

CONTROL OF POSITION SENSORLESS PMSLDC MOTOR DRIVE FOR SOLAR-PV ASSISTED LIGHT ELECTRIC VEHICLES

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DRIVE FOR SOLAR-PV ASSISTED LIGHT ELECTRIC
VEHICLES**

by

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This thesis is dedicated to my parents.

For their endless love, support and encouragement

CERTIFICATE

This is to certify that the thesis entitled, “**CONTROL OF POSITION SENSORLESS PMBLDC MOTOR DRIVE FOR SOLAR-PV ASSISTED LIGHT ELECTRIC VEHICLES**” being submitted by **Mr. Biswajit Saha** 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. Biswajit Saha 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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ABSTRACT

The rapid urbanization and industrialization of modern society have led to a significant rise in energy consumption and environmental pollution, primarily due to the extensive use of fossil fuel-powered transportation. To address the growing concerns over climate change, greenhouse gas emissions, and the depletion of non-renewable energy resources, the global automotive industry is undergoing a paradigm shift toward Electric Vehicles (EVs). Range anxiety” is a major obstacle to the rapid adoption of EVs, and drivers' fear about being stranded with insufficient range to reach the destination.

However, the adoption of EVs, particularly in the category of Light Electric Vehicles (LEVs) such as e-rickshaws, scooters, and small delivery vehicles, is often constrained by limited battery range, long charging times, and insufficient charging infrastructure. To overcome these limitations, integrating Solar Photovoltaic (PV) systems with EVs has emerged as a promising solution. Solar-PV-assisted EVs can harness clean, renewable energy directly from the sun to charge their batteries, thus reducing reliance on grid electricity and enabling energy autonomy, especially in remote or off-grid areas. This makes the system not only more sustainable but also economically attractive in regions with abundant sunlight.

The heart of any EV lies in its electric drivetrain, and among various motor technologies available, the Permanent Magnet Brushless DC (PMBLDC) motor stands out as an ideal choice for LEVs. PMBLDC motors are known for their high efficiency, compact size, low maintenance, and excellent torque-speed characteristics. These features make them particularly well-suited for the frequent start-stop cycles and variable load conditions typical in urban driving environments.

Despite their advantages, conventional PMBLDC motor drives rely on position sensors like Hall-Effect sensors to detect rotor position for proper commutation. These sensors increase system cost, reduce reliability (especially under harsh environmental conditions), and add to mechanical complexity. To address these challenges, position sensorless control techniques have been developed. By estimating rotor position from the motor's back Electromotive Force (back-EMF), these methods eliminate the need for physical sensors, enhancing system robustness and reducing costs.

This research presents the analysis, design, and control of various configurations of solar photovoltaic (PV)-assisted brushless DC (BLDC) motor drives with advanced motor control algorithms for light electric vehicles (LEVs). Comprehensive modelling and control of BLDC motor drives are performed with an emphasis on automotive applications, incorporating regenerative braking strategies to alleviate range anxiety by enhancing energy recovery during deceleration. Dual-stage solar-PV assisted BLDC motor drives are investigated, employing multiple DC–DC converter topologies with maximum power point tracking (MPPT) control, and their performance is compared through simulation and experimental validation. In parallel, single-stage solar-PV assisted drive configurations are developed to eliminate intermediate DC–DC converters, thereby reducing system cost and complexity. A position sensorless control scheme is implemented using advanced observer-based estimation techniques to accurately determine rotor position and speed with minimal offset and delay, eliminating the need for Hall-effect sensors. Furthermore, an ultra-low-speed sensorless starting method and a wide-speed range control scheme are proposed to improve startup performance and ensure smooth operation across the entire automotive speed spectrum. To address inherent torque pulsations, a novel torque ripple mitigation strategy is integrated within the sensorless control framework, providing an efficient and complete drive solution for EV applications. Multiple DC–DC converter designs are developed, and a detailed comparative performance analysis is conducted using both simulation and hardware implementation results. The proposed integrated approach—combining renewable energy integration, advanced control strategies, and optimized power electronics—offers a cost-effective, efficient, and reliable solar-PV assisted BLDC motor drive solution tailored for next-generation light electric vehicles.

