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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electrical Engineering

DIRECT TORQUE CONTROL OF DUAL INDUCTION MOTOR DRIVES FED BY FIVE-LEG INVERTER FOR ELECTRIC VEHICLES

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DIRECT TORQUE CONTROL OF DUAL INDUCTION MOTOR DRIVES FED BY FIVE-LEG INVERTER FOR ELECTRIC VEHICLES

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

Faculty of Electrical Engineering

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2018

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Doctor of Philosophy.

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DECLARATION

I declare that this thesis entitled "Direct Torque Control of Dual Induction Motor Drives fed by Five-Leg Inverter for Electric Vehicles" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : Nurazlin Binti Mohd Yaakop

Date : 15/10/2018

DEDICATION

For you,

My dearest grandmother

My dearest mother and father

My lovely husband, son and daughter

My brothers and sisters

ABSTRACT

Multi motor drives system is the current trend in electric vehicle application. Conventionally, each induction motor will have its own dedicated three-phase inverter. However, dual motor drives using dedicated three-phase inverter have its limitation, it is difficult to control, synchronise and not cost effective. This research aims to develop and implement a combined electric differential (ED) for torque distribution of electric vehicle steering action and independent speed control for dual induction motors drives fed by a single Five-Leg Inverter (FLI). It is desired for having fewer components and reduces size and cost for multi motor drives system. Recent research has shown that, dual motors drives can be independently controlled by using FLI. Direct torque control (DTC) scheme for induction motor with space vector pulse width modulation (SVPWM) technique is used for the drive in this research. Flux and torque responses are estimated by DTC estimator. Additionally, the special 6 to 5 duty cycle SVPWM is used to trigger the FLI in order to control the torque and speed of the dual induction motors. These motors are directly coupled to the wheels of the electric vehicle test rig in the laboratory. The ED is used to distribute the torque for both of the wheels. The employment of ED method allows the investigation of the effects of steering angle input variation and different speed command towards detail study of electric motor drives performance in an electric vehicle application. Upon the completion of the research based on simulation and experimental works it is proves that the proposed technique has produced good expected result of the combined ED and independent speed control for dual induction motors drives fed by a single FLI. The system has been tested with steering angle variation from 20°, 45°, 80° and 100° to compare the performance of dual motor controller for right turn manoeuvre and left turn manoeuvre for low speed operation fix at 200 rpm. It is show that the speed difference between M1 and M2 increase with the increasing of steering angle as well as the cornering distance and angle also increase respectively. It is confirmed that there is a correlation between the linear velocities of the car (kmph) is decreasing with the increasing of steering angle for both right turn and left manoeuvre.

ABSTRAK

Sistem pemacu banyak motor secara serentak telah menjadi pilihan di dalam aplikasi kenderaan elektrik pada masa kini. Pada kebiasaannya, setiap motor aruhan akan mempunyai penyongsang tiga fasa yang khusus bagi setiap unit. Walau bagaimanapun, bagi aplikasi dua motor secara serentak dengan menggunakan satu penyongsang tiga fasa bagi setiap unit mempunyai kelemahan, iaitu sukar untuk dikawal, diselaras dan tidak kos efektif. Selain itu, ia juga menghadapi kesukaran dalam kawalan dan komunikasi data. Kajian ini bertujuan untuk membangunkan dan melaksanakan kombinasi Pengkamiran Elektrik (ED) digunakan untuk mengagihkan dayakilas hasil aksi stereng kenderaan elektrik dan kawalan kelajuan bebas untuk dua motor aruhan secara serentak dijana oleh Penyongsang Lima Kaki (FLI).tunggal. Ia bermatlamat untuk mengurangkan penggunaan komponen serta mengecilkan saiz dan kos sistem pemacu banyak motor. Penyelidikan terkini menunjukkan bahawa, pemacu dua motor secara serentak boleh dikawal secara bebas dengan menggunakan FLI. Skim Kawalan Dayakilas Terus (DTC) untuk motor aruhan dengan teknik Modulasi Ruang Vektor Lebar-Denyut (SVPWM) digunakan dalam menjayakan kajian ini. Tindakbalas fluks dan dayakilas dikira dan dianggar menggunakan penganggar DTC. Sebagai tambahan, modulasi khas 6 - 5 kitaran tugas SVPWM digunakan bagi mencetuskan FLI untuk mengawal/memandu dua motor aruhan secara serentak. Motor-motor ini digabungkan secara terus dengan tayar-tayar pada rig ujian kenderaan elektrik di dalam makmal. ED digunakan untuk mengagihkan dayakilas bagi kedua-dua belah tayar. Penggunaan kaedah ED membolehkan kajian terperinci terhadap kesan input sudut putaran stereng dan perbezaan arahan kelajuan terhadap prestasi pemacu motor elektrik dalam aplikasi kenderaan elektrik. Setelah kajian selesai, berdasarkan simulasi dan kerja eksperimen dapat dibuktikan bahawasanya teknik yang dicadangkan telah menghasilkan keputusan yang baik mengikut jangkaan dalam melaksanakan kombinasi ED dan kawalan kelajuan bebas untuk dua motor aruhan secara serentak dijana oleh FLI. Sistem ini telah diuji dengan variasi sudut stereng 20°, 45°, 80° dan 100° untuk membandingkan prestasi kawalan dua motor bagi pemanduan belok kanan dan pemanduan belok kiri dengan kelajuan operasi yang rendah iaitu pada 200 rpm. Didapati, bahawa perbezaan halaju antara M1 dan M2 meningkat dengan peningkatan sudut stereng, begitu juga dengan jarak pembelokkan dan sudut pembelokkan masing-masing turut meningkat. Adalah disahkan terdapat kolerasi antara halaju linear bagi kereta (kmph) adalah menurun dengan penambahan sudut stereng bagi pemanduan belok kanan dan belok kiri.

