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

MOHD FIRDAUS MOHD AB HALIM

A thesis submitted in fulfilment of the requirement for the award of the Doctor of Philosophy in Electrical Engineering

> Faculty of Electrical and Electronic Engineering Universiti Tun Hussein Onn Malaysia

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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





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/m³. 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		
Grn	-	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	PUS	Radial Length or Thickness of Outer Yoke		
n_p, n_s	-	Number of Ferromagnetic Pole Piece		
Р	-	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		
pi, po	-	Number of Outer Pole Pairs		
Po 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
<i>R2</i>	-	Outer Radius of Slot
<i>R3</i>	-	Outer Radius of Outer PM
<i>R4</i>	-	Inner Radius of Slot
Т	-	Tesla
V	-	Machine Volume
Vin	-	Inner Rotor Speed
V_M	-	Magnet Piece Volume
Vout	-	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
Wr	-	Ring Gear Speed
Ws	-	Sun Gear Speed
α	-	Ratio of Magnet Arc to PM Pole Pitch
Δ	-	Change in
Δη	151	Change in Gear Efficiency
Δ_{τ} DERV	0	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
θ1	-	Arc Angle of Outer PM
<i>Θ2</i>	-	Angle Between Slots
<i></i>	-	Arc Angle of Slot
<i>Θ</i> 4	-	Arc Angle of Tooth
θ5	-	Half of Arc Angle of Slot
θarc	-	Arc Angle
Θ_s	-	Skew Angle
λ_1	-	Highest Harmonic Order Created from IPP and FMP

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λ_2	-	Highest Harmonic Order Created from OPP and FMP		
ρ	-	Magnet Resistivity		
$ au_d$	-	Torque Density		
$ au_{i}, au_{in}$	-	Average Inner Rotor Torque		
τ j 20	-	Average Torque at 20 A/mm ² of Current Density		
$ au_{jo}$	-	Average Torque at 0 A/mm ² of Current Density		
$ au_o, au_{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	ist	Hybrid-excited Magnetic Gear		
LCM = R	0	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		

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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:

- 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.
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- (vi) M. F. M. A. Halim and E. Sulaiman, "Permanent Magnet Flux Switching Torque Performance Indicator," El-Cezerî Journal of Science and Engineering, vol. 8, no. 2, pp. 582–591, 2021.

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Proceedings:

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- M. F. M. A. Halim, E. Sulaiman, and R. Aziz, "Rotating Pole Piece Magnetic (ii) 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.

