Design, Optimization, and Realization of Salient-Pole Electromagnetic Gear for Variable-Transmission Applications

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An electromagnetic gear has been developed for variable-transmission applications such as wind power generators and electric hoists. It overcomes the problems of friction, noise, and the need for oil lubrication, which its mechanical counterparts suffer from. This paper explains how the gear operates according to the principle of magnetic gearing and how the concept of pole changing is utilized to change the gear ratio. The transmitted torques are derived and expressed in terms of the physical dimensions, and the optimization factors are identified. Simulation and experimental results confirmed the validity of the developed approach.

Keywords: magnetic gear, variable transmission, pole changing, salient pole, finite element method

1. Introduction

Mechanical gears have many drawbacks such as mechanical wear, the need for lubrication, and frequent maintenance. Magnetic gears are contactless, lubrication-free, and immune to overloading.

A breakthrough research was published by Atallah et al in which a high performance magnetic gear was proposed\(^1\). Since then, numerous papers have been published on the same topic\(^2\)–\(^5\).

In Ref. (6), a new technique for variable transmission using magnetic gears was presented. The technique had limited applications due to the requirement of two contra-rotating shafts and a control drive. Moreover, the prototype was not optimized.

We have been conducting research on magnetic gearing and have developed various prototypes\(^7\)–\(^11\). Recently, we proposed several novel techniques for the realization of magnetic gears for variable-transmission applications\(^12\).

In this study, an electromagnetic gear was designed and optimized for discrete variable-transmission applications but it is also suitable for continuous variable-transmission applications. Some of the possible applications include wind turbogenerators, pumps and electric hoists. In these applications, speed or torque need to be varied either continuously or discretely.

Some researchers\(^13\)–\(^16\) have derived general expressions of torques which are not useful to a designer, and optimization has not been studied. In this paper, the transmitted torques are analytically derived and expressed in terms of the physical dimensions, and the optimization factors are identified and studied thoroughly.

The design and optimization guidelines covered in this paper may be generalized and applied to Atallah’s magnetic gear. The design and optimization were carried out using finite element analysis. Our approach is novel because no previous study in the literature has used it. The approach was verified experimentally.

2. Principle of Operation

Fig. 1(a) shows the optimized electromagnetic gear and Fig. 1(b) shows the prototype. The design parameters are listed in Table 1. The gear consists of three basic parts: a stator, an outer rotor and an inner rotor. The stator and the inner rotor contain concentrated windings which are excited using direct current. The outer rotor is a set of pole pieces made of a ferromagnetic material. The excited windings create magneto-motive forces that, along with the permeance function of the pole pieces, create harmonic poles in the air gaps between the stator and the outer rotor and between the inner rotor and the outer rotor.

If both windings are excited and if, say, the inner rotor is rotated at a speed \(\omega_i\), the outer rotor will rotate at a different speed \(\omega_o\) in the same or in a different direction depending on the selected topology that dictates how the number of the pole pieces is calculated.

The number of the pole pieces, \(P_o\), was selected as the sum of electromagnetic pole pairs

\[
P_o = P_i + P_s, \quad \omega_o = \frac{T_o}{T_i}
\]

where \(P_i\) and \(P_s\) are the number of pole pairs of the stator and the inner rotor, respectively.

The fundamental gear ratio can be calculated as

\[
Gr = \frac{P_o}{P_i} = \frac{\omega_o}{\omega_i} = \frac{T_o}{T_i}
\]

where \(T_o\) and \(T_i\) are the torques of the outer and the inner

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![Diagram of electromagnetic gear](image)

