HYBRID-EXCITED MAGNETIC GEAR EMPLOYING ROTATING-POLE-PIECE TOPOLOGY WITH IMPROVED GEAR EFFICIENCY FOR ELECTRIC VEHICLE APPLICATION

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Dedicated to my beloved wife,
Nurul Wahida;
my children,
Firhan, Fahim, Hani and Hanani;
and my siblings and friends.
Thank you for always encouraging me with your love and prayers.
I love you all deeply.

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ABSTRACT

Magnetic gear (MG) is an attractive option to mechanical gear due to its contactless nature, which contributes to lower losses and higher efficiency. Different types of MG, differs in physical construction. Concentric magnetic gear (CMG) exhibits the highest torque production compared with other MGs. Yet, CMGs are generally analysed in low-speed applications due to eddy current loss from the permanent magnet (PM) during high-speed operations. This loss leads to decrease in output torque and gear efficiency. To overcome these in high-speed applications, as in electric vehicles (EVs), a different CMG topology known as rotating-pole-piece magnetic gear (RPMG) is more practical. RPMGs have fewer number of poles and hence higher transmitted torque and efficiency, although claimed to cause higher torque ripple than CMGs in some pole pair combinations. Therefore, in this work, torque characteristics were evaluated in RPMGs for several pole pair combinations and compared with the CMG topology. The second combination of gear ratio 7.66 was found to be the most practical option due to its lower number of pole pairs and 1% of torque ripple produced. Next, to improve gear efficiency, three strategies are considered and compared with the original RPMG. The strategies are lowering PM residual magnetic flux density level, performing rotor skewing and employing second flux source to the RPMG, which then transformed the RPMG into a hybrid-excited magnetic gear (HMG). Results gathered reveals that the HMG strategy produced the best improvement. To optimize the gear efficiency produced further, stator slot and tooth design of the HMG structures is improved, thus producing two other different variants; HMG C1 and HMG C5 and analysed using 2D finite element method. Gear efficiency achieved by the proposed HMG structures were above 96%. Meanwhile, the torque densities are above 200 kN.m/m^3. These numbers are the highest if compared with previous studies. The newly proposed HMG structure has shorter flux path to the air gap and utilised smaller PM volume. It is hoped that the torque density and gear efficiency produced will elevate the overall performance of the drive system in EVs.

ABSTRAK

Gear magnetik (MG) ialah pilihan menarik berbanding gear mekanikal kerana sifat tanpa sentuhannya, menyumbang kepada kehilangan yang rendah dan kecekapan yang tinggi. Jenis MG berbeza dalam binaan fizikalnya. Gear magnetik sepusat (CMG) mempamerkan pengeluaran daya kilas tertinggi berbanding dengan MG lain. Namun, ia biasanya dianalisa pada aplikasi berkelajuan rendah kerana kehilangan arus pusar daripada magnet kekal (PM) semasa berkelajuan tinggi. Kehilangan ini menyebabkan penurunan daya kilas dan kecekapan gear. Untuk mengatasi kehilangan ini, seperti pada kenderaan elektrik (EV), topologi CMG berbeza, dikenali sebagai gear magnet kutub berputar (RPMG) adalah lebih praktikal. RPMG mempunyai bilangan kutub yang lebih sedikit, daya kilas dan kecekapan yang dihantar juga lebih tinggi. Namun ia didakwa menyebabkan riak daya kilas lebih tinggi dari CMG pada sesetengah kombinasi kutub. Dalam kerja ini, ciri daya kilas dinilai dalam RPMG pada beberapa kombinasi kutub dan dibandingkan dengan CMG. Kombinasi kedua gear nisbah 7.66 didapati paling praktikal kerana bilangan pasangan kutub yang lebih rendah, hanya 1% riak daya kilas yang dihasilkan. Untuk meningkatkan kecekapan gear, tiga strategi dibandingkan dengan RPMG asal. Strateginya adalah menurunkan tahap ketumpatan fluks magnet sisa, pencongan rotor dan menambah sumber fluks kedua pada RPMG, mengubahnya kepada gear magnetik hibrid (HMG). Hasil simulasi mendedahkan strategi HMG adalah yang terbaik. Bagi meningkatkan kecekapan gear yang dihasilkan, struktur HMG ditambahbaik, menghasilkan dua varian; HMG C1 dan HMG C5, dan dianalisis menggunakan kaedah unsur terhingga 2D. Kecekapan gear yang dicapai oleh struktur yang dicadangkan adalah melebihi 96% manakala ketumpatan daya kilas melebihi 200 kN.m/m^3. Jumlah ini adalah yang tertinggi dibandingkan dengan kajian-kajian lepas. Struktur HMG yang baru dicadangkan mempunyai laluan fluks yang lebih pendek ke jurang udara dan menggunakan isipadu PM yang lebih kecil. Ketumpatan daya kilas dan kecekapan gear yang dihasilkan diharap dapat meningkatkan prestasi keseluruhan sistem pemacu dalam EV.