सारांश

आधुनिक समाज के तीव्र शहरीकरण और औद्योगीकरण ने ऊर्जा खपत और पर्यावरण प्रदूषण में उल्लेखनीय वृद्धि की है, मुख्यतः जीवाश्म ईंधन-चालित परिवहन के व्यापक उपयोग के कारण। जलवायु परिवर्तन, ग्रीनहाउस गैस उत्सर्जन, और गैर-नवीकरणीय ऊर्जा संसाधनों की कमी को लेकर बढ़ती चिंताओं का समाधान करने के लिए, वैश्विक ऑटोमोबाइल उद्योग इलेक्ट्रिक वाहनों (EVs) की ओर एक मौलिक परिवर्तन कर रहा है। “रेंज चिंता” EVs के तीव्र अपनाने में एक प्रमुख बाधा है, और चालकों का डर कि वे गंतव्य तक पहुँचने के लिए अपर्याप्त रेंज के साथ फँस सकते हैं।

हालाँकि, EVs का अपनाना, विशेष रूप से हल्के इलेक्ट्रिक वाहनों (LEVs) जैसे ई-रिक्शा, स्कूटर और छोटे डिलीवरी वाहनों की श्रेणी में, अक्सर सीमित बैटरी रेंज, लंबे चार्जिंग समय और अपर्याप्त चार्जिंग अवसंरचना से बाधित होता है। इन सीमाओं को दूर करने के लिए, इलेक्ट्रिक वाहनों के साथ सौर फोटोवोल्टाइक (PV) प्रणालियों का एकीकरण एक आशाजनक समाधान के रूप में उभरा है। सौर-PV-सहायता प्राप्त EVs सीधे सूर्य से स्वच्छ, नवीकरणीय ऊर्जा प्राप्त कर अपनी बैटरियों को चार्ज कर सकते हैं, जिससे ग्रिड बिजली पर निर्भरता कम होती है और विशेष रूप से दूरस्थ या ऑफ-ग्रिड क्षेत्रों में ऊर्जा स्वायत्तता सक्षम होती है। यह प्रणाली को न केवल अधिक टिकाऊ बनाता है बल्कि प्रचुर धूप वाले क्षेत्रों में आर्थिक रूप से भी आकर्षक बनाता है।

किसी भी EV का हृदय उसका इलेक्ट्रिक ड्राइवट्रेन होता है, और उपलब्ध विभिन्न मोटर तकनीकों में, स्थायी चुंबक ब्रशलेस DC (PMBLDC) मोटर हल्के इलेक्ट्रिक वाहनों के लिए एक आदर्श विकल्प के रूप में उभरता है। PMBLDC मोटर अपनी उच्च दक्षता, कॉम्पैक्ट आकार, कम रखरखाव और उत्कृष्ट टॉर्क-गति विशेषताओं के लिए जाने जाते हैं। ये विशेषताएँ उन्हें शहरी ड्राइविंग वातावरण में सामान्य बार-बार स्टार्ट-स्टॉप चक्रों और परिवर्तनीय लोड स्थितियों के लिए विशेष रूप से उपयुक्त बनाती हैं।

उनके लाभों के बावजूद, पारंपरिक PMBLDC मोटर ड्राइव उचित कम्प्यूटेशन के लिए रोटार स्थिति का पता लगाने हेतु हॉल-इफ़ेक्ट सेंसर जैसे स्थिति सेंसरों पर निर्भर करते हैं। ये सेंसर प्रणाली की लागत बढ़ाते हैं, विश्वसनीयता कम करते हैं (विशेष रूप से कठोर पर्यावरणीय परिस्थितियों में), और यांत्रिक जटिलता जोड़ते हैं। इन चुनौतियों का समाधान करने के लिए, स्थिति सेंसरलेस नियंत्रण तकनीकें विकसित की गई हैं। मोटर के बैक इलेक्ट्रोमोटिव फोर्स (back-EMF) से रोटार स्थिति का अनुमान लगाकर, ये विधियाँ भौतिक सेंसरों की आवश्यकता को समाप्त करती हैं, प्रणाली की मजबूती बढ़ाती हैं और लागत कम करती हैं।

