ANALYSIS OF POWER LOSSES AND LIFETIME FOR THE INVERTER IN ELECTRIC VEHICLES USING VARIABLE VOLTAGE CONTROL AND VARIABLE SWITCHING FREQUENCY MODIFIED PWM

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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Thesis submitted in fulfillment of the requirements
for the award of the degree of
Master of Science

College of Engineering

UNIVERSITI MALAYSIA PAHANG

NOVEMBER 2020

ACKNOWLEDGEMENTS

First and foremost, all thanks and glory are due to “ALLAH” the Almighty, who gave me the power, the health and patience to accomplish this research.

It is my great fortune to have Ir. Dr. Ing. Muhamad Zahim Bin Sujod as the supervisor during my Master. I would like to express my warmest appreciation, gratitude and sincere thanks to him for his guidance, encouragement, support, kind help and sound advice throughout the period of this research. Dr. Zahim’s technical expertise, and energy have been invaluable during my study and I am truly honored to have worked with a world class researcher such as him.

I would like to acknowledge the administrative and teaching staff of University Malaysia Pahang (UMP) for providing the facilities to conduct this research. Also, I am very grateful to the Ministry of Higher Education Malaysia (MOHE) for their financial support of this research through the Fundamental Research Grant Scheme (RDU1803165).

Lastly, I would like to express my deepest gratitude and greatest appreciation to my parents, brothers, and sisters for their enormous love, inspiration, and prayers. They always respect what I want to do and give me their full support and encouragement over the years. I just want to say that I love you all very much and that dedicated this thesis to all of you.

ABSTRAK

Dengan meningkatnya permintaan untuk pengurangan emisi dan penjimatan bahan bakar, pembuat kenderaan memberi tumpuan kepada pembangunan kereta elektrik (EV). Prestasi EV dinilai dari segi jarak pemanduan dan jangka hayat komponennya. Penukar kuasa adalah antara komponen pemacu EV yang paling terkesan dan kurang kebolehpercayaan. Oleh itu, meningkatkan jangka hayat penukar kuasa adalah perkara yang penting untuk penggunaan EV yang baik. Jangka hayat penukar kuasa dapat ditingkatkan dengan mengurangkan kitaran haba peranti kuasa, yang merupakan penyebab utama kerosakan. Oleh kerana suhu dan kehilangan kuasa penukar kuasa adalah berkadar terus, kitaran haba boleh dikurangkan dengan meminimumkan kehilangan kuasa. Sebagai tambahan kepada peningkatan jangka hayat, meminimumkan kehilangan kuasa penukar kuasa dapat meningkatkan julat EV kerana penggunaan kuasa dikurangkan dalam keadaan tertentu. Sehubungan itu, tesis ini bertujuan untuk mengkaji kesan teknik pengurangan kehilangan kuasa yang dikenali sebagai kawalan voltan arus-terus (VVC) bolehubah pada jangka hayat penyongsang. Di samping itu, tesis ini mengusulkan strategi baru iaitu modulasi lebar pulsa (PWM) yang dikenali sebagai frekuensi pensuisan bolehubah PWM (VSF-MPWM) untuk tiga fasa dua level penyongsang sumber voltan. VSF-MPWM bertujuan untuk mengurangkan kehilangan kuasa penyongsang tanpa mengurangkan kualiti arus keluaran. Untuk mengkaji kesan VVC pada jangka hayat penyongsang, kaedah anggaran jangka hayat dikemukakan. Kaedah ini menggunakan kitaran pemanduan Artemis Urban dan US06 untuk mendapatkan pemuatan haba, dan seterusnya penggunaan jangka hayat peranti kuasa penyongsang. Kemudian, VSF-MPWM digunakan bagi meminimumkan kehilangan kuasa dengan menyepit mana-mana kaki tiga fasa pada puncak arus fasa untuk mengurangkan jumlah peralihan melalui frekuensi pensuisan bolehubah. Walau bagaimanapun, untuk mencapai kualiti arus yang boleh diterima, VSF-MPWM digunakan bagi mengawal kedua-dua tempoh pengapit dan frekuensi pensuisan bolehubah mengikut had kualiti arus konvensional PWM. Kesan VVC pada jangka hayat penyongsang dan prestasi VSF-MPWM terhadap kehilangan kuasa penyongsang dan kualiti arus dilakukan menggunakan perisian MATLAB Simulink. Analisis jangka hayat menunjukkan bahawa VVC mempunyai kemampuan untuk meningkatkan jangka hayat penyongsang dengan faktor 5.06 bagi Artemis Urban dan 3.43 bagi US06 berbanding dengan kawalan voltan arus-terus konvensional (CVC). Hasil simulasi menunjukkan bahawa VSF-MPWM dapat mengurangkan sehingga 35.4% kehilangan pensuisan dan 23.8% kehilangan kuasa dibandingkan dengan konvensional PWM. Sementara itu, VSF-MPWM dapat mengekalkan kualiti arus keluaran yang sama dengan konvensional PWM.

