A NEW METHOD OF TORQUE RIPPLE MEASUREMENT FOR MAGNETIC GEARS

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ABSTRACT

Torque ripple analysis and calculation methods in an axial-type Magnetic Gear (MG) design with four rectangular NdFeB magnetic layers have been reviewed and discussed. Smooth and steadily transmitted torque is an essential characteristic of a magnetic gear. Reducing possible mechanical vibration, position inaccuracy, and acoustic noise is necessary. Therefore, this study aims to design a new engineering method appropriate for calculating the torque ripple of the MG transmission by testing its mechanical and electrical properties. Motor torque testing is carried out experimentally. Two simultaneous torque tests compare the MG brakes from zero to full load. In addition, the transmission torque of the axial MG is measured and calculated using technical methods. The results showed that differences in dynamic torque occurred in the MG at various air gap distances.

Keywords: *Dynamic Torque, Design, NdFeB magnet, Air Gap*

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1. INTRODUCTION

Magnetic gear (MG) transmits torque without frictional contact compared to mechanical gear. Its advantages include maintenance costs, high reliability, adequate efficiency, and precision [1, 2]. However, the problem associated with regularly transmitting sufficient torque, such as the reduced possibility of mechanical vibrations, inaccurate positioning, and acoustic noise, is essential for an MG. A common disadvantage of these devices is the torque ripple attached to the output shaft, which induces speed fluctuations [3-8]. When an MG rotates at a constant angular speed under load, it slows down. This condition can impair the MG mechanism's output performance and service life in high-precision position and motion control applications. Torque ripple is also associated with increased harmonic electromotive force, which needs to be reduced due to its ability to improve noise and vibration in the motor [9]. In recent years, torque suppression has become essential for engineers designing MGs. For instance 2009, Frank and Toliyat designed a concentric MG mechanism for high torque as one of the main requirements for using low-speed wind turbines [10] and marine propulsion systems [11]. Frank et al. analyzed the effect of gear ratios on torque ripples from concentric MG mechanisms with the initial configuration proposed by Atallah and Howe [12]. It showed that generally, the highest occur in MGs with a high number of pole pairs for high speed and those that utilized the stationary steel pole pieces, which produced fewer values.

In contrast, a literature survey of various papers concluded that MG was very efficient, with torque obtained by eliminating friction. However, researchers did not validate the above statement through experimentation. Generally, the torque ripples of MG are calculated using finite element analysis [13]. At the same time, in [14], we quantitatively compared two coaxial MG using 3-dimensional finite element analysis (FEA) on radial and Halbach magnets. The result showed that the coaxial MG with Halbach magnets provides higher/lower torque ripples and lower iron losses than radial MG. Furthermore, in 2010, Jian et al. also formulated the magnetic field distributions inside the inner and outer air gaps, while the magnetic and ripple torque of the coaxial MG were analytically determined [15].

Regarding the torsion ripple of the MG, we have not obtained a reference on the experimental torsion ripple test. Generally, researchers use numerical analysis and simulation, as previously mentioned. A new method to be introduced measures the torsional ripple of MG experimentally. This method compares the measurement of mechanical force and electrical force. The power from MG is obtained through mechanics testing on the output side and the electric current and voltage on the input side, which are measured simultaneously. The load given to the axial MG varies until it experiences breaking or slipping.

2. MATERIALS AND METHODS

2.1 Geometry of MG

Using the parallel-axial model, the 10mm x 20mm x 1mm rectangular NdFeB was used to produce MG and two disk models with a 1:2 diameter ratio [16]. Figure 1 shows the MG configuration using an acrylic disk consisting of a 4-layer arrangement, with the geometric parameters of the prototype shown in Table 1.