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LIST OF SYMBOLS AND ABBREVIATIONS

B_m	-	Magnetic flux density
B_r	-	Residual Magnetic flux density
c_o	-	Ratio of Air Slot Opening to Pole Pitch
D	-	Thickness
f	-	Magnetic Field Frequency
f_c	-	Cogging Torque Factor
g	-	Gram
G_r	-	Gear Ratio
G_{rn}	-	Gear Ratio at Specific Speed
h_m	-	PM Thickness
K_e,	-	Eddy Current Loss Coefficient
Kg	-	Kilogram
$kN.m$	-	Kilonewton Meter
$L1$	-	Radial Length or Thickness of Stator Tooth
$L2$	-	Radial Length or Thickness of Outer Yoke
n_p, n_s	-	Number of Ferromagnetic Pole Piece
P	-	Number of Pole Pairs (p_h, p_o or n_p)
Pc	-	Eddy Current Loss at PM
$P_{eddy\ i}$	-	Eddy Current Loss at Inner Ring
$P_{eddy\ o}$	-	Eddy Current Loss at Outer Ring
P_{eddy},	-	Eddy Current Loss
p_h, p_i	-	Number of Inner Pole Pairs
$P_{i\ eddy}$	-	Eddy Current Loss of Inner PM Piece
p_l, p_o	-	Number of Outer Pole Pairs
$P_{o\ eddy}$	-	Eddy Current Loss of Outer PM Piece
P_r	-	Number of Ring Gear Pole Pairs

P_s	-	Number of Sun Gear Pole Pairs
$R1$	-	Outer Radius of Outer Yoke
$R2$	-	Outer Radius of Slot
$R3$	-	Outer Radius of Outer PM
$R4$	-	Inner Radius of Slot
T	-	Tesla
V	-	Machine Volume
v_{in}	-	Inner Rotor Speed
V_M	-	Magnet Piece Volume
v_{out}	-	Outer Rotor Speed
V_{PM}	-	PM Total Volume
w	-	Magnet Width
$W1$	-	Ferromagnetic Pole Piece Radial Width
$W2$	-	Outer Yoke Radial Width
$W3$	-	Inner Yoke Radial Width
w_p	-	Carrier Speed
w_r	-	Ring Gear Speed
w_s	-	Sun Gear Speed
α	-	Ratio of Magnet Arc to PM Pole Pitch
Δ	-	Change in
$\Delta\eta$	-	Change in Gear Efficiency
Δ_τ	-	Change in Average Torque
η_G	-	Gear Efficiency
η_{j20}	-	Gear Efficiency at 20 A/mm^2 of Current Density
η_o	-	Gear Efficiency at 0 A/mm^2 of Current Density
$\Theta 1$	-	Arc Angle of Outer PM
$\Theta 2$	-	Angle Between Slots
$\Theta 3$	-	Arc Angle of Slot
$\Theta 4$	-	Arc Angle of Tooth
$\Theta 5$	-	Half of Arc Angle of Slot
θarc	-	Arc Angle
Θ_s	-	Skew Angle
λ_1	-	Highest Harmonic Order Created from IPP and FMP

λ_2	-	Highest Harmonic Order Created from OPP and FMP
ρ	-	Magnet Resistivity
τ_d	-	Torque Density
τ_i, τ_{in}	-	Average Inner Rotor Torque
τj_{20}	-	Average Torque at 20 A/mm^2 of Current Density
τ_{jo}	-	Average Torque at 0 A/mm^2 of Current Density
τ_o, τ_{out}	-	Average Outer Rotor Torque
ω_h	-	Frequency of Harmonic Magnetic flux density at Inner Air
ω_i	-	Frequency of Input Pole Pair
ω_l	-	Frequency of Harmonic Magnetic flux density at Outer Air
ω_x	-	Harmonic Frequency
CMG	-	Concentric Magnetic Gear
CVT	-	Continuous Variable Transmission
DC	-	Direct Current
DOM	-	Deterministic Optimization Methoc
EV	-	Electrical Vehicle
FEM	-	Finite Element Method
FMP	-	Ferromagnetic Pole Piece
IPP	-	Inner Pole Pair
OPP	-	Outer Pole Pair
HMG	-	Hybrid-excited Magnetic Gear
LCM	-	Least Common Multiple
MG	-	Magnetic Gear
MGORPM	-	Magnetic-Geared Outer-Rotor-PM
MMF	-	Magnetomotiveforce
NdFeB	-	Neodymium-Iron-Boron
NEV	-	Neighbourhood Electric Vehicle
PED	-	Power Electronics Driver
PM	-	Permanent Magnet
PMG	-	Planetary Magnetic Gear
PMSM	-	PM Synchronous Machines
RPMG	-	Rotating-Pole-Piece Magnetic Gear
SMG	-	Spur Magnetic Gear