यह शोध हल्के इलेक्ट्रिक वाहनों (LEVs) के लिए उन्नत मोटर नियंत्रण एल्गोरिदम के साथ सौर फोटोवोल्टाइक (PV)-सहायता प्राप्त ब्रशलेस DC (BLDC) मोटर ड्राइव के विभिन्न विन्यासों का विश्लेषण, डिज़ाइन और नियंत्रण प्रस्तुत करता है। BLDC मोटर ड्राइव का व्यापक मॉडलिंग और नियंत्रण ऑटोमोटिव अनुप्रयोगों पर जोर देते हुए किया गया है, जिसमें मंदी के दौरान ऊर्जा पुनर्प्राप्ति को बढ़ाकर रेंज चिंता को कम करने के लिए पुनर्योजी ब्रेकिंग रणनीतियाँ शामिल हैं। द्वि-स्तरीय सौर-PV-सहायता प्राप्त BLDC मोटर ड्राइव की जाँच की गई है, जिसमें अधिकतम शक्ति बिंदु ट्रैकिंग (MPPT) नियंत्रण के साथ कई DC-DC कन्वर्टर टोपोलॉजी का उपयोग किया गया है, और उनके प्रदर्शन की तुलना सिमुलेशन और प्रायोगिक सत्यापन के माध्यम से की गई है। समानांतर में, एकल-स्तरीय सौर-PV-सहायता प्राप्त ड्राइव विन्यास विकसित किए गए हैं ताकि मध्यवर्ती DC-DC कन्वर्टर को समाप्त किया जा सके, जिससे प्रणाली की लागत और जटिलता कम हो।

एक स्थिति सेंसरलेस नियंत्रण योजना उन्नत ऑब्ज़र्वर-आधारित अनुमान तकनीकों का उपयोग करके लागू की गई है ताकि न्यूनतम ऑफ़सेट और विलंब के साथ रोटार स्थिति और गति को सटीक रूप से निर्धारित किया जा सके, जिससे हॉल-इफ़ेक्ट सेंसर की आवश्यकता समाप्त हो जाती है। इसके अलावा, एक अल्ट्रा-लो-स्पीड सेंसरलेस स्टार्टिंग विधि और एक व्यापक गति सीमा नियंत्रण योजना प्रस्तावित की

गई है ताकि स्टार्टअप प्रदर्शन में सुधार हो और पूरे ऑटोमोटिव गति स्पेक्ट्रम में सुचारू संचालन सुनिश्चित हो सके। अंतर्निहित टॉर्क स्पंदनों को संबोधित करने के लिए, सेंसरलेस नियंत्रण ढाँचे के भीतर एक नवीन टॉर्क रिपल शमन रणनीति को एकीकृत किया गया है, जो EV अनुप्रयोगों के लिए एक कुशल और पूर्ण ड्राइव समाधान प्रदान करता है।

कई DC-DC कन्वर्टर डिज़ाइन विकसित किए गए हैं, और सिमुलेशन और हार्डवेयर कार्यान्वयन परिणामों का उपयोग करके एक विस्तृत तुलनात्मक प्रदर्शन विश्लेषण किया गया है। प्रस्तावित एकीकृत दृष्टिकोण—नवीकरणीय ऊर्जा एकीकरण, उन्नत नियंत्रण रणनीतियों और अनुकूलित पावर इलेक्ट्रॉनिक्स को संयोजित करके—अगली पीढ़ी के हल्के इलेक्ट्रिक वाहनों के लिए एक किफायती, कुशल और विश्वसनीय सौर-PV-सहायता प्राप्त BLDC मोटर ड्राइव समाधान प्रदान करता है।