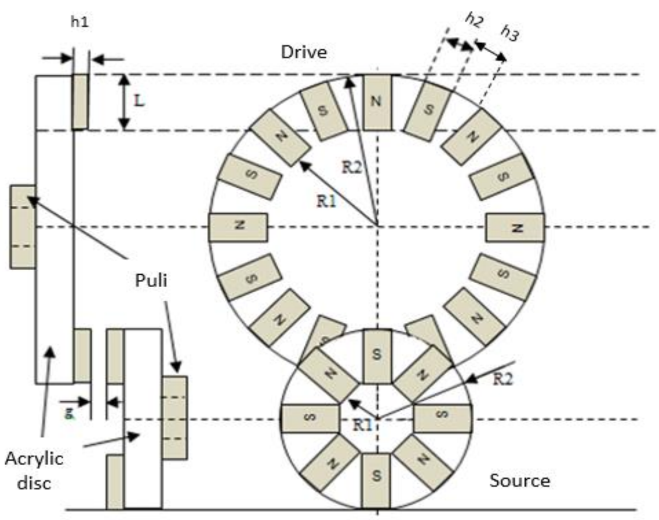


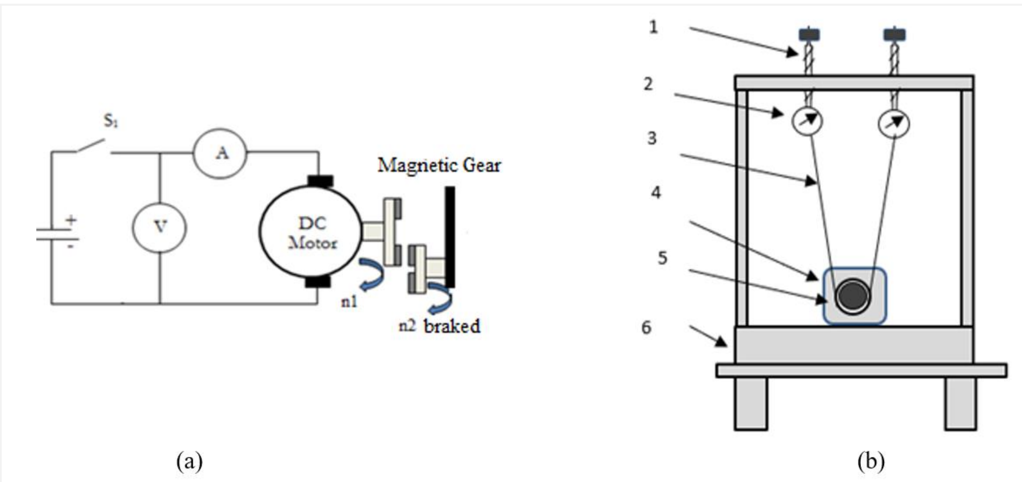
Figure 1. Geometric parameters of the axial MG using the NdFeB magnetic layer

Table 1. Parameters and specifications of axial MG

No	Quantity	Value	Unit	Symbol
1	Inner radius, source magnets	10	mm	R_{1s}
2	Outer radius, source magnets	30	mm	R_{2s}
3	Inner radius, drive magnets	40	mm	R_{1d}
4	Outer radius of the acrylic discs, drive magnets	60	mm	R_{2d}
5	Length of air gap	0.5	mm	g
6	Magnet length	20	mm	L
8	Magnet thickness	1	mm	h_1
7	Magnet height	10	mm	h_2
8	Magnet gap distance	10	mm	h_3
9	Number of pole pairs (source magnets)	8	-	N_d
10	Number of pole pairs (drive magnets)	4	-	N_s
11	Remanence of the permanent magnets	0.57	mT	Br
12	Direction of magnetization	Axial	-	-