THD	-	Total Harmonic Distortion
WMG	-	Worm Magnetic Gear

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CHAPTER 1

INTRODUCTION

1.1 Research background

Electric vehicles (EVs) offer a promising solution for a sustainable future, but EV advancement is restrained by a variety of technological demands, such as extra driving range, competitive costs, battery reliability and charging infrastructures [1]. EV penetration has been growing rapidly over the past 12 years, with the global stock of electric passenger cars surpassing the five-million mark in 2018, an increase of 63% from the previous year. China presents the highest EVs on the road of around 45% compared with 39% in 2017. Elsewhere, in the same year, Europe and the United States registered 24% and 22% of EVs on the road, respectively [2]. Figure 1.1 shows the number of electric cars in circulation in selected countries between 2013–2017.

The range capability of an electric vehicle is subjected to load capacity and energy storage capability, influenced by the car's total weight and the efficiency of the propulsion [3]. Thus, a closer look at the drive system should be carried out. As shown in Figure 1.2, the loss in the drive system contributes to 72% of total energy losses compared with losses in the battery at 9% and in the converter at 19%. Hence, improving the efficiency and power density of the drive system, such as the transmission system, power electronics and drives, could elevate the overall performance of EVs [3]–[4].

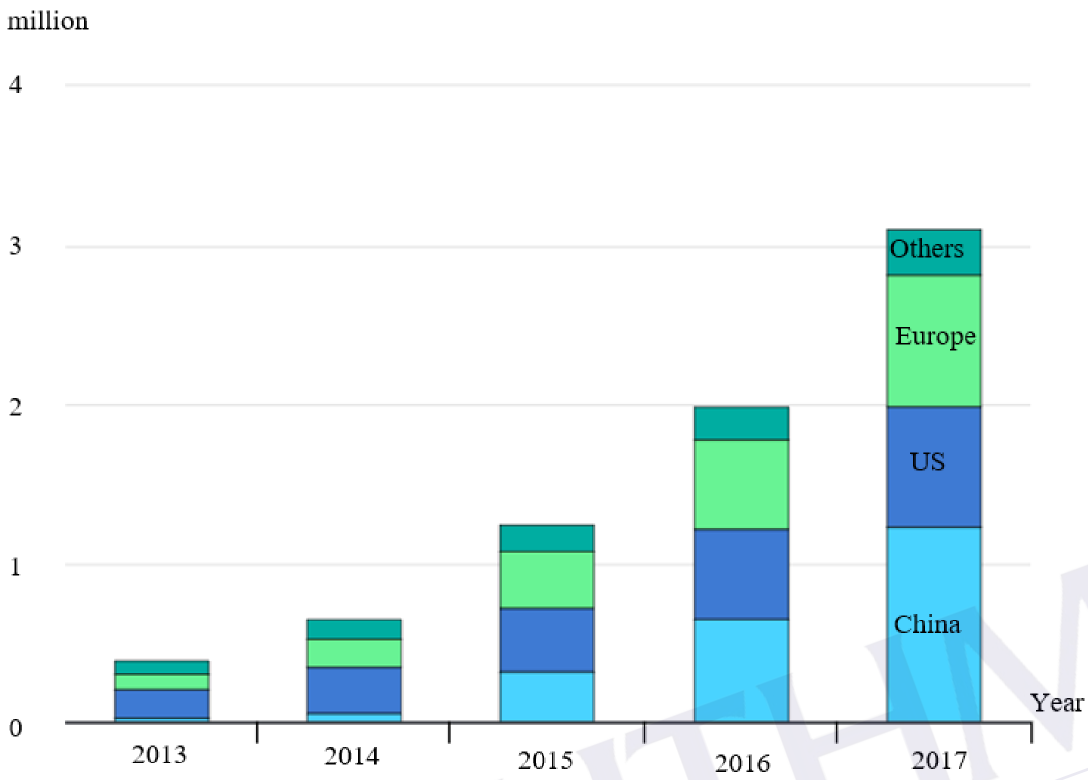

Figure 1.1: Number of electric cars in circulation in selected countries, 2013–2017 [2]

