Comparison of the Radial Force at the Modulating Pieces in the Coaxial Magnetic Gear and the Magnetic Geared Machine

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The magnetic geared machine has been studied in both the traction motor for battery electric vehicles and the transmission system for hybrid electric vehicles. Unlike the coaxial magnetic gear, it has the AC armature winding on the inner part or the outer part. Besides, because the AC armature field and PM excitation field have different space harmonic components from each other, the flux modulation characteristics by the modulating pieces are also different. Thus, in this paper, firstly, the space harmonic components of AC armature field in the magnetic geared machine and PM excitation field in coaxial magnetic gear are presented, and the flux modulation characteristics are also compared. Secondly, the unmodulated space harmonic components of the magnetic fields at the outer air-gap are defined, and the resultant magnetic radial forces at modulating pieces in coaxial magnetic gear and the magnetic geared machine are analyzed.

***Index Terms*— Coaxial magnetic gear, electric continuously variable transmission (E-CVT), magnetic geared machine, radial force space harmonic.**

I. Introduction

The various structures of the coaxial magnetic gear (CMG) have been proposed as an alternative to the mechanical gear in low-speed, high-torque application or power transmission system. Particularly, the magnetic geared machine, which has the AC armature winding on the inner part or the outer part instead of the permanent magnet (PM) rotor, has been studied [1]. When it is designed as the traction motor, in general, the inner PM rotor is replaced by the AC armature winding, and the outer PM rotor is used as the output. This structure can get the improved torque by the modulation effect between the magnetic fields at the inner air-gap and the outer air-gap [2]. In case of the gearing operation such as the electric continuously variable transmission (E-CVT) of the hybrid electric vehicle, the magnetic geared machine has two rotors and one stator [3]. Generally, the outer PM rotor is replaced by the AC armature winding, and the inner PM rotor and the modulating pieces rotor are connected with the engine and the torque regulating machine, respectively.

Both the magnetic geared machine and CMG are operated by the flux modulation effect. Thus, there are plenty of space harmonic components in the magnetic field at the inner and outer air-gap. These space harmonic components in the magnetic field cause the radial force at the modulating pieces, and the resultant vibration and noise occur. However, it should be noted that because the AC armature field and PM excitation field have different space harmonic components from each other, the flux modulation characteristics by the modulating pieces in AC armature field and PM excitation field are also different. Thus, in this paper, firstly, the space harmonic components of AC armature field in the magnetic geared machine and PM excitation field in CMG are presented, and the flux modulation characteristics by the modulating pieces are also compared. Secondly, the unmodulated space harmonic components in the magnetic fields at the outer air-gap are defined as they are relatively bigger amplitude compared with the other harmonics. Finally, the resultant magnetic radial forces at modulating pieces in CMG and the magnetic geared machine are analyzed.

II. Analysis Models

Fig. 1 shows the topologies of the CMG and the magnetic geared machine. The CMG consists of the two PM rotors and one modulating pieces part, and the magnetic geared machine has the AC armature winding at the inner part instead of the PM rotors. In the case of AC armature winding, the concentrated winding is employed, and the pole pairs are defined as the same pole pairs with that of the inner PM rotor in CMG. The PM excitation field in CMG or AC armature field in the magnetic geared machine is modulated by the modulating pieces, and it is synchronized with the PM excitation field, produced by the outer PM [2]. In both the CMG and the magnetic geared machine, the inner part and the outer PM have the pole pairs of 4 and 22, respectively, and the number of the modulating pieces, N_s is designed as 26.

III. Space Harmonic Analysis of the Flux Density

Fig. 2 shows the space harmonic spectra of the radial and tangential flux density distribution at the inner air gap in the CMG and the magnetic geared machine. It is produced by the inner magnetic source, when both of the modulating pieces

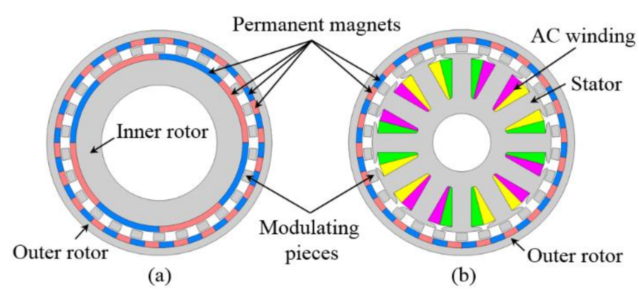


Fig. 1. Topology of analysis model: (a) Coaxial magnetic gear (CMG), (b) Magnetic geared machine.

and the PM on the outer rotor are replaced by the air region. In case of CMG, because the PM has the radial magnetization, the PM excitation field is distributed with half-wave symmetry at the air-gap, and it has the space harmonic components which correspond to an odd harmonic (m = 1, 3, 5, … , ∞) as shown in Fig. 2(a). These space harmonic components are synchronized with the inner PM rotor and rotate with the same speed and direction. But, the AC armature field in the magnetic geared machine has all space harmonic components (n = 1, 2, 4, 5, 7, 8, … , ∞) except the multiple of third order harmonic as shown in Fig. 2(b). These space harmonic components rotate with different speed and direction. In other words, these are distinguished into the positive phase sequence and negative phase sequence.

The space harmonic spectra of the radial and tangential flux density distribution at the outer air gap in CMG and the magnetic geared machine, which passed through the modulating pieces, are presented in Fig. 3. To clearly see the space harmonic component produced by inner source, the outer PM is replaced by the air region. We can show that the 22nd space harmonic component corresponding to the number of pole pairs of the outer PM, which is working harmonic producing the torque at the outer air-gap. But, it should be noted that there are unmodulated space harmonic components which have bigger radial component than that of the working harmonic. Actually, these unmodulated space harmonic are the main cause of the radial force at the modulating pieces. To know how these unmodulated space harmonic components are produced, the modulating function is expressed as in (1).