2.2 Experiment Set-up

Figures 2 (a) and (b) show the electrical and mechanical torque measurement methods. Experiments were carried out using DC motor drives with power supplies. Furthermore, pulleys are installed on the secondary side to connect the transmission belt to the spring balance and various load-regulating threads. In contrast, an ampere and voltmeter were installed on the primary side to obtain data flow and voltage input. In addition, rotational measurements are taken using a tachometer from zero to full load, where the second condition of the MG cannot rotate.First, this test is carried out on variations in the distance of 1 mm, 2 mm, and 3 mm between 2 discs. It aims to obtain axial MG torque change based on the influence of the flux on distance changes. Secondly, the load regulating screw is set to obtain data on the current, voltage, and force based on its variation from zero till it is fully loaded. Then, the second disk (n2) stops spinning or slips. Finally, data analysis is calculated to obtain the characteristics of the axial MG in the form of static and dynamic torque, input and output power, and torque ripple.



where:
1. load Regulator
2. spring balance
3. transmission belts
4. motor drive
5. pulley
6. frame

Figure 2. Torque testing series
(a) electrical system; (b) mechanical systems

3. RESULT AND DISCUSSION

3.1 Torque Testing

Several related mechanical variables determine the functional performance of a rotating machine, such as power, speed, and torque. Torque is a measure of the tendency of a force to rotate an object about a particular axis. The force must act a certain distance from the axis or pivot point to produce torque. The test can be done in two ways: mechanical and electrical systems. Both provide torsion test results; even different equations and data retrieval can be experimentally measured simultaneously. The paper [17] describes the formula for analyzing torque mechanically, as shown in Figure 3.

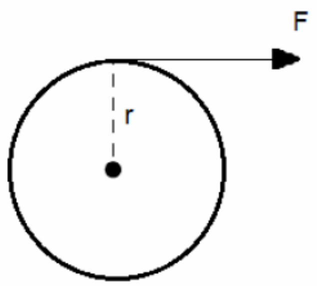


Figure 3. Mechanical torque

The circle represents a wheel of radius (r); the dot in the middle represents the axle or shaft, and the force (F) is applied tangentially at the periphery. The amount of torque to the gear shaft is:

Torque = force x radius, or

formulated as:

$$T = F \, x \, r \qquad \text{(N-m)} \qquad (1)$$

where:

- F is the vector of force.
- r is the vector from the axis of rotation to the point on which the force is acting.

It shows that torque measures the power or force that causes an object to rotate. Therefore, torque on a particle is equal to the first derivative of its angular momentum concerning time.

In more detail, [17] describes the power formula obtained from mechanical testing. Power is defined as energy per unit of time or the rate at which work is done and thus:

$$\boldsymbol{P}=\Delta \boldsymbol{E}/\Delta \boldsymbol{t}=\boldsymbol{W}/\Delta \boldsymbol{t} \qquad (2)$$

When a force (F) moves an object a measured distance (Δd), the work done (W) is given by:

W (work) = Force x Distance; or,

$$\boldsymbol{W}=\boldsymbol{F} \,.\, \Delta \boldsymbol{d} \qquad (3)$$

This equation is valid for linear motion, but the appropriate definition of work for the transmission of rotational power is given by Torque (T) and angular displacement (Δθ). Therefore, the work done for the rotary motion is:

$$\boldsymbol{W} = \boldsymbol{T} \,.\, \Delta\boldsymbol{\theta} \qquad (4)$$

Rotation is the change in the angular position of the reference point on the body over some time interval, Dt. The power transfer in a rotary device is therefore given by:

$$\boldsymbol{P} = \boldsymbol{W}/\Delta \boldsymbol{t} = \boldsymbol{T}\Delta\boldsymbol{\theta}/\Delta\boldsymbol{t} \qquad (5)$$

Rotational motion is characterized by its angular velocity (ω) and is defined as:

$$\boldsymbol{\omega} = \Delta\boldsymbol{\theta}/\Delta\boldsymbol{t} \qquad (6)$$

Substituting the rotary definition from Eq. (5) to equation (6), we get:

$$\boldsymbol{P} = \boldsymbol{T\omega} \qquad (7)$$

Then, substituting Eq. (7) into Eq. (1), we get:

$$\boldsymbol{P} = \boldsymbol{F} \,.\boldsymbol{r}.\boldsymbol{\omega} \qquad (8)$$