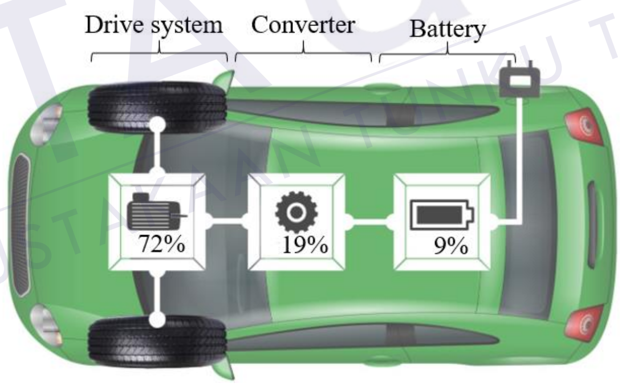

Figure 1.2: Losses in drive system, converter and battery of EVs [3]

Mechanical gears are among the major components in a transmission system. A mechanical gear can produce a high gear ratio and torque density, but it suffers from inherent problems, such as friction, noise, heat, vibration and reliability problems [5]. It requires contact to transmit torque and motion. Due to the engagement of the toothed gears, regular maintenance is required, especially on the lubrication, to reduce the wear and tear. Manual differential gears in a transmission system are recommended to undergo a lubricant change at least once every two years. For automatic transmission and continuous variable transmission (CVT) systems, the lubricant has to be changed

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APPENDIX C

LIST OF PUBLICATION

Journals:

(i) M. F. M. Ab Halim, E. Sulaiman, and R. N. F. K. R. Othman, “Flux switching machine: Design variation review,” International Journal of Advanced Trends in Computer Science and Engineering, vol. 9, no. 2, pp. 2422-2430, 2020.

(ii) M. F. Mohd Ab Halim, E. Sulaiman, and R. N. F. K. R. Othman, “Preliminary magnetization pattern study on magnetic gear,” International Journal of Advanced Trends in Computer Science and Engineering, vol. 9, no. 3, pp. 4063–4067, 2020.

(iii) M. F. Mohd Ab Halim, E. Sulaiman, R. N. F. K. R. Othman, and A. A. Rahman, “A new speed multiplier coaxial magnetic gear,” Progress in Electromagnetics Research M, vol. 93, pp. 145–154, Jan. 2020.

(iv) M. F. M. A. Halim, E. Sulaiman, I. A. Soomro, and S. M. N. S. Othman, “Preliminary study on yoke sizing of concentric magnetic gear,” International Journal of Emerging Trends in Engineering Research, vol. 8, no. 8, pp. 4613–4617, 2020.

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(ix) M. F. M. A. Halim, E. Sulaiman, R. Aziz, S. M. Naufal, A. A. Rahman, and T. Kosaka, “Electromagnetic Torque Performance Evaluation of Concentric Magnetic Gear Alternative Conditions using Finite Element,” International Journal of Nanoelectronics and Materials, vol. 14, pp. 59-67, 2021.

(x) M. Firdaus, M. Ab, E. Sulaiman, and M. Jenal, “Preliminary analysis of eddy current and iron loss in magnetic gear in electric vehicle,” International Journal of Electrical and Computer Engineering, vol. 12, no. 2, pp. 1161–1167, 2022.

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(i) M. F. M. A. Halim, E. Sulaiman, M. Jenal, and R. N. F. K. R Othman, “Buried PM inner rotor magnetic gear evaluation,” in *IOP Conference Series: Materials Science and Engineering*, 2020.

(ii) M. F. M. A. Halim, E. Sulaiman, and R. Aziz, “Rotating Pole Piece Magnetic Gear with Low Torque Ripple,” in *International Conference on Electrical & Electronic Engineering*, 2021.

APPENDIX D

VITA

The author was born on February 13th, 1982, in Kota Bharu Kelantan. He received his Bachelor's degree from Tenaga Nasional University in 2004 in Electrical Power Engineering. His first employment was at Sony EMCS, Bangi, as a design engineer from 2004 to 2005. He then joined Intel Corp. in Kulim before becoming an academic staff at Universiti Teknikal Malaysia Melaka in 2008. In 2012, the author continued his education to pursue his Master of Electrical, Electronic and Information Technology at Rosenheim University. He attended Universiti Tun Hussein Onn Malaysia to pursue his degree of Doctor of Philosophy (PhD) in Electrical Engineering.