**Fig. 1.** Electromagnetic gear (a) schematic diagram (b) prototype (c) speed vectors

**Table 1.** Design parameters of electromagnetic gear

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of stator</td>
<td>170 mm</td>
</tr>
<tr>
<td>Diameter of inner rotor</td>
<td>88 mm</td>
</tr>
<tr>
<td>Air-gap length</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Stack length</td>
<td>100 mm</td>
</tr>
<tr>
<td>Number of poles of stator</td>
<td>30</td>
</tr>
<tr>
<td>Number of poles of outer rotor</td>
<td>20</td>
</tr>
<tr>
<td>Number of poles of inner rotor</td>
<td>30</td>
</tr>
<tr>
<td>Pole arc-to-pitch ratio of stator</td>
<td>0.7</td>
</tr>
<tr>
<td>Pole arc-to-pitch ratio of outer rotor</td>
<td>0.5</td>
</tr>
<tr>
<td>Pole arc-to-pitch ratio of inner rotor</td>
<td>0.7</td>
</tr>
<tr>
<td>Number of turns per slot of stator</td>
<td>600</td>
</tr>
<tr>
<td>Rated winding current per slot of inner rotor winding</td>
<td>0.5 A</td>
</tr>
</tbody>
</table>

The speed vectors are shown in Fig. 1(c) where the inner and the outer rotors rotate in the same direction and the stator rotates in an opposite direction.

The gear ratio can be changed by exciting the correct number of poles of both windings such that Eq. (1) is satisfied.

3. **Design and Optimization Guidelines**

Because this research area is relatively new, the following discussion aims at establishing approximate guidelines for the design and optimization of magnetic gears. There are no proper or integrated guidelines for designing magnetic gears in the literature.

The initial design stage of Atallah's magnetic gear is briefly illustrated by the flow chart of Fig. 2(a). The design parameters are the dimensions of the parts of the magnetic gear, and optimization is the process of finding the optimum dimensions that would produce the maximum torque density.

The same design process applies to the electromagnetic gear except that the magnets are replaced by electromagnetic poles. The main stages of the process of the initial design are the selection of the appropriate topology, type of winding, and pole design. Then the initial design is optimized by varying the design parameters until optimum values are reached. This stage is referred to as original design.

The final stage of the design process is the modification of the original design for prototyping, and this stage is referred to as prototype design. Fig. 3 shows the schematic diagram of the prototype design where the stator core is slightly modified to have small notches, and the pole pieces are connected by a thin bridge. The prototype design produces lower torques than the original design. The whole process is summarized by the flow chart of Fig. 2(b).

3.1 **Topology Selection**

The first step of the design process is the selection of the magnetic gear topology. The selected topology should allow for a wide range of gear ratio, and pole changing should be as symmetrical as possible. Table 2 shows some of the possible topologies.

This paper focuses on the topologies 15-5-20 and 5-15-20...
inner rotor, the pole pieces, and the stator are, respectively, pole occupies a portion of its full pitch. The pitches of the end winding, and lower copper losses. Moreover, more coil turns can be applied.

3.4 Pole Design The poles of the stator and the inner rotor are of salient-type (Fig. 4). There is an optimum arc length of each pole at which the torques are maximum. Each pole occupies a portion of its full pitch. The pitches of the inner rotor, the pole pieces, and the stator are, respectively,

\[ \theta_i = \frac{\pi}{P_i} \]
\[ \theta_o = \frac{2\pi}{P_o} \]
\[ \theta_s = \frac{\pi}{P_s} \]

The circumferential widths of each loop and pole piece are

\[ l_i = \alpha_i \theta_i r_1 = \alpha_i \frac{\pi}{P_i} r_1 \]
\[ l_o = \alpha_o \theta_o r_2 = \alpha_o \frac{2\pi}{P_o} r_2 \]
\[ l_s = \alpha_s \theta_s r_3 = \alpha_s \frac{\pi}{P_s} r_3 \]

where \( \alpha_i, \alpha_o \) and \( \alpha_s \) are the arc-to-pitch ratios of the inner rotor loops, the pole pieces and the stator loops, respectively. \( r_1, r_2 \) and \( r_3 \) are the radii of the inner rotor, the outer rotor and the stator, respectively.