ω is the angular speed or rotational speed measured in the number of complete revolutions per minute (rpm) or per second (RPS). Usually expressed as:

$$\boldsymbol{\omega} = \boldsymbol{2\pi N/60} \qquad (9)$$

N = rotations/minute (RPM)

Substituting equation (9) into equation (8) we get:

$$\boldsymbol{P} = \boldsymbol{F}.\boldsymbol{r} \;\; \boldsymbol{2\pi N/60} \qquad (10)$$

Testing of mechanical power used for electric motors and transmission gears (mechanical and magnetic gears), as shown in Fig. 2 (b).

Another way to get the power (P) is to measure the power of the gear transmission drive motor. As shown in Fig. 2 (a), the motor power can be obtained between the current (I) and voltage (V) measurements. The formula determines the electric power consumed by the motor:

$$\boldsymbol{P\_in}=\boldsymbol{I} \,.\, \boldsymbol{V} \qquad (11)$$

where:

P_{in} = input power, measured in watts (W);
I = current, measured in amperes (A);
V = applied voltage, measured in volts (V).

Output mechanical power of the motor could be calculated by using the following formula:

$$\boldsymbol{P\_out}=\boldsymbol{T} \,.\, \boldsymbol{\omega} \qquad (12)$$

where:

P_{out} = output power, measured in watts (W);
T = torque, measured in Newton meters (N - m);
ω = angular speed, measured in radians per second (rad/s)

It is very easy to calculate the angular speed by changing the rotational speed of the motor in rpm:

$$\omega = rpm \,.\, 2\pi/60 \qquad (13)$$

where:
rpm = rotational speed in revolutions per minute;
π = mathematical constant phi (3.14);
60 = number of seconds in a minute

Efficiency of the motor is calculated as mechanical output power divided by electrical input power:

$$E = P\_out/P\_in \quad (14)$$

Therefore,

$$P\_out = P\_in \ .E \quad (15)$$

after substitution, we get

$$T\,.\,\omega = I\,.\,V\,.\,E \quad (16)$$

$$T\,.\,rpm\,.\frac{2\pi}{60} = I\,.\,V\,.\,E \quad (17)$$

and the equation for calculating torque will be,

$$T = \frac{(I.V.E.60)}{rpm\ .2\pi} \quad (18)$$

This study's torque symbol (T) is analogous to two types. Static conditions are called static mechanical torque (Tsm), static electric torque (Tse), and dynamic conditions as electrical torque (Te), mechanical torque (Tm).

Table 2. Data on the results of rotation, current, voltage and force for MG

No	Speed (Rpm)		Angular Speed (rad/sec)		Electrics				Mechanics					Note
	n1	n2	ω1	ω2	V (volt)	I (mA)	P (mW)	Tse (Eq.21)	F1 (N)	F2 (N)	F1-F2 (N)	r (cm)	Tsm Eq.19)	
1.	402.4	805.9	42.12	84.35	6.42	0	0	0	0	0	0	0	0	No. load
2.	0	0	0	0	6.33	35.8	226.61	2.68	2.5	1.5	1	2.68	2.68	Full load

The experimental setup regarding static and dynamic torque testing is shown in Figure. 4. Static torque does not produce angular acceleration or MG under braking/full load, while dynamic torque MG rotation at light load conditions to maximum load. Table 2 compares mechanical and electrical static torque based on MG test data at no-load and full-load/braking rotation. Static torque values are obtained:

$$Ts_m = F\ x\ r \quad \text{(N-m)} \quad (19)$$

where,

T_{sm} = mechanical static torque,
F = Force (Newton)
F = $F_1 - F_2$
r = Radius (m)

