for increasing the permeance.

With this in mind, we have developed a consequent-pole transverse-flux motor with almost half amount of magnets compared with conventional surface-mounted arrangement from the viewpoint of both increasing permeance and saving scarce rare-earth magnets (Ueda, et al., 2013). This motor has high permeance because of the field magnets not located in the flux path by the armature current, and can generate comparable torque with a conventional transverse-flux motor. However, this motor also has large cogging torque due to asymmetrically deformed bipolar magneto-motive force of the consequent poles. And, conventional skewed cores around the drive axis, effective for reducing cogging torque of conventional motors with armature coils put into slots, cannot be applied to transverse-flux motors due to their non-uniform structure along the axial direction. There is also a prior transverse-flux motor having skewed multiple segments around the axial direction in each phase (Dreher and Parspour, 2012). However, this segmented structure requires a proportionally increased large number of cores, magnets, and coils with increasing number of the segmentation. To reduce the cogging torque without introducing complicated structures, we proposed applicable skewed cores to the transverse-flux motors and validated the cogging-torque reduction with FEM magnetic analysis (Ueda, et al., 2016). This paper reports experimental validation of the skewed cores with a fundamental one-phase prototype of our proposed consequent-pole transverse-flux motor.

2. Consequent-pole transverse-flux motor

2.1 Fundamental structure

Our proposed transverse-flux motor consists of the permanent-magnet consequent-pole rotor and circumferentially unipolar stator. Fundamental structure of this motor is shown in Fig. 1, describing its magnetic materials and armature coils. The motor has three-phase structure, having the U-, V-, and W-phases. Each-phase structure of the rotor and stator is aligned along the axial direction. The pole arrangement in the U-phase is same as that in the V- and W-phases. However, there are 120° and 240° phase differences in electrical angle in the rotor-pole arrangement of the V- and W-phases, respectively from that of the U-phase.
Fig. 1 Fundamental structure of the transverse-flux motor. This motor has three-phase structure. Both the rotor and stator structures in each phase are aligned along the axial direction. There is 120° phase difference in the circumferential direction between the rotor structures of different phases.

2.2 Stator

The stator poles consist of U-shaped (armature) cores surrounding ring coils, coaxially arranged to the drive shaft of this motor. Number of the U-shaped cores in each phase is half as many as that of poles of this motor, and the cores are arranged with 2τ interval circumferentially, where τ represents pole pitch of this motor. In this structure, the coils are not wound around the teeth, and are independent on shape of the teeth in terms of geometry. Therefore, multipole structures can be easily constructed by increasing the number of the U-shaped cores.

This stator configuration allows magnetic circuits to be mainly formed in planes perpendicular direction to the circumference so that a lot of the circuits can be arranged on the circumference even though this motor structure is not axially uniform.

2.3 Rotor

The rotor poles consist of permanent magnets, I-shaped cores, and ring cores. The magnets and I-shaped cores face the U-shaped cores of the stator, and are fixed on the two ring cores in each phase. Number of the I-shaped cores in each phase is also half as many as that of poles of this motor. The I-shaped cores are arranged with 2τ interval circumferentially on the two ring cores. The magnets are arranged on the two ring cores and between adjacent I-shaped cores. Number of the magnets is equal to that of the I-shaped cores, and is half less than number of the magnets of conventional surface-mounted magnet rotors having the same number of poles. All the magnets of this motor are radially magnetized, but magnetization directions of the magnets on the one ring core are opposite to those on the other ring core in each phase. Magnetic flux resulting from the magnets mostly passes the U-shaped cores through both the ring and I-shaped cores, and consequently interlinks the ring coil. Therefore, this rotor configuration allows to generate 2τ periodicity distribution of the magnetic flux on the circumferential direction.

3. Cogging torque

The stator and rotor structures of this motor have 2τ periodicity in the circumferential direction. Therefore, cogging-torque waveform generated from the single-phase structure also has 2τ periodicity as shown in Fig. 2, describing FEM analysis result of the cogging-torque waveform for the rotor position. In this figure, the torque and
rotor position are normalized by the maximum torque and $2\tau$, respectively. The cogging-torque waveform has $2\tau$ periodicity fundamental (first order) component and can be expressed by its harmonics. Frequency spectrum of the cogging-torque waveform is shown as Fig. 3, in which amplitudes in each harmonic component are normalized by that in the third order component. As described in Section 2, this motor has the three-phase structure, and the stator and rotor structures in each phase are same as those in the other phases. In addition, relative position of the rotor poles to stator poles differs by $120^\circ$ among different two phases in electrical angle. Therefore, cogging-torque waveform in each phase differs by $120^\circ$ from that in the other two phases in terms of the rotor position. Note that this $120^\circ$ angular length is corresponding to two-thirds length of periodicity of the pole structure, $2\tau/3$. Thus, the fundamental components resulting from the three phases are mutually offset. With respect to all harmonics except those with the order of integral multiple of three, the harmonic waveforms resulting from the three phases also mutually differ by two-thirds length of periodicity of the waveforms in terms of the rotor position. Therefore, these harmonics resulting from the three phases are also mutually offset. However, with respect to all harmonics with the order of integral multiple of three, the harmonic waveforms are same among the three phases in terms of the rotor position. Thus, these harmonics resulting from the three phases are not mutually offset, and the third order component is largest in the order of integral multiple of three. Therefore, decreasing the magnitude of the third component is effective for suppressing the cogging torque. FEM analysis result of the cogging-torque waveform resulting from the three phases is shown in Fig. 4, indicating that periodicity of the waveform for the rotor position is $2\tau/3$, corresponding to that of the third component.