For an axial length \( l_o \), the areas occupied by each loop and pole piece are

\[ A_i = l_i l_o \theta_i = \alpha_i \frac{\pi r_1}{P_i} l_o \]
\[ A_o = l_o l_o l_o \theta_o = \alpha_o \frac{2\pi r_2}{P_o} l_o \]
\[ A_s = l_s l_s l_s \theta_s = \alpha_s \frac{\pi r_3}{P_s} l_o \]

3.5 Thickness of Bridge Connecting Pole Pieces The pole pieces need to be connected together by a bridge to provide a mechanical support. The bridge should be thin yet strong enough without reducing the torques significantly.

3.6 Optimization The objective of optimization is to increase the torque density. The optimization factors influence the transmitted torques and they are listed below:

- The arc-to-pitch ratio of the electromagnetic poles
- The arc-to-pitch ratio of the pole pieces
- The radial thickness of the pole pieces

These factors can be identified by the analysis of the magnetic field and the transmitted torques of a basic magnetic gear.

4. Basic Analysis

To simplify the analysis, the following assumptions are made:

1. The most useful magnetic flux crosses the air gaps radially
2. There is no flux leakage or fringing
3. The permeability of iron is infinite
4. Saturation, eddy currents and hysteresis are ignored
5. The effects of pole saliency are ignored

Fig. 5(a) illustrates that the stator and the inner rotor of a magnetic gear can be basically thought of as current-carrying loops (17)-(20). There are 30 loops in the stator, 20 pole pieces and 10 loops on the inner rotor. Each loop has \( N \) turns and carries a current \( I \). The magnetic field \( \phi \) produced by the loops and modulated by the pole pieces creates a magnetic field density near each loop face.

4.1 Mutual Flux The flux that links both windings and that crosses the air gaps is the most important flux that produces electromagnetic torques.

The heart-shaped flux path in Fig. 5(a) is between two pole pairs of stator loops and one pole pair on the inner rotor. The equivalent magnetic circuit of this path is shown in Fig. 5(b). The magnetic circuit contains the reluctance of the air gap, \( R_g \), the permeability of iron, \( N \), and the pole pieces, \( R_s \).

\[ R_g = R_o = R_i = 0 \] with the assumption that \( \mu = \infty \) of a ferromagnetic material. Hence, the circuit can be reduced to include only \( R_g \). \( F_{m1} \) is the mmf due to only the inner rotor loops, \( F_{m2} \) is the mmf due to only the stator loops and \( F_m \) is the resultant mmf.

\[ \phi(\theta) \approx F_m(\theta)/R_g = F_m(\theta) \times \Lambda_g(\theta) \]

The flux is proportional to the magneto-motive forces of the loops and the permeance of the magnetic path between
For the convenience of analysis, the schematic is laid out flat in Fig. 5(c). The mmf and flux waveforms are obtained during two pitches of the inner rotor (2θi).

The mmf waveforms are obtained by applying Ampere’s law around the path abcd.

\[ \oint_{abcd} \mathbf{H} \, d\mathbf{l} = I_{\text{enclosed}} \] \hspace{1cm} (8)

This path is θ0 wide and is moved in steps of one slot length of a stator loop (0.5θ0) until two pitches of the inner rotor loops (2θi). Then, the total current enclosed by the path equals the resultant mmf.

Applying Fourier series to the waveforms in Fig. 5(d),

\[ F_m(\theta) = \sum_{m=1,3,5,\ldots}^{\infty} \frac{2NI_m}{m\pi} [\sin(mP\theta) + 2\sin(mP_i\theta)] \] \hspace{1cm} (9)

\[ \Lambda_{\phi}(\theta) = a_o + \sum_{n=1}^{\infty} a_n \cos(nP\theta) + b_n \sin(nP\theta) \] \hspace{1cm} (10)

\[ \phi(\theta) = |\phi| \sum_{n=1}^{\infty} \sin(mP\theta) + 2\sin(mP_i\theta) \times \left[ a_o + \sum_{n=1}^{\infty} a_n \cos(nP\theta) + b_n \sin(nP\theta) \right] \] \hspace{1cm} (11)

where

\[ a_o = \frac{2\pi I_o l_o}{gP_o} \frac{1 + \frac{a_o^2 l_o}{g}}{1 + \frac{a_o l_o}{g}} \]

\[ a_n = \frac{2\pi I_o l_o}{gP_o} \frac{1 + a_o(2 + \frac{a_o l_o}{g}) \sin(2n\pi a_o)}{n\pi} \] \hspace{1cm} (12)

\[ b_n = \frac{2\pi I_o l_o}{gP_o} \frac{1 + a_o(2 + \frac{a_o l_o}{g})(1 - \cos(2n\pi a_o))}{n\pi} \]