$$Ts_m = 1\ x\ 2.68 = 2.68\ N.cm \quad (20)$$

Then,

$$Ts_e = \frac{P}{\omega_2} \quad (21)$$

Tse = electric static torque

$$Ts_e = \frac{226.61}{84.35} = 2.68\ \ N.cm \quad (22)$$

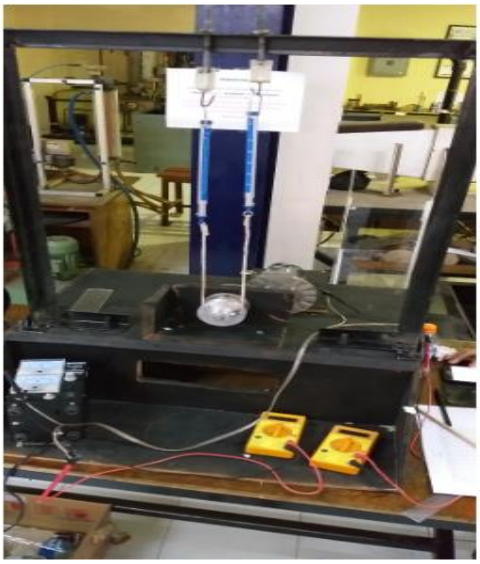


Figure 4. Static and dynamic torque testing

Similarly, the input torque (T_{in}) and dynamic torque (T_e, T_m) values can also be obtained based on the test at any change in the load applied to the MG, as shown in Figure 5.

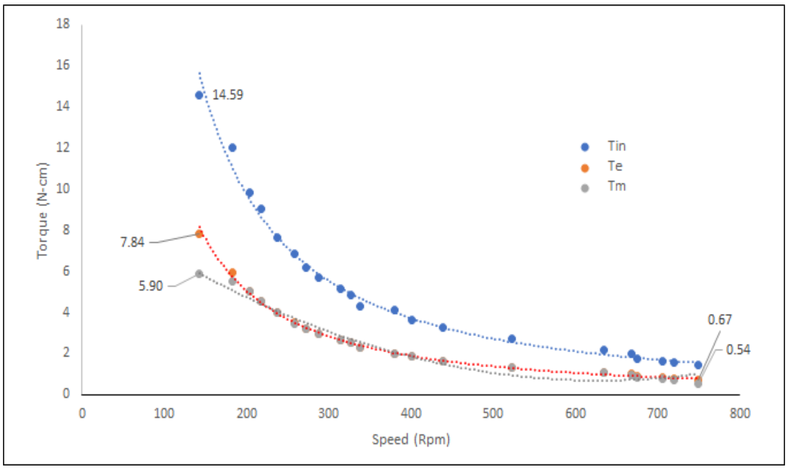
3.2 Effect of Air Gap Distance

Table 3 compares the torque values of three magnetic layer compositions with varying air gap distances. It is seen that the addition of a magnetic layer will increase the static torque and dynamic torque. Each addition of some magnetic layers made of rectangular magnets with a thickness of 1 mm can increase the torque of the magnetic gear. On the other hand, dynamic torque will decrease in proportion to the setting of the air gap spacing.

