DESIGN AND CONTROL OF PMSM DRIVE FOR LIGHT EV WITH SOLAR PV INTEGRATION

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by

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Submitted
in fulfilment of the requirements of the degree of Doctor of Philosophy

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Dedicated to

my beloved Parents

and

to the memory of my Grandparents

CERTIFICATE

This is to certify that the thesis entitled, **"Design and Control of PMSM Drive for Light EV with Solar PV Integration"** being submitted by **Mr. Sreejith R.** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Sreejith R. has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained here in have not been submitted to any other University or Institute for the award of any degree.

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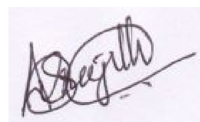

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Sreejith Raveendran

ABSTRACT

With ever increasing energy consumption, volatile crude oil prices, global warming and consequent climate change concerns, both Government organizations as well as Industries globally are heavily pitching for the implementation of electric and hybrid electric vehicles. However, due to lack of ample charging infrastructure, which needs huge initial capital investments and development time, the acceptance of electric vehicles (EVs) are going on in a slow pace in India. Out of the various EV segments, light electric vehicles (LEVs) such as e-rickshaws and e-autorickshaws are an attractive and affordable EV segment in Asian countries such as India. Although there are Govt. efforts for developing indigenous products, the power train components are mostly imported without proper design, sizing and selection catering to the needs of Indian terrain and climatic conditions.

In fact, there is currently no universal international standard developed for arriving at the motor and battery size rating for an EV. This can lead to massive blow to the EV targets both technologically and economically if proper ratings are not selected as per the requirement. Therefore, a detailed methodology is developed for the optimal size selection of propulsion motor and battery ratings for an EV without under-rating or over-rating of the machine. Further, comparative analysis is carried out for lead acid and Li-ion based LEVs with and without gear for Indian Drive Cycle. Furthermore, a feasibility study is conducted for solar PV array based three wheeler EVs and found out that these systems are highly feasible and can contribute enough power for motor propulsion at steady state operation. The payback period of such system is less compared to the conventional LEVs.

Currently, light EVs are mostly driven by brushed DC motors, induction motors and per-

manent magnet brushless DC motors. As these motors suffer setback due to various drawbacks, six different surface mounted permanent magnet synchronous motors (SPMSM) based low voltage and interior PMSM (IPMSM) based high voltage LEV configurations with and without solar PV array are proposed in this research work. These high performance drives are operated in online MTPA control for high efficiency while eliminating the mechanical position sensors for improved reliability, compactness and cost-effectiveness. Different low computational high performance sliding mode observer techniques are proposed for wide speed range closed loop sensorless control operation of the drive. These methods have achieved the superior performance compared to the conventional back-EMF and sliding mode control techniques available for the rotor speed and position estimation. Nonetheless, the proposed sensorless control strategies are useful and well applicable for variable speed domestic and industrial electric drive applications too.

Maximum power point tracking control is utilized in solar PV array assisted LV and HV configurations for extracting optimum power under varying atmospheric conditions. Along with the solar power, regenerative braking feature is utilized in all the configurations for improving the vehicle range and to increase the battery life cycle. Therefore, the proposed PMSM based LEV configurations with the aforesaid mentioned features lead to a zero carbon emission true EV. All the designed LEV configurations and their control algorithms are modelled, simulated and analyzed in the MATLAB/Simulink environment and experimentally validated using the laboratory hardware prototype. Detailed discussion on their control performance and efficacy during starting, steady state and dynamic drive operating conditions are presented in this research work.