It is deduced from Eqs. (10)–(12) that the permeance and the flux are maximum at α=0.5. Thus, the pole pieces should be designed with this value. In terms of position, the permeance varies between a maximum at θ=θ0 and a minimum at θ=π/2P o.

Shown in Fig. 5(d) is the flux at two different positions of the pole pieces. The average flux per pole at θ=γ is different from that at θ=0. The waveforms depict that the average flux is maximum wherever the peak of the permeance is coincident with the peak of the mmf. The average flux per pole pair is zero.

The amplitude of the fundamental flux maybe expressed as

\[ |\phi| \approx \frac{I_o NI_o (1 - \cos(2\pi a_o))}{P_o g} \] \hspace{1cm} (13)

4.2 Analysis of Harmonics With the aid of Fourier transform, the harmonics of the mmf, permeance and flux have been investigated using Eqs. (9)–(11).

4.2.1 mmf Harmonics In the absence of the pole pieces, the resultant mmf creates kP i and kP o poles in the air gaps between the stator and the inner rotor as concluded from Eq. (9). When k=1, P i=5 and P o=15, there are two significant components of pole pairs: 5 pairs and 15 pairs (Fig. 6(a)).
4.2.2 Permeance Harmonics  The air gap permeance (Eq. (10)) creates \( nPo+1 \) harmonic components. For \( \alpha_o=1 \) and \( n=1 \), there is only one component which is due to \( a_o \) (Fig. 6(b)). In this case, the flux is not modulated. Fig. 6(c) shows the harmonics for different values of \( \alpha_o \). There are many harmonics but the significant ones are due to \( P_o=20 \) and the highest amplitude is when \( \alpha_o=0.5 \).

4.2.3 Flux Harmonics  The flux harmonics are due to the contribution of the mmf and the permeance harmonics. The harmonic spectrum for different values of \( \alpha_o \) are shown in Fig. 6(d). As predicted previously, the ratio of 0.5 gives the highest amplitude of the flux. In addition, the following pole pair harmonics appear with significant amplitudes in the air gap due to the flow of the modulated flux: \( P_i=5, P_s=15, P_i+P_o=25 \) and \( P_s+P_o=35 \).

4.3 Torques Exerted on Inner Rotor and Stator  For design and optimization purposes, only the amplitudes of the transmitted torques will be derived and there is no need to include harmonics.

For a flux density \( B_i \) in the air gap near a loop face on the inner rotor, each conductor experiences an electromagnetic force:

\[
F_i = IB_il_a\sin\beta 
\tag{14}
\]

where \( \beta \) is the angle between the current and the flux density vectors.

\[
B_i = \frac{\phi}{A_i} 
\tag{15}
\]

For \( 2P_i \) poles with \( N \) turns on the inner rotor and for \( \beta=\pi/2 \), the total torque can be derived from Eq. (5) and Eqs. (13)–(15):

\[
T_i = 2P_iF_ir_1 = \frac{2(P_i)^2r_1NI}{\pi\alpha_i} \phi 
\tag{16}
\]

Substituting Eq. (11) in Eq. (4) and Eq. (16) yields

\[
T_i(\theta) = k_i \left(1 - \cos(2\pi\alpha_o)\right) \frac{P_i^2r_1N^2I^2}{\alpha_i P_o\ g + l_ow} 
\tag{17}
\]

Although the stator loops are stationary, they would turn if allowed to move. The torque \( T_s \) exerted on the stator can be determined in the same fashion:

\[
T_s(\theta) = k_s \left(1 - \cos(2\pi\alpha_o)\right) \frac{P_s^2r_1N^2I^2}{\alpha_s P_o\ g + l_ow} 
\tag{18}
\]

where \( k_i \) and \( k_s \) are constants.