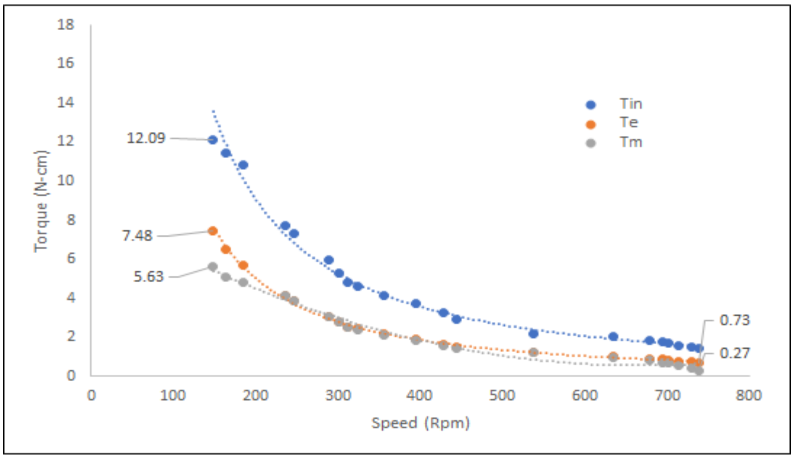
The effect of torque ripples can also be seen in the change in the gap between the two disks. For example, the air gap is 3 mm; the more significant the air gap between the two disks, the higher the torque ripple on the MG. Like 1 mm and 2 mm, torque ripples in the 3 mm gap occur at the light and full loads. However, the difference between the two torques shown here is quite significant. Electric torque is twice as large as mechanical for both loading cases (Fig. 5c). The change in the MG torque value also changes with the addition of the air gap distance. Maximum electric torque with 7.84 N-cm at a distance of 1 mm decreases to 7.6 N-cm at 3 mm. Therefore, the greater the gap air, the lower the torque produced due to the influence of flux. Conversely, adding a magnetic layer on each gear can increase the torque. Figure 6 shows that the change in the air gap between the discs affects the MG torque with a 3-layer magnetic composition.

Table 3. Results of torque measurements for varying air gap distances

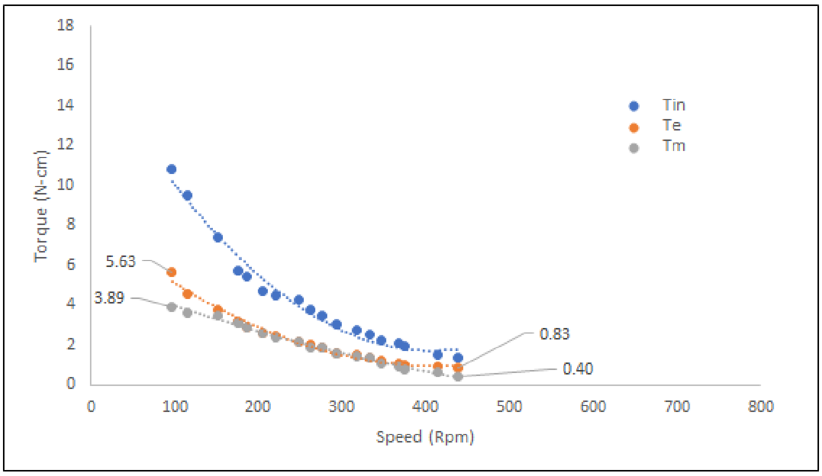
Air gap (mm)	Input Torque, Tin (N-cm)			Electric Torque, Te (N-cm)			Mechanical Torque,Tm (N-cm)			Static torque, Ts (N-cm)	
	layer-1	layers-2	layers-3	layer-1	layers-2	layers-3	Layer-1	layers-2	Layers-3	(Tse)	(Tsm)
1	2.58	10.97	15.49	1.40	5.59	8.01	1.39	3.08	6.03	2.7	2,7
2	1.7	9.21	14.59	0.89	4.59	7.84	0.80	2.14	5.63	2.15	2,15
3	1.69	7.27	14.51	0.86	3.57	7.61	0.67	1.88	3.89	1.88	1,88



(a)



(b)



(c)

Figure 5. Test of MG torque for the magnetic composition of 3 layers with a varying air gap (mm): (a) 1; (b) 2; (c) 3