![Fig. 2 FEM analysis result of the cogging-torque waveform for the rotor position of the transverse-flux motor due to the single-phase structure. The torque and position are normalized by the maximum torque and twice the length of the pole pitch, respectively.](image1)

![Fig. 3 Frequency spectrum of the FEM analysis result of the cogging-torque waveform for the rotor position of the](image2)
transverse-flux motor due to the single-phase structure. The fundamental (first) order component has $2\tau$ periodicity for the rotor position. Torque amplitudes in each harmonic component are normalized by that in the third order component.

**Fig. 4** FEM analysis result of the cogging-torque waveform for the rotor position of the transverse-flux motor due to the three-phase structure. The torque and position are normalized by the maximum torque and two thirds of the pole pitch, respectively.

**4. Introduction of radially skewed cores**

For the purpose of reducing cogging torque, skew of the magnetic cores around the axial direction in axially uniform motors is well known to effectively eliminate specific order components of the cogging torque. These motors typically have circular cores laminated for the axial direction, and therefore, skewed cores can be easily introduced by shifting several magnetic steel sheets for the rotational direction in either the stator or rotor.

On the other hand, most transverse-flux motors including our proposed motor comprise of discretely distributed iron cores for the rotational direction in the stator and rotor. The iron cores should be designed so as for magnetic flux to flow both axially and radially with high permeability and little inducing eddy current in them. Therefore, laminated steel cores along almost the circumferential direction are one of the suitable choices as above-described iron cores. The lamination direction is not corresponding to the axial direction differently from the axially uniform motors, and shift of the steel sheets are not valid for reducing the cogging torque.

We have introduced skewed (tilted) stator cores about the radial direction, shown in **Fig. 5**, for the cogging-torque reduction (Ueda, et al., 2016). The stator (U-shaped) cores are easier to be skewed than the rotor cores, in which the permanent magnets and I-shaped cores are tightly arranged along the rotational direction. Owing to this skew geometry, center positions of the two tooth surfaces in each U-shaped core can be shifted so that attraction forces exerted on the one tooth due to the rotating magnets are offset by those on the other tooth. As described in Chapter 3, the third component is most dominant in the cogging torque resulting from the three-phase structure. The shift amount caused by the skew between the two teeth for the rotational direction in each U-shaped core should be corresponding to half the periodicity of the third-order component of the cogging torque for effectively decreasing the cogging torque by offsetting the third components exerted on the two teeth. Thus, in this study, the skew angle is set so as for the third component to be theoretically offset. FEM analysis result of the single-phase cogging-torque waveform, shown in **Fig. 6**, indicates that peak-to-peak value of the cogging torque decreases by 16% by skewing the stator cores. However, magnitude of the third component decreases by 96% as compared between Figs. 3 and 7, indicating frequency spectrum of the single-phase cogging-torque waveform of this motor without and with the skewed cores, respectively. The peak-to-peak value of the three-phase cogging torque, shown in **Fig. 8**, decreases by 87% by skewing the cores even though analytically obtained average torque roughly decreases by 11% to 12% as shown in **Fig. 9**. These analysis results demonstrate that the cogging torque can be effectively reduced by skewing the stator cores.
Fig. 5 Configuration of the single-phase structure with the U-shaped cores skewed about the radial direction for reducing the cogging torque of the transverse-flux motor. This structure allows two teeth of each U-shaped core to have attraction-force distributions with the same amplitudes and different phases for the rotor position. The attraction forces exerted on the two teeth can be effectively offset by setting the appropriate skew angle.

Fig. 6 FEM analysis result of the cogging torque waveform for the rotor position of the transverse-flux motor with the skewed cores due to the single-phase structure. The red solid line and gray dashed line describe cogging-torque waveform of the motor with and without the skewed cores, respectively. The torque and position are normalized by the maximum torque in the motor without the skewed cores and twice the length of the pole pitch, respectively.

Fig. 7 Frequency spectrum of the FEM analysis result of the cogging torque waveform for the rotor position of the...
transverse-flux motor with the skewed cores due to the single-phase structure. The fundamental (first) order component has 2\(\tau\) periodicity for the rotor position. Torque amplitudes in each harmonic component are normalized by that in the third order component described in Fig. 3.