4.4 Torque Exerted on Outer Rotor  The pole pieces experience a reluctance torque \( T_o \) that, along with \( T_i \), tends to align the poles of the stator and the inner rotor. Fig. 7(a) is the case when the poles of the stator and the inner rotor are fully aligned with the pole pieces, and Fig. 7(b) is the case when the pole pieces are fully unaligned with the electromagnetic poles. The dotted path abcdefgh is the ideal flux.

From Eq. (10), \( \Lambda_g \) has a high value at the aligned position at \( \theta=\pi/2P_o \) and a low value at the unaligned position at \( \theta=2\pi/P_o \).

One method to derive the torque exerted on the outer rotor is via the rate of change of the magnetic field energy, \( W_F \), from a high-permeance position to a low-permeance position.
The energy density inside the pole pieces is too small compared to the energy density in the air gaps. Hence, the torque is calculated from the energy density in the air gap.

The air gap between the stator and the inner rotor varies with the variation of the position of the pole pieces. The air gap is minimum in the aligned position, and it is maximum in the unaligned position.

The field energy stored in the air gap is

$$W_F = \frac{1}{2} \mu_0 H^2 \int dV$$

(19)

$H$ can be found by applying Eq. (8) to the flux path.

In the aligned position at $\theta = \pi/2$, $P_o$,

$$H_1 = \frac{NI}{g}$$

$$W_{F1} = 2\alpha_o \frac{\mu_p r_2 l_o N^2 I^2}{q P_o}$$

(20)

In the unaligned position at $\theta = 2\pi/P_o$,

$$H_2 = \frac{NI}{(g + l_o)}$$

$$W_{F2} = 2(1 - \alpha_o) \frac{\mu_p r_2 l_o N^2 I^2}{(g + l_o) P_o}$$

(21)

The total torque exerted on the outer rotor can now be expressed as

$$T_o = k_o P_o \frac{\Delta W_F}{\Delta \theta}$$

$$= k_o P_o r_2 l_o N^2 I^2 \left[ \frac{\alpha_o}{g} \left( \frac{1 - \alpha_o}{g + l_o} \right) \right]$$

(22)

where $k_o$ is a constant that depends on the topology of the electromagnetic gear.

Eqs. (17)–(18) and Eq. (22) are approximate but enough for design and optimization purposes. They offer many useful design hints and they give us an insight into the factors that affect the transmitted torques.

The transmitted torques increase with the number of poles. Eq. (17) says that the torque of the inner rotor would increase four folds if the number of its poles were doubled.

The transmitted torques vary linearly with the axial length $l_o$, and they are inversely proportional with the air gap and the radial length of the pole pieces. Another factor is the mmf which highly influences the torques. If the mmf was doubled, the torques would be four folds. The arc-to-pitch ratios of the poles are important design parameters, and there are optimum values at which the torques are maximum. These optimum values elevate the transmitted torques by 10–40%.

5. Simulation Results

2D Finite element method was employed for the simulation of the electromagnetic gear during all the stages of the design process. The discretization data of the simulated original design are listed in Table 3.

5.1 Optimization Results

The optimization results are expressed in per unit (p.u) because they are not specific to our prototype and maybe applicable to magnetic gears of different topologies.

5.1.1 Variable mmf

By increasing the current or number of turns of any winding, all the transmitted torques increase to the square. In Fig. 8, for mmf = 0.2 p.u the torque is around 0.06 p.u; for mmf = 0.4 p.u, the torque is around 0.23 p.u which is close to four times its previous value. This agrees with Eqs. (17)–(18) and Eq. (22). The current can be increased when the load increases to avoid overloading the gear.

5.1.2 Variable Air Gap

For any topology and for the same radial length of the pole pieces, the torque of the outer rotor is inversely proportional to the variation of the air gap length. Fig. 9 shows the results which agree with Eq. (22).