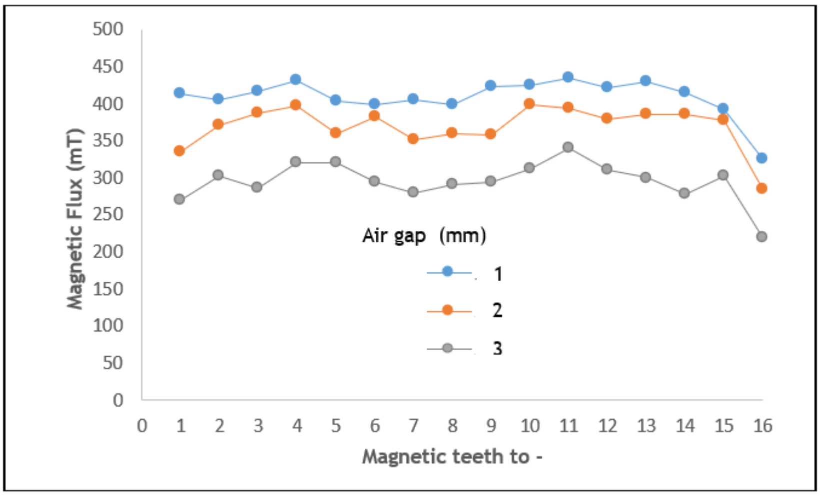


Figure 6. Results of magnetic flux measurements in the air-gap area

3.3 Analysis of Torque Ripple

Torque ripple is the instantaneous power consumed by MG or the product of the instantaneous torque by the angular velocity. It is not constant because the torque generated is also not constant. Therefore, torque ripple is one of the quantities used to describe MG performance. Torque ripple is the value of torque that constantly changes per unit of time. The value of the torque ripple is defined as the difference between the peak torque (T_{max}), the minimum torque (T_{min}), and the average torque (T_{avg}) and is defined as:

$$T_{rf} = \frac{T_{max} - T_{min}}{T_{avg}} \quad (23)$$

where:

T_{max} = Maximum torque
T_{min} = Minimum torque
T_{rf} value of 1 indicates stable/steady

In this study, a new approach was taken regarding the value of the ripple torque by comparing the values of the electric torque (Te) and the mechanical torque (T_m), measured simultaneously. Both are obtained from zero loads to full load, where the electrical torque (T_e) is measured electrically, and the mechanical torque (T_m) is measured mechanically. Electrical measurements were carried out by observing changes in current (I), voltage (V), and rotation (N) (Eq. 21). In contrast, mechanical measurements were carried out by observing changes in force and distance (Eq. 19).

As shown in Fig. 5, the two torques show the difference in the value of each load change from maximum rotation to rest. At a distance of 1 mm, the difference in measurement occurs in light loading and total loading. At light loading with 142.1 rpm, the mechanical torque (T_m) is 5.9 N-cm, while the electrical torque (T_e) is 7.84 N-cm for the same rotation. Likewise, at full load with a maximum rotation of 749 rpm, 0.54 N-cm and 0.73 N-cm were used for mechanical and electrical torque. The deviation of this dynamic torque value indicates that a fluctuation or ripple factor occurs between the magnetic interactions of the two gear discs.

Similarly, when one of the poles of n1 is aligned with n_2, a force known as the cogging torque is required to prevent pulling; the cogging torque depends on the location of the MG with a minimum flux effect. Therefore, one of the MG characteristics' essential factors in determining the optimal point of MG loading where the torque ripple is as small as possible or not at all. Fig. 7 shows torque ripples that occur at the difference in the values of T_e and Tm at speeds of 100 – 780 Rpm with the same load.