![Fig. 8 FEM analysis result of the cogging torque waveform for the rotor position of the transverse-flux motor with the skewed cores due to the three-phase structure. The red solid line and gray dashed line describe cogging-torque waveform of the motor with and without the skewed cores, respectively. The torque and position are normalized by the maximum torque in the motor without the skewed cores and two thirds of the pole pitch, respectively.](image)

![Fig. 9 FEM analysis result of reduction rate of the average torque resulting from the three-phase structure of the transverse-flux motor by skewing the stator cores. The reduction ratio represents ratio of reduction amount of the average torque to the average torque of the motor without the skewed cores. The current is normalized by the rated current.](image)

5. Experiment for verifying the design on cogging-torque reduction

To verify the design for reducing the cogging torque, an elementary testing machine shown in Fig. 10 was built up, and the cogging torque was measured. This testing machine has single-phase stator and rotor structures. In the stator, the U-shaped cores can be fixed with specific skew angles. In this experiment, the skew angle was set to be zero and theoretically optimal angle for reducing the third-order component of the cogging torque as described in Chapter 4. This testing machine was mounted on a test bench, and its rotor was connected to and rotated by the high-torque motor at low speed through the beam couplings and torque meter measuring the cogging torque.
Experimentally obtained cogging-torque waveforms resulting from the single-phase structure are nearly equal to analytically obtained waveforms described in Figs. 2 and 6 regardless of having the skewed structure as shown in Fig. 11. Frequency spectrum calculated from the cogging-torque waveform indicates the third-order component can be effectively reduced (86% reduction) as shown in Fig. 12 even through the third-order components for the machine without and with the skewed cores obtained from the experiment are a little larger than those from the FEM analysis. The major error between the experimental and analysis results can be considered to result from uneven gap length along the circumference between the stator and rotor cores. If same single-phase cogging-torque waveforms as the experimentally obtained result are assumed to obtain from all the three phases, the three-phase cogging torque can be calculated as described in Fig. 13. This calculation result indicates that peak-to-peak value of the three-phase cogging torque would be able to decrease by 82% by radially skewing the stator cores in a prototype of the transverse-flux motor. Reduction ratio of the three-phase average torque due to the skew is also estimated, as described in Fig. 14, with this single-phase testing machine. In this estimation, single-phase torque waveforms generated from each phase of the three-phase motor have 120° phase difference among all the three phases and are equal to the experimentally obtained single-phase torque waveform with the testing machine. The experimentally estimated reduction ratio is mostly in the range within 2% error for the analysis results and can be considered to agree with the analysis results.

Fig. 10 Experimental apparatus for measuring the cogging torque resulting from the single-phase structure of the transverse-flux motor. The testing machine for measuring the single-phase cogging torque consists of single-phase stator and rotor structures. The stator has U-shaped cores fixed with specific skew angles. This machine was rotated by the motor at low speed through the torque meter.
Fig. 11 Experimental result of the cogging-torque waveform for the rotor position of the transverse-flux motor without and with the skewed cores due to the single-phase structure. The solid lines and gray dashed lines describe experimental result and analysis result of the cogging-torque waveform, respectively. The torque and position are normalized by the analytically obtained maximum torque in the motor without the skewed cores and twice the length of the pole pitch, respectively.

Fig. 12 Frequency spectrum of the experimental result of the cogging-torque waveform for the rotor position of the transverse-flux motor without and with the skewed cores due to the single-phase structure. The fundamental (first) order component has 2τ periodicity for the rotor position. Torque amplitudes in each harmonic component are normalized by that in the analytically obtained third-order component described in Fig. 3.
Fig. 13 Approximate three-phase cogging-torque waveform estimated from the experimentally obtained single-phase
cogging torque under assumption of the single-phase cogging-torque waveforms being completely same with 120°
phase difference among all the three phases. The red solid line and gray dashed line describe the approximate
cogging-torque waveform of the motor with and without the skewed cores, respectively. The torque and position are
normalized by the analytically obtained maximum torque in the motor without the skewed cores and two thirds of the
pole pitch, respectively.

Fig. 14 Approximate reduction ratio of the three-phase average torque by skewing the stator cores. These data are
estimated from the experimentally obtained single-phase torque under assumption of the single-phase torque
waveforms being completely same with 120° phase difference among all the three phases. The red square markers and
gray circular markers describe the reduction ratio obtained experimentally and analytically, respectively. The current is
normalized by the rated current.

6. Conclusions

We have designed a transverse-flux motor with a consequent-pole rotor having almost half amount of permanent
magnets but causing larger cogging torque compared with that with a surface-mounted permanent-magnet rotor. This
paper focuses on reduction of the cogging torque, and presents investigation of its most dominant component by FFT
spectral analysis and radially skewed armature cores at the optimal angle for effectively reducing the cogging torque,
capable of being applied to transverse-flux motors having axially non-uniform structure. In our designed
transverse-flux motor, the third-order component is dominant in the three-phase cogging torque. FEM analysis result
and its FFT spectral analysis result indicate the skewed cores allow the third-order component to decrease by 96% and
magnitude of the three-phase cogging torque to decrease by 87% with at most 12% decrease of the average torque. In
addition, experimental result of the single-phase cogging torque is almost agreed with the analysis result. Therefore,
these results demonstrate that skew of the armature cores are effective for reducing the cogging torque, and this skew
structure can be applied to various transverse-flux motors having axially non-uniform structure.

References