5.1.3 Variable Pole-piece Length

Eq. (7) offers a hint for the design of the pole pieces which is that there is a ratio between its radial and circumferential length. The radial length increases the reluctance of the pole pieces. If $\alpha_o$

Table 3. Discretization data of simulation

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements</td>
<td>62546</td>
</tr>
<tr>
<td>Number of nodes</td>
<td>32145</td>
</tr>
<tr>
<td>Number of steps</td>
<td>300</td>
</tr>
<tr>
<td>Total simulation time</td>
<td>2h</td>
</tr>
</tbody>
</table>

Fig. 7. Generation of torque of outer rotor (a) fully aligned position (b) fully unaligned position

Fig. 8. Variation of torque with mmf
Electromagnetic Gear (Mustafa Husain et al.)

5.1.4 Thickness of Bridge Connecting Pole Pieces

The torque of the outer rotor is reduced when the pole pieces are connected by a bridge. Fig. 11 shows the results. If the thickness of the bridge is 10% of the radial thickness of the pole pieces, the torque is reduced by around 15%. If the ratio is 50%, the torque is reduced by 80%.

5.1.5 Variable Arc-to-pitch Ratio

To investigate the influence of the arc-to-pitch ratios of the poles on the transmitted torques, the arc-to-pitch ratios of the poles of the stator were varied from 0 to 1 for different ratios of the poles of the inner rotor. Likewise, the arc-to-pitch ratios of the poles of the inner rotor and the pole pieces were varied.

In Fig. 12(a), the outer rotor torque is maximum at $\alpha_i=0.5\text{–}0.7$ and $\alpha_s=0.7$. In Fig. 12(b), the outer rotor torque is maximum at $\alpha_s=0.5\text{–}0.7$ and $\alpha_i=0.5$.

In Fig. 13(a), the inner rotor torque is maximum at $\alpha_i=0.5\text{–}0.7$ and both $\alpha_s=0.5$ and $\alpha_i=0.7$. In Fig. 13(b), the inner rotor torque is maximum at ratios of $\alpha_s=0.5\text{–}0.7$ and $\alpha_i=0.5$.

A ratio of 0.7 was selected for the stator and the inner rotor because it produces high torques. A ratio of 0.5 was not considered for the inner rotor because of coil placement issues, and because it allows for less turns per slot.

When the arc-to-pitch ratio of the pole pieces is varied, the transmitted torques vary in a similar trend. Maximum torque occurs at a ratio $\alpha_o=0.5$ (Fig. 14). A ratio of 1 means all the pole pieces are connected together with no space in between; no useful torques are transmitted as predicted by Fig. 6(b). A ratio of 0.5 was selected for the optimized design.

5.2 Transmitted Torques

The topologies 5-15-20 and 15-5-20 were adopted. The simulated torques were calculated by transient analyses when one of the rotors was turned at 1 rpm while the other was stationary. Two analyses were carried out; one for the original design and another for the actual prototype. In the original design, the pole pieces are separated. In the prototype design, the pole pieces are connected by a 0.5 mm bridge. The effective values are listed in Table 4. The results are shown in Fig. 15 and Fig. 16. The actual torque of the outer rotor is around 90% of that of the original design whereas the actual torque of the inner rotor is around 60%. The reason is that some of the flux does not travel through the pole pieces.
reach the inner rotor but it flows through the bridge connecting the pole pieces. Fig. 17 shows part of the simulated flux of the prototype model. The torque is produced by the flux that crosses the air gap radially. The flux flowing through the bridge does not contribute to torque production and so it is regarded as lost flux. The bridge does not alter the shape of the waveforms.

Table 4. Simulated torques

<table>
<thead>
<tr>
<th>Topology</th>
<th>Outer rotor (Nm)</th>
<th>Inner rotor (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-15-20 topology</td>
<td>3.1</td>
<td>2.1</td>
</tr>
<tr>
<td>15-5-20 topology</td>
<td>1.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Fig. 13. Influence of pole arc-to-pitch ratio on torque of inner rotor (a) $\alpha_i$ varied (b) $\alpha_s$ varied

Fig. 14. Influence of pole arc-to-pitch ratio of pole pieces on transmitted torques

Fig. 15. Simulated torque of outer rotor (a) 5-15-20 topology (b) 15-5-20 topology

Fig. 16. Simulated torque of inner rotor (a) 5-15-20 topology (b) 15-5-20 topology
By switching from one topology to the other, the torques are changed. The gear ratio cannot be calculated from these values because they represent fundamental and other harmonic components while Eq. (2) is valid for effective values of only fundamental components.