सार

लगातार बढ़ती ऊर्जा खपत के साथ, कच्चे तेल की अस्थिर कीमतें, ग्लोबल वार्मिंग और परिणामी जलवायु परिवर्तन संबंधी सरोकार, सरकारी संगठन और उद्योग दोनों वैश्विक स्तर पर इलेक्ट्रिक और हाइब्रिड इलेक्ट्रिक वाहनों के कार्यान्वयन के लिए भारी जोर दिया जा रहा है। हालांकि, पर्याप्त चार्जिंग इंफ्रास्ट्रक्चर की कमी के कारण, जिसके लिए बड़ी प्रारंभिक पूंजी की आवश्यकता होती है निवेश और विकास का समय, इलेक्ट्रिक वाहनों (ईवी) की स्वीकृति जारी है भारत में धीमी गति से। विभिन्न ईवी खंडों में से, हल्के इलेक्ट्रिक वाहन (एलईवी) जैसे कि ई-रिक्शा और ई-ऑटोरिक्शा भारत में एक आकर्षक और किफायती ईवी सेगमेंट हैं भारत जैसे एशियाई देश। हालांकि सरकार हैं। स्वदेशी विकसित करने के प्रयास उत्पादों, पावर ट्रेन घटकों को ज्यादातर उचित डिजाइन, आकार के बिना आयात किया जाता है और चयन भारतीय भूभाग और जलवायु परिस्थितियों की जरूरतों को पूरा करता है।

वास्तव में, वर्तमान में आने के लिए कोई सार्वभौमिक अंतरराष्ट्रीय मानक विकसित नहीं किया गया है ईवी के लिए मोटर और बैटरी आकार रेटिंग पर। इससे ईवी को भारी झटका लग सकता है तकनीकी और आर्थिक रूप से दोनों लक्ष्यों को लक्षित करता है यदि उचित रेटिंग के अनुसार चयन नहीं किया जाता है मांग। इसलिए, इष्टतम आकार चयन के लिए एक विस्तृत कार्यप्रणाली विकसित की गई है बिना रेटिंग या ओवर-रेटिंग के ईवी के लिए प्रणोदन मोटर और बैटरी रेटिंग का यंत्र। इसके अलावा, लेड एसिड और ली-आयन आधारित के लिए तुलनात्मक विश्लेषण किया जाता है भारतीय ड्राइव साइकिल के लिए गियर के साथ और बिना एलईवी। इसके अलावा, एक व्यवहार्यता अध्ययन है सौर पीवी सरणी आधारित तिपहिया वाहनों के लिए आयोजित किया गया और पता चला कि ये प्रणालियां अत्यधिक व्यवहार्य हैं और स्थिर अवस्था में मोटर प्रणोदन के लिए पर्याप्त शक्ति का योगदान कर सकते हैं कार्यवाही। ऐसी प्रणाली की वापसी अवधि पारंपरिक एलईवी की तुलना में कम है।

वर्तमान में, हल्के ईवी ज्यादातर ब्रश डीसी मोटर्स, इंडक्शन मोटर्स और स्थायी चुंबक ब्रशलेस डीसी मोटर्स द्वारा संचालित होते हैं। चूंकि इन मोटरों को विभिन्न कमियों के कारण झटका लगता है, इसलिए इस शोध कार्य में छह अलग-अलग सतह पर लगे स्थायी चुंबक तुल्यकालिक मोटर्स (एसपीएमएसएम) आधारित कम वोल्टेज और आंतरिक पीएमएसएम (आईपीएमएसएम) आधारित उच्च वोल्टेज एलईवी विन्यास सौर पीवी सरणी के साथ और बिना प्रस्तावित हैं। ये उच्च प्रदर्शन ड्राइव उच्च दक्षता के लिए ऑनलाइन एमटीपीए नियंत्रण में संचालित होते हैं जबकि बेहतर विश्वसनीयता, कॉम्पैक्टनेस और लागत-प्रभावशीलता के लिए यांत्रिक स्थिति सेंसर को समाप्त करते हैं। विभिन्न कम कम्प्यूटेशनल उच्च प्रदर्शन स्लाइडिंग मोड पर्यवेक्षक तकनीक प्रस्तावित हैं वाइड स्पीड रेंज के लिए ड्राइव के बंद लूप सेंसरलेस कंट्रोल ऑपरेशन। रोटर गति और स्थिति आकलन के लिए उपलब्ध पारंपरिक बैक-ईएमएफ और स्लाइडिंग मोड नियंत्रण तकनीकों की तुलना में इन विधियों ने बेहतर प्रदर्शन हासिल किया है। बहरहाल, प्रस्तावित सेंसर रहित नियंत्रण रणनीतियाँ उपयोगी हैं और परिवर्तनीय गति घरेलू और औद्योगिक इलेक्ट्रिक ड्राइव अनुप्रयोगों के लिए भी लागू हैं।