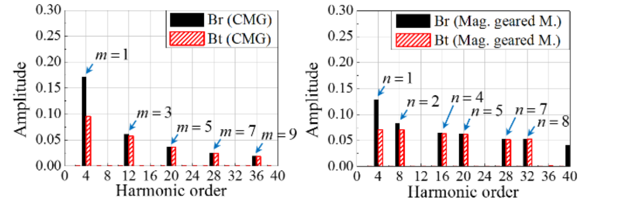
$$\lambda_k(r,\theta) = \lambda_{r0} + \sum_k \lambda_{rk} \cos[kN_s(\theta - \Omega_s t)],\ k = 0, \pm 1, \pm 2, \pm 3, \ldots, \infty \quad (1)$$

where the k is the space harmonic order of the modulation function, Ω_s is the rotating speed of the modulating pieces rotor, and the λ_{r0} is the dc component of the modulating function. Thus, we can get all space harmonic components of the flux density at the outer air gap using the space harmonic order of the PM excitation field, AC excitation field, and modulation function as presented in table I [2]. The unmodulated space harmonic orders corresponding the dc component of the modulating function are highlighted in grey.

IV. Radial Force on the Modulating Pieces

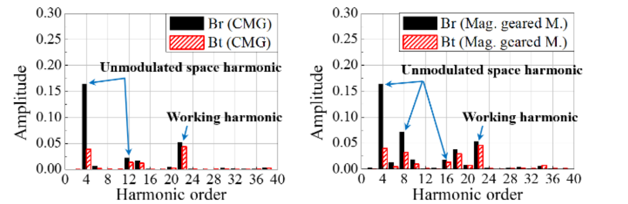
The modulating pieces part suffers from the radial force by plenty of space harmonic component in the magnetic field at the inner and outer air-gap. Thus, the characteristics of the radial force are considerably different in the CMG and the magnetic geared machine because of the difference of the space harmonic components in the AC armature field and PM excitation field.

Fig. 4 shows the maximum radial force at one point of the inner and outer surface of the modulating pieces when the CMG and the magnetic geared machine operate with the full load condition. In case of CMG, the maximum radial forces at each modulating piece are similar to each other, however, in



(a) (b)

Fig. 2. Comparison of space harmonic spectra of the radial and tangential flux density distribution at the inner air gap by the inner magnetic source when both the modulating pieces and the outer PM are replaced by the air region: (a) CMG, (b) Magnetic geared machine.



(a) (b)

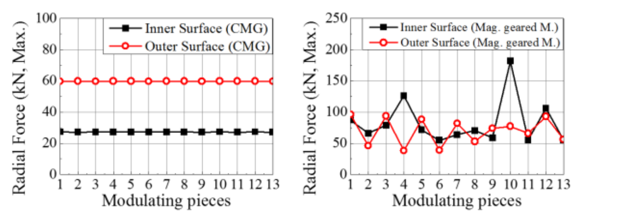
Fig. 3. Comparison of space harmonic spectra of the modulated radial and tangential flux density distribution at the outer air gap by the inner magnetic source when the outer PM is replaced by the air region: (a) CMG, (b) Magnetic geared machine.

TABLE I

Space Harmonic Orders of the Flux Density at the Outer Air Gap

Space Harmonc Components of the Flux Density Distribution According to the Harmonic Order of the PM Excitation Field and AC Armature Field

Order		PM excitation field						AC armature field							
		$m=1$		$m=3$		$m=5$		$n=1$		$n=2$		$n=4$		$n=5$	
$k=0$		**4**		**12**		**20**		**4**		**-8**		**16**		**-20**	
$k=1$	$k=-1$	30	**-22**	38	-14	46	-6	30	**-22**	-34	18	42	-10	-46	6
$k=2$	$k=-2$	56	-48	64	-40	72	-32	56	-48	-60	44	68	-36	-72	32
$k=3$	$k=-3$	82	-74	90	-66	98	-58	82	-74	-86	70	94	-62	-98	58



(a) (b)

Fig. 4. Maximum radial force at one point of the inner and the outer surface of the modulating pieces when the CMG and the magnetic geared machine operate with the full load condition: (a) CMG, (b) Magnetic geared machine.

the magnetic geared machine, it is quite different. This is because the unmodulated space harmonics, which rotate at different directions, and the reluctance difference depending on the relative position of the modulating piece and the tooth of stator. In the full paper, the correlation between the radial force and the reluctance difference will be presented, and the characteristics of the radial force at the modulating pieces by the unmodulated space harmonic components in the magnetic field will be specifically presented

References

[1] L. L. Wang, J. X. Shen, Y. Wang and K. Wang, “A Novel magnetic-geared outer-rotor permanent-magnet brushless motor,” in *Proc.* PEMD, pp. 33-36, Apr. 2008.

[2] K. Atallah, S. D. Calverley, and D. Howe, “Design, analysis and realization of a high-performance magnetic gear,” *IEE Proc-Electr. Power Appl.*, vol. 151, pp. 135-143, Mar. 2004.

[3] P. Zheng, J. Bai, C. Tong, J. Lin, and H. Wang, “Research on electromagnetic performance of a novel radial magnetic-field-modulated brushless double-rotor machine,” in *Proc.* ICEMS, Aug. 2011.