

DESIGN, DEVELOPMENT AND CONTROL OF
COPPER ROTOR INDUCTION MOTORS FOR
ELECTRIC VEHICLE

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DEPARTMENT OF ELECTRICAL ENGINEERING
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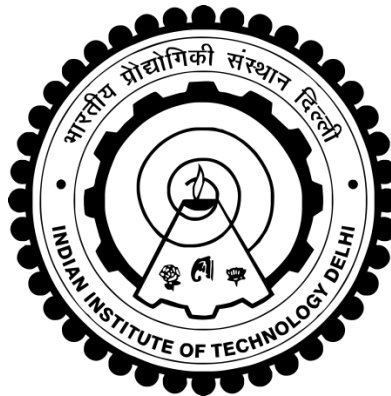
**DESIGN, DEVELOPMENT AND CONTROL OF
COPPER ROTOR INDUCTION MOTORS FOR
ELECTRIC VEHICLE**

by

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CERTIFICATE

It is certified that the thesis entitled “**Design, Development and Control of Copper Rotor Induction Motors for Electric Vehicle,**” being submitted by **Mr. Soby T. Varghese** for award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of the student work carried out by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma.

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ABSTRACT

Conservation of energy and promotion of alternative energy sources in place of conventional resources has emerged as an important issue in effectively meeting the growing energy crisis. Since motor is the main work force for the industry and commercial sectors, improvement in efficiency in these areas is a matter of great concern. Hike in price due to limited and rapidly exhausting oil deposition has forced the automobile industry to find economically feasible alternative sources of energy to drive them forward. In this context, the use of battery operated EV's becomes poignantly significant all over the world. Not much effort has been taken to counter this crisis, especially in developing countries such as India due to the non-availability of technology and expert knowledge in this domain. This research work elaborates the design and development of EV drive motors using die-cast copper rotor technology and regulating it with an economic and efficient drive controller.

The use of copper rotor in induction motors is one of the feasible solutions for improving the efficiency in this type of motors. However, the challenges associated with the implementation of die-cast copper technology in induction motor has retrogressing impact upon commonizing this technology in the global market. Die-cast copper rotor motors occurs to be the better cost effective and energy efficient solution for EV application, compared to permanent magnet motors. Although the motor industry is totally aware of the advantages of die-cast copper rotor, die-cast copper due to its casting difficulties, in terms of high temperature and pressures, has not been fully accepted like die-cast aluminum. The additional cost involved in the production of die-cast copper has to be justified by the improved motor efficiency and other performances. The first part of this research work concentrates on understanding the challenges associated with die-cast copper casting and providing the test equipments to detect the faults in the cast rotor. Seven common rotor problems are investigated in the die-cast copper rotor manufacturing that cause inferior performances in the

newly fabricated motor. A rotor quality test system is designed and developed so as to establish the inspection that can find various defects in the newly manufactured die-cast copper rotors. While examining the rotor stack laminations for copper die-cast process, it is necessary to use adequate insulation coating on the lamination surfaces for withstanding the elevated pressures and temperatures that arise during the die-cast copper rotor manufacturing process.

After the successful development of error-free die-cast copper rotor, the work concentrates on developing the induction motors for EV drive application, where the use of copper rotor achieves maximum benefit. An EV motor of 3kW capacity is chosen to compare and measure the advantages of die-cast copper rotor when it is used in the place of aluminium rotor. The performance of two 3kW EV motors, one with aluminium rotor and the other with copper rotor, is compared for evaluating their performance advantages by using specially constructed EV motor test-set up. A 3kW EV motor with die-cast copper rotor is subjected to more than one hour operation by incorporating forced-air and water cooling methods. By designing and developing a die-cast copper rotor motor for an existing EV drive, its improvements in terms of efficiency, range and speed performances are practically verified. The work also describes in detail the design principles for deriving the torque-speed and power-speed characteristics of an EV drive, to be calculated from various tractive forces. The use of solid copper bars in the construction of stator winding demonstrates the optimum benefit of copper rotor in EV motor. The construction of solid copper bar winding in the stator is realized stage by stage with regard to design and fabrication methods. The completion of the total AC drive system is achieved by adding cost effective and efficient AC controller, designed and developed for EV application, where die-cast copper rotor motor is used as the driving force.

सार

बढ़ते ऊर्जा संकट को प्रभावी ढंग से नियंत्रण करने के लिए, ऊर्जा का संरक्षण तथा पारंपरिक ऊर्जा स्रोतों के स्थान पर वैकल्पिक ऊर्जा स्रोतों के उपयोग को बढ़ावा देना एक प्रभावी माध्यम के रूप में उभरकर आया है। चूंकि विद्युत मोटर, उद्योग और वाणिज्यिक क्षेत्रों के लिए मुख्य कार्यबल है, इसलिए इन क्षेत्रों में कार्यक्षमता में सुधार एक बड़ी चिंता का विषय है। सीमित तथा तेज़ी से घटते तेल के भंडारों के कारण तेल के मूल्यों में वृद्धि ने ऑटोमोबाइल उद्योग को आगे बढ़ने के लिए ऊर्जा के किफायती स्रोतों को खोजने के लिए मजबूर किया है। इस संदर्भ में, बैटरी संचालित ईवी का इस्तेमाल दुनिया भर में बेहद महत्वपूर्ण होता है। इस संकट से निपटने के लिए विशेष रूप से विकासशील देशों जैसे भारत में प्रौद्योगिकी की उपलब्धता और इस डोमेन में विशेषज्ञ ज्ञान की वजह से ज्यादा प्रयास नहीं किए गए हैं। यह शोध कार्य ईवी ड्राइव मोटर्स के डिजाइन और विकास को डाई कास्ट कॉपर रोटार प्रौद्योगिकी का उपयोग करके और एक आर्थिक और कुशल ड्राइव नियंत्रक के