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LIST OF SYMBOLS

B	-	Motor friction constant
$d^s i$	-	d-axis stator current in stationary reference frame
$q^s i$	-	q-axis stator current in stationary reference frame
$d^r i$	-	d-axis rotor current in stationary reference frame
$q^r i$	-	q-axis rotor current in stationary reference frame
i_a, i_b, i_c	-	stator phase a, b, c current
i_{ds}	-	d -axis stator current
i_{qs}	-	q-axis stator current
J	-	Motor moment of inertia constant
L	-	inductance
P	-	number of pole pairs
θ	-	rotor position angle
R_s, R_r	-	Stator and rotor resistance
S	-	switching function
T_{ref}	-	Reference torque
u	-	control signal
v_a, v_b, v_c	-	line to neutral voltage of phase *a, b, c.*

V_s	-	stator voltage
$d^s v$	-	d-axis stator voltage in stationary reference frame
$q^s v$	-	q-axis stator voltage in stationary reference frame
$d^r v$	-	d-axis rotor voltage in stationary reference frame
$q^r v$	-	q-axis rotor voltage in stationary reference frame
T_r	-	Rotor time constant
φ	-	flux linkage
ω	-	Angular speed
T_e	-	Instantaneous value of electromagnetic torque
T_{error}	-	Error torque
T_L	-	load torque
T_s	-	sampling time
L_m	-	Magnetizing self-inductance
L_s	-	Stator self-inductance
L_r	-	Rotor self-inductance
$S_a S_b S_c$	-	Switching states *a, b, c.*
p	-	Number of pole

LIST OF ABBREVIATIONS

AC	-	Alternating Current
DC	-	Direct Current
DOF	-	Degree Of Freedom
DSP	-	Digital Signal Processing
DTC	-	direct torque control
DTFC	-	Direct Torque Flux Control
ED	-	Electric/Electronic Differential
EV	-	Electric Vehicle
FLI	-	Five-leg inverter
FOC	-	Field Oriented Controlled
HIL		Hardware In-Loop
IGBT	-	Insulated Gate Bipolar Transistor
IM	-	Induction Motor
MMDS	-	Multi-Motor Drive System
MMS	-	Multi-Motor System
PC	-	Personal Computer
PMSM	-	Permanent Magnet Synchronous Motor
PWM	-	Pulse Width Modulation
SV	-	Space Vector
SVM	-	Space Vector Modulation

SVPWM	-	Space vector pulse width modulation
THD	-	Total Harmonic Distortion
TLI	-	Three-Leg Inverter
TT	-	Switching Transistor
VC	-	Vector Controlled
V_{DC}	-	Direct voltage
VSI	-	Voltage Source Inverter
VUF	-	Voltage Utility Factor

LIST OF PUBLICATIONS

Journal Paper

1. Zulkifilie Ibrahim, **Nurazlin Mohd Yaakop**, Fauzi Ahmad, Marizan Sulaiman, Kamaruzaman Jusoff, Zanariah Jano, Linda Khoo Mei Sui, Ahmad Shukri Abu Hasim and Siti Noormiza Mat Isa "Improved Direct Torque Control Load Torque Estimator with the Influence of Steering Angle for Dual Induction Motors Electric Vehicle Traction Drive System" World Applied Sciences Journal 21 (Special Issue of Engineering and Technology): pp. 11-22, 2013
2. Zulkifilie Ibrahim, **Nurazlin Mohd Yaakop**, Marizan Sulaiman, Jurifa Mat Lazi, Ahmad Shukri Abu Hasim and Fizatul Aini Patakor, "Electric differential with SVPWM Direct Torque Control using Five-Leg Inverter for Electric Vehicle." Journal of theoretical and applied information technology (JATIT), vol. 46, no. 2, pp. 599-609, December 2012.

Published Conference Proceedings

1. Z. Ibrahim, **N. Mohd Yaakop,** M. Sulaiman, J. Mat Lazi and S. N. Mat Isa "Controlled of five-leg vsi fed dual induction motor for electric vehicle traction wheels drive ", in Power and Energy Conversion Symposium (PECS), Melaka, Malaysia, 2012
2. **N. Mohd Yaakop**, Z. Ibrahim, M. Sulaiman and M. H. N. Talib "Speed Performance of SVPWM Direct Torque Control for Five Leg Inverter Served Dual Three-Phase Induction Motor" IEEE International Power Engineering and Optimization Conference (PEOCO2012), Melaka, Malaysia, June 2012, pp. 323-328.