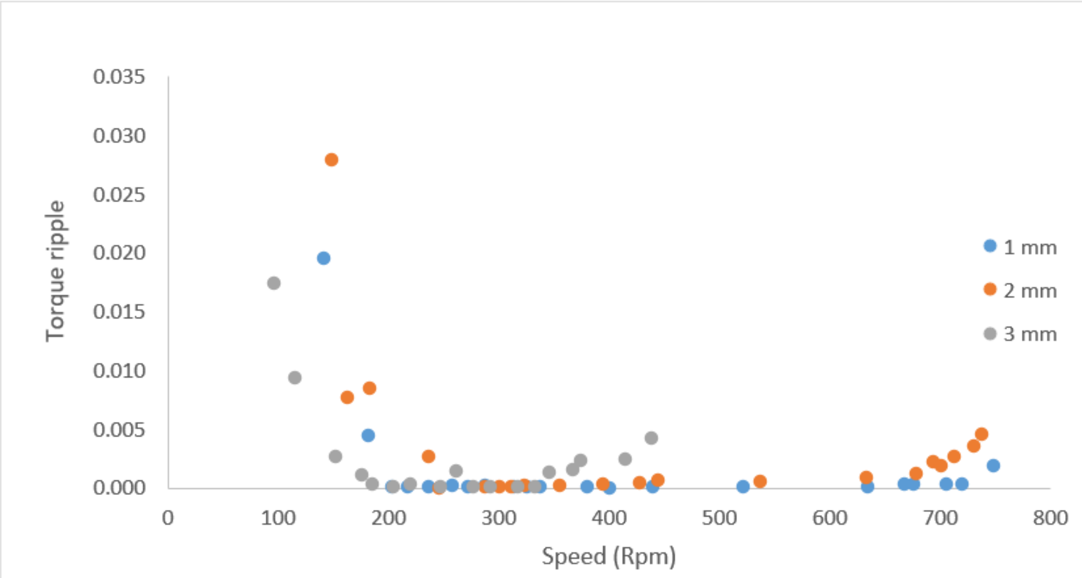


Figure 7. Torque ripple for axial MG VS changes in air gap distance (mm): (a) 1; (b) 2; (c) 3

Figure 7 shows torque ripples at low speed (heavy load) and high speed (light load) with various air gap distances. Generally, torque ripple occurs below 25% and above 80% at nominal speed for all air gap variations. This shows that the torque ripple of an MG occurs at light loads and overloads. The larger the flux in the MG, the smaller the ripple factor. In other words, adding three layers of magnets to each tooth of the magnet indicates an increase in the torsional strength during rotation.

4. Discussion

According to [18] and [19], the parameters used to determine the torque of MG are the number of poles, affected area, flux strength, and distance of the air gap between the couplings. The greater the distance of the air gap, the higher the torque ripple. In addition, the range for small torque ripples that occur at a relatively wide rotation of MG needs to utilize a low magnetic flux of torque ripples. In [20] stated that the distance of 1 mm between two MGs is ideal for transferring high torque rotation.

Furthermore, in [21], the torque decreases with the distance between the air gap and vice versa. Subsequently, when the distance of the air gap increases, there is a decrease in the torque, and the effect of the thickness of the air gap becomes smaller. The impact, therefore, can reduce the torque ripple.

MG layers are added to determine the effect of dynamic torque by testing electrical and mechanical systems. That also showed the difference in values associated with the mathematical analysis in two disks at a 0-800 rpm rotation. This fluctuation shows the torque ripples, which occur due to the loading and rotation influence of the MG. In addition, the percentage of ripple factors increases with a decrease in rotations. According to [22], torque ripples are not eliminated under changing load conditions. However, it is reduced by simultaneously optimizing the tilt and forward phase angle in a loaded condition. In addition, the optimal ripple factor is reduced by setting the rotation between 75-85% according to the variation of air gap distance between the two MG disks, as shown in Figure 6. Therefore, the torque ripple of the MG is reduced by increasing the magnetic flux, setting the distance of the air gap, and carrying out optimal loading.

The high ripple torque effect causes MG vibration during operation. Opinion [23] confirms that the torque ripple reduction can increase the power coefficient. Meanwhile, [24] argues that torsional ripples produce vibration, noise, frequency, and amplitude. Torque ripples can affect power output and even result in errors when measuring motor power output and MG.

4. CONCLUSION

1. The simultaneous measurement of electrical and mechanical torque is one method used to determine the torque ripple of the MG.
2. The difference in the value of electric and magnetic torque with the same load indicates torque ripple in the MG.
3. Increased torque ripple occurs in light and heavy loading. That is fluctuations or ripples in the magnetic gear torque increase at high and low revs.

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