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LIST OF ABBREVIATIONS

ABS	Anti-lock Braking System
ADC	Analog-to-Digital Converter
AI	Artificial Intelligence
ANN	Artificial Neural Network
ASMO	Adaptive Sliding Mode Observer
BDC	Bi-Directional Converter
BMS	Battery Management System
BLDC	Brushless DC
BLDCM	Brushless DC Motor
CCF-PLL	Complex-Coefficient-Filter-based Phase-Locked Loop
CCM	Continuous Conduction Mode
CLP	Connector LED Panel
CSC	Canonical Switching Cell
DAC	Digital-to-Analog Converter
DC	Direct Current
DCM	Discontinuous Conduction Mode
DOB	Disturbance Observer
DSP	Digital Signal Processor
DSOGI-PLL	Dual Second-Order Generalized Integrator Phase-Locked Loop
EKF	Extended Kalman Filter
EMF	Electromotive Force
EMI	Electromagnetic Interference
EV	Electric Vehicle
FDF	Fixed Delay Filter
FLC	Fuzzy Logic Controller
HFSI	High-Frequency Signal Injection
ICE	Internal Combustion Engine
IGBT	Insulated-Gate Bipolar Transistor
InC	Incremental Conductance
IPM	Interior Permanent Magnet
LEV	Light Electric Vehicle
LPF	Low-Pass Filter
MAF	Moving Average Filter
ML	Machine Learning
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MRAS	Model Reference Adaptive System
P&O	Perturb and Observe
PCB	Printed Circuit Board
PI	Proportional-Integral
PLL	Phase-Locked Loop
PM	Permanent Magnet
PMBLDC	Permanent Magnet Brushless DC

PWM	Pulse Width Modulation
PV	Photovoltaic
QPLL	Quadrature Phase-Locked Loop
QSG	Quadrature Signal Generator
RLS	Recursive Least Squares
RPM	Revolutions Per Minute
SEPIC	Single-Ended Primary-Inductor Converter
SMO	Sliding Mode Observer
SOC	State of Charge
SPMSM	Surface-Mounted Permanent Magnet Synchronous Motor
SRF-PLL	Synchronous Reference Frame Phase-Locked Loop
STA	Super-Twisting Algorithm
STC	Standard Test Conditions
THD	Total Harmonic Distortion
VMC	Voltage Multiplier Cell
VSI	Voltage Source Inverter
ZCD	Zero-Crossing Detection
ZCP	Zero-Crossing Point

LIST OF SYMBOLS

V, v	Voltage	(V)
I, i	Current	(A)
R, r	Resistance	(Ω)
$L,$	Inductance	Henry (H)
M	Mutual Inductance	Henry (H)
C, c	Capacitance	Farad (F)
ω, ω_r	Angular Speed / Frequency	rad/s
F, f	Frequency	Hertz (Hz)
T, T_e	Torque (Electromagnetic)	Newton-meter (Nm)
N	Rotational Speed	RPM
P	Power	Watt (W)
D, d	Duty Cycle	
t_{on}, t_{off}	On-time, Off-time	Seconds (s)
f_{sw}	Switching Frequency	Hertz (Hz)
λ	Flux Linkage	Weber (Wb)
K_p, K_i	Proportional and Integral gains	
T_s	Sampling Time	
K, K_1, K_2	Observer / Sliding Mode gains	
ε	Error signal	
σ	Sliding surface / Equivalent control signal	
H	Lyapunov function candidate	

k	Damping factor (e.g., in SOGI)	
ω_c	Cut-off frequency	
ΔI_L	Inductor current ripple	
ΔV_{ripple}	Capacitor voltage ripple	
V_{con}	Converter output voltage	
K_{sv}	Voltage safety factor	
K_{si}	Current safety factor	
e	Back Electromotive Force (Back-EMF)	Volt (V)
K_b	Back-EMF Constant	V/(rad/s) or V/kRPM
K_T	Torque Constant	Nm/A
L_s	Stator Self-Inductance	Henry (H)
R_s	Stator Resistance	Ohm (Ω)
p	Number of poles	-
J	Moment of Inertia	kg·m ²
B	Viscous Friction Coefficient	Nm/(rad/s)