ABSTRACT

With the increasing demand for reduced emissions and improved fuel economy, the automakers are focusing on the development of electric vehicles (EVs). The performance requirements for EVs includes high driving range and long life of its components. The power converters are among the most stressed and less reliable EV drivetrain components. Hence, improving the lifetime of the power converters is essential for the success of EV adoption. The lifetime of the power converters can be improved by reducing thermal stress of the power devices, which represents the main cause of failure. Since the temperature and power losses of the power device are proportional, thermal stress can be reduced by minimizing the power losses. In addition to the lifetime improvement, minimizing the power losses of the power converters can extend the EV range since the power demand under a given loading conditions is reduced. In this regard, this thesis aims to study the impact of an existing power loss reduction technique known as variable dc-bus voltage control (VVC) on the inverter lifetime. In addition, it proposes a new pulse width modulation (PWM) strategy called variable switching frequency modified PWM (VSF-MPWM) for three-phase two-level voltage source inverter. The VSF-MPWM aims to minimize the inverter power losses, but without sacrificing the output current quality. In order to study the impact of the VVC on the inverter lifetime, a lifetime estimation method is first presented. This method uses the Artemis urban and US06 driving cycles in order to obtain the thermal loading, and consequently the lifetime consumption of the inverter power devices. Then, the VSF-MPWM is proposed, which minimizes the switching loss by clamping any of the three-phase legs at the phase current peak and by reducing the number of commutations through variable switching frequency. However, in order to achieve an acceptable current quality, the proposed VSF-MPWM controls both the clamping period and the switching frequency according to the current quality constraints of the conventional PWM strategy. The impact of the VVC on the inverter lifetime and the performance of the proposed VSF-MPWM on the inverter power losses and current quality are investigated through MATLAB Simulink. The lifetime analysis reveals that the VVC has the ability to improve the lifetime of the inverter by a factor of 5.06 and 3.43 under Artemis urban and US06 driving cycles, respectively, compared to the conventional constant dc-bus voltage control (CVC). On the other hand, the simulation result shows that the proposed VSF-MPWM can save up to 35.4 % and 23.8 % of switching and power losses, respectively, compared to the conventional PWM. Meanwhile, the VSF-MPWM can obtain the same output current quality as that of the conventional PWM.

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LIST OF SYMBOLS

α	Grade angle
M	Mass
v	Velocity
F_t	Tractive effort
F_R	Resisting forces
F_r	Rolling resistance
C_r	Rolling resistance coefficient
g	Gravitational acceleration
F_{ad}	Aerodynamic drag
ρ	Air density
C_d	Aerodynamic drag coefficient
A_f	Vehicle frontal area
F_g	Grade resistance
T	Motor torque
ω_m	Mechanical speed
i_g	Gear ratio of the gearbox
i_o	Differential gear ratio
r_d	Radius of the wheel
η_t	Transmission efficiency
d, q	Axis in the rotating reference frame.
V_{ds}, V_{qs}	Stator voltages in the *d*-*q* reference frame
i_{ds}, i_{qs}	Stator currents in the *d*-*q* reference frame
L_{ds}, L_{qs}	Winding inductances in the *d*-*q* reference frame
R_s	Stator resistance
P	Number of pole pairs
ψ_{pm}	Rotor flux produced by the permanent magnets
ω_m^*	Reference mechanical speed
T^*	Reference motor torque
i_{ds}^*, i_{qs}^*	Reference stator currents in the *d*-*q* reference frame
V_{ds}^*, V_{qs}^*	Reference stator voltages in the *d*-*q* reference frame
θ_m	Rotor position

V_{as}^{*}, V_{bs}^{*}, V_{cs}^{*}	Reference stator voltages in the *abc* reference frame
S_a, S_b, S_c	gating signals of the inverter
Δi_{ds}^{*}	Extra negative *d*-axis current for flux weakening
ω_{base}	Base speed
$V_{s\text{-}limit}$	Stator voltage limit
V_s^{*}	Reference stator voltage
$i_{s\text{-}limit}$	Stator current limit
n	Negative dc-bus
V_{dc}	Dc-bus voltage
S_1	Upper inverter switch of phase-*a*
S_4	Lower inverter switch of phase-*a*
V_{an}	Voltage from phase-*a* to the negative dc-bus
V_o	Output voltage vector of the inverter
V_1	Active voltage vector V_1 (100)
V_2	Active voltage vector V_2 (110)
V_0	Zero voltage vector V_0 (000)
V_7	Zero voltage vector V_7 (111)
V_{ref}	Reference voltage vector
θ	Position of the reference voltage vector
T_s	Sub-cycle duration
T_1	Dwell time of active voltage vector V_1
T_2	Dwell time of active voltage vector V_2
T_3	Dwell time of the two zero voltage vector V_0 and V_7
T_{sw}	Switching cycle duration
m_{tri}	Triangular carrier
f_{sw}	Switching frequency
m_{cmv}	Common mode voltage signal
m_{as}^{*}, m_{bs}^{*}, m_{cs}^{*}	Modulating signals of the inverter
I_1	RMS value of the fundamental current
I_n	RMS value of the *nth* harmonic current component
I_r	Current ripple
L_s	Equivalent stator winding inductance
V_Z	Applied voltage vector

N_f	Number of cycles to failure
T_{jm}	Mean junction temperature
ΔT_j	Thermal cycle amplitude
K_b	Boltzmann constant
E_a	Activation energy
a_1, a_2	Experimentally determined factors for lifetime estimation
n_i	Number of cycles at a certain stress level (T_{jm} and ΔT_j)
N_{fi}	Number of cycles to failure at a certain stress level (T_{jm} and ΔT_j)
LC	Accumulated damage
T_j	Power device junction temperature profile
Z_{j-c}	Junction to case thermal impedance
Z_{c-h}	Case to heat sink thermal impedance
Z_{h-a}	Heat sink to ambient thermal impedance
T_h	Temperature of the heat sink
T_a	Temperature of the ambient
R	Resistance
C	Capacitance
P_{loss}	Total losses of a power device
S_{up}	Upper inverter switch
$P_{C,T}$ (S_{up})	Conduction loss of an IGBT in an upper inverter switch
$P_{C,D}$ (S_{up})	Conduction loss of an FWD in an upper inverter switch
V_{ce}	IGBT on-state voltage drop
V_F	FWD on-state voltage drop
$T_{j,T}$	IGBT junction temperature
$T_{j,D}$	FWD junction temperature
i_{xs}	Stator phase current
d_{xs} (S_{up})	Duty ratio of an upper inverter switch
$P_{sw,T}$ (S_{up})	Switching loss of an IGBT in an upper inverter switch
$P_{sw,D}$ (S_{up})	Switching loss of an FWD in an upper inverter switch
E_{on}	IGBT turn on energy loss
E_{off}	IGBT turn off energy loss
E_{rr}	FWD reverse recovery energy loss
V_{dc-ref}	Reference dc-bus voltage in the manufacturer datasheet

p	Positive dc-bus
f_{nom}	Nominal switching frequency
I_{rp}	Peak current ripple over a fundamental cycle for the CSVPWM
I_{rms}	RMS current ripple over a fundamental cycle for the CSVPWM
V_B	Battery voltage
V_R	Rated dc-bus voltage
P_o	Motor output power
V_{dc}^*	Reference dc-bus voltage
D	gating signal of the dc-dc converter
V_{xs}	Stator phase voltage
t	Time
O	Origin point (0,0)
q_{y}, d_{y}	Corner points of Current ripple trajectory
$T_{s,nom}$	Nominal sub-cycle duration
$I^2_{\mathrm{(sequence)}}$	RMS current ripple over a sub-cycle for a switching sequence
$I^2_{\mathrm{(CSVPWM)}}$	RMS current ripple over a sub-cycle for the CSVPWM
$I^2_{\mathrm{(DPWM)}}$	RMS current ripple over a sub-cycle for the DPWM
i_{as}^*, i_{bs}^*, i_{cs}^*	Reference stator currents in the *abc* reference frame
K_f	Switching frequency coefficient

LIST OF ABBREVIATIONS

ICE	Internal combustion engine
EV	Electric vehicle
dc	Direct current
ac	Alternating current
PWM	Pulse width modulation
VVC	Variable dc-bus voltage control
CVC	Constant dc-bus voltage control
CSVPWM	Conventional space vector pulse width modulation
DPWM	Discontinuous pulse width modulation
VSF	Variable switching frequency
VSF-MPWM	Variable switching frequency modified pulse width modulation
PMSM	Permanent magnet synchronous motor
EMF	Back-electromotive force
MTPA	Maximum torque per ampere
FW	Flux weakening
MMF	Magnetomotive force
VSI	Voltage source inverter
CBPWM	Carrier based pulse width modulation
CCBPWM	Conventional carrier based pulse width modulation
CTHD	Current total harmonic distortion
RMS	Root mean square
Si	Silicon
DBC	Direct bonded copper
Cu	Copper
Al	Aluminium
CTE	Coefficient of thermal expansion
IGBT	Insulated gate bipolar transistor
FWD	Freewheeling diode
DPWM1	DPWM with clamping duration at the voltage reference peak
DPWM0	DPWM with clamping duration shifted by -30° with respect to DPWM1

DPWM2	DPWM with clamping duration shifted by +30° with respect to DPWM1
HP-PWM	High performance- pulse width modulation
ADPWM	Advanced discontinuous pulse width modulation
EMI	conducted electromagnetic interference
USV-RPWM	Universal space vector-random pulse width modulation
CSF	Constant switching frequency
VSF1	VSF using peak current ripple requirement
VSF2	VSF using RMS current ripple requirement
VSFSVPWM	Variable switching frequency space vector pulse width modulation
SPMSM	Surface permanent magnet synchronous motor
LUT	Lookup table
WBG	Wide bandgap
SiC	Silicon Carbide
GaN	Gallium Nitride

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