6. Experimental Results

The same conditions applied during the simulations were applied in the experiments. The 15-5-20 and 5-15-20 topologies were used to verify experimentally the proposed concept of electromagnetic variable transmission. Each winding was supplied with a dc current of 0.5 A per slot.

The experimental setup is shown in Fig. 18. Because the electric current was supplied to the inner rotor via slip rings, the torque of the outer rotor could not be measured directly and belts and pulleys were used to transmit the torque to the torque transducer II for measurement.

6.1 Gear Ratio

The inner rotor was driven at different speeds, and the corresponding speeds of the outer rotor were measured with an optical tachometer. The measured gear ratios are shown in Fig. 19. The speed ratio is 4 in the 15-5-20 topology, and it is 1.3 in the 5-15-20 topology as predicted by Eq. (2).

6.2 Transmitted Torques

To measure the torques, one rotor was turned at 1 rpm by the servomotor and its torque was measured simultaneously while the other rotor was locked. The same condition was applied in the simulations.

The effective values of the measured maximum torques are listed in Table 5. The highest torques are produced in the 5-15-20 topology where the outer rotor produces 2.4 N.m and the inner rotor 1 N.m. Compared with the simulation results in Table 4 of the prototype design, the measured torques are between 86% to 77% of the simulated values.

The discrepancy can be mainly due to mechanical issues. The actual air gap is affected by the balance of the inner rotor and it is different from the simulated value. Mechanical friction due to the bearings and slip rings play a role in decreasing the measured torques. In addition, the winding resistance changes with temperature and so does current. Hence, the actual torques are slightly reduced.

The waveforms of the simulated and measured torques are presented simultaneously in Figs. 20–21. The waveforms are similar in shape, and it is observed that the shapes of the waveforms are changed when switching from one topology.
Temperature Rise and Heat Losses

The windings produce heat losses that cause a temperature rise of the prototype. Because the stator is stationary and because it has a higher number of coil turns per slot than the inner rotor, the heat loss in the stator is higher. The temperature of the stator has been measured with an infrared sensor and a digital multimeter (DMM). The setup is shown in Fig. 22. The graph in Fig. 23 is the temperature rise of the stator winding when both windings draw rated currents. The stator winding reaches around 75°C after 30 minutes which is below the rated winding temperature of 150°C.

The total heat losses depend on the selected topology. The heat loss of each winding is plotted in Fig. 24 as a function of the current density where the current density varies from 0 to the rated value of around 8 MA/m². A maximum of 5 W/slot is dissipated in the stator and 1.5 W/slot in the inner rotor.

7. Conclusion

An electromagnetic gear has been developed which is capable of realizing variable transmission. The simulation and experimental results confirmed the validity of the method of changing the gear ratio by pole changing. The same method can be utilized to develop other types of gears to be used for various applications.

The transmitted torques have been analytically derived and expressed in terms of design and optimization parameters. Novel guidelines have been set for the design of magnetic gears which aid in reducing the time and efforts during the design and optimization process. Some of these guidelines are also valid for magnetic gears made up of permanent magnets. It has been shown that the transmitted torques of an optimized gear are 10–40% higher than that of a non-optimized gear.

References

(7) Y. Yamamoto and K. Hirata: “Study on a Hybrid-Type Magnetic Gear”.

Fig. 21. Measured torque of inner rotor (a) 5-15-20 topology (b) 15-5-20 topology

Fig. 22. Setup of temperature measurement

Fig. 23. Temperature rise of stator winding at rated current

Fig. 24. Heat losses per slot
Electromagnetic Gear (Mustafa Husain et al.)

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