अधिकतम पावर प्वाइंट ट्रैकिंग नियंत्रण का उपयोग सौर पीवी सरणी सहायता प्राप्त एलवी और एचवी विन्यास में अलग-अलग वायुमंडलीय परिस्थितियों में इष्टतम शक्ति निकालने के लिए किया जाता है। सौर ऊर्जा के साथ, सभी विन्यासों में पुनर्योजी ब्रेकिंग सुविधा का उपयोग किया जाता है वाहन रेंज में सुधार और बैटरी जीवन चक्र को बढ़ाने के लिए। इसलिए, उपरोक्त उल्लिखित विशेषताओं के साथ प्रस्तावित पीएमएसएम आधारित एलईवी

विन्यास शून्य कार्बन उत्सर्जन वास्तविक ईवी की ओर ले जाता है। सभी डिज़ाइन किए गए हल्का इलेक्ट्रिक वाहन कॉन्फ़िगरेशन और उनके नियंत्रण एल्गोरिदम को मैटलैब/सिमुलिंक वातावरण में मॉडलिंग, नकली और विश्लेषण किया गया है और प्रयोगशाला हार्डवेयर प्रोटोटाइप का उपयोग करके प्रयोगात्मक रूप से मान्य किया गया है। प्रारंभ, स्थिर स्थिति और गतिशील के दौरान उनके नियंत्रण प्रदर्शन और प्रभावकारिता पर विस्तृत चर्चा इस शोध कार्य में ड्राइव ऑपरेटिंग परिस्थितियों को प्रस्तुत किया गया है।

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog to Digital Converter
ARAI	Automotive Research Association of India
BDC	Bidirectional DC-DC Converter
CPSR	Constant Power Speed Range
DC	Direct Current
DSOGI-FLL	Dual Second Order Generalized Integrator-Frequency Locked Loop
DSP	Digital Signal Processor
DTC	Direct Torque Control
EMF	Electro Motive Force
EUDC	Extra Urban Driving Cycle
FOC	Field Oriented Control
FOCV	Fractional Open Circuit Voltage
FTP-75	Federal Test Procedure-75
FFT	Fast Fourier Transform
GUUB	Globally Uniformly Utimately Boundedness
HFI	High Frequency Injection
HV	High Voltage
ICE	Internal Combustion Engine
IEEE	Institute of Electrical and Electronics Engineers
IM	Induction Machine
INC	Incremental Conductance
IPMSM	Interior Permanent Magnet Synchronous Motor
KF	Kalman Filter
LCF	Lyapunov Candidate Function
LEV	Light Electric Vehicle
LPF	Low Pass Filter
LV	Low Voltage

MAF	Moving Average Filter
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MRAC	Model Reference Adaptive Control
MTPA	Maximum Torque Per Ampere
NEDC	New European Driving Cycle
NVH	Noise Vibration and Harshness
PI	Proportional Integral
PMSyRM	Permanent Magnet Synchronous Reluctance Motor
PLL	Phase Locked Loop
PV	Solar Photovoltaic
P and O	Perturb and Observe
QPLL	Quadrature Phase Locked Loop
RBS	Regenerative Braking System
SASTSMO	Speed Adaptive Super Twisting Sliding Mode Observer
SMO	Sliding Mode Observer
SOC	State of Charge
SOGI	Second Order Generalized Integrator
SPMSM	Surface Mounted Permanent Magnet Synchronous Motor
SRF	Synchronous Reference Frame
SRM	Switched Reluctance Motor
VRLA	Valve Regulated Lead Acid
VSI	Voltage Source Inverter
WLTP	Worldwide Harmonized Light Vehicle Test Procedure

LIST OF SYMBOLS

a	Over loading factor
C	DC bus capacitor (F)
D	Duty cycle of boost converter
D_b	Duty ratio of BDC
e_{vdc}	DC-link voltage error
e_α, e_β	$\alpha - \beta$ back-EMF components at DSOGI-FLL output (V)
f_{sw}	switching frequency (Hz)
F_s	Sampling frequency (kHz)
f_{se}	Series compensator switching frequency (kHz)
G	Solar PV irradiance (W/m^2)
GR	Gear ratio
H_a, H_b, H_c	Hall-Effect signals
I_b	Battery current (A)
I_b	Battery current (A)
I_α, I_β	Three phase motor currents in $\alpha - \beta$ domain (A)
i_a, i_b, i_c	Motor three phase currents (A)
i_d, i_q	Actual motor phase currents in d-q domain (A)
i_d^*, i_q^*	Reference motor phase currents in d-q domain (A)
I_{pv}	PV array current (A)
I_{mpp}	PV array maximum power point current (A)
I_{sc}	PV array short circuit current (A)
k_1	Variation of energy in dynamics
K_{sv}	IGBT Switch voltage safety factor
K_{sI}	IGBT Switch voltage safety factor
K_p,K_i	Gains of DC-link voltage PI controller
K_{pv}, K_{iv}	PI controller gains of BDC current controller
L_d, L_q	Direct axis and quadrature axis IPMSM phase inductance (H)
L_p	Solar PV array boost inductor (H)
L_b	BDC inductor (H)
k	Sampling instant
N_{act}	Actual motor speed (RPM)
N_{est}	Estimated motor speed (RPM)
N_{ref}	Reference motor speed (RPM)
P	Number of poles

P_{pv}	PV array power (W)
P_{mpp}	PV array power at MPP (W)
s	Laplace operator
T_L	Load torque (N.m)
T_{ref}	Reference torque (N.m)
T_s	Sampling time (s)
N_w	Window length of moving average filter (s)
v	Linear velocity (ms^{-1})
V_b	Battery voltage (V)
V_{dc}	DC-link voltage (V)
V_{dc}^*	Reference DC-link voltage (V)
v_α, v_β	Three phase motor terminal voltages in $\alpha - \beta$ domain (V)
V_{Ld}^*, V_{Lq}^*	Three phase load reference voltages in $d - q$ domain (V)
V_{mpp}	PV array maximum power point voltage (V)
V_{oc}	PV array open circuit voltage (V)
V_{pv}	PV array voltage (V)
$v_{\alpha-\beta}$	Voltage vector in $\alpha - \beta$ domain (V)
Z	Z-domain operator
z_α, z_β	$\alpha - \beta$ back-EMF components at prefilter output (V)
V_{derr}	DC-link voltage error
ΔP_{pv}	Change in PV array power
ΔD	Duty cycle step size
θ_{ref}	Reference rotor position (rad)
θ_{est}	Estimated rotor position (rad)
θ_{error}	Error between estimated rotor position and reference rotor position (rad)
ω_{ref}	Reference speed (rad/s)
ω_{est}	Estimated speed (rad/s)
ω_{ff}	Feedforward speed factor(rad/s)
ω_c	Cut-off frequency of LPF (rad/s)
Ψ_{PM}	Permanent magnet flux linkage (V.s)
λ_1,λ_1	Speed adaptive gains of SASTSMO
Γ	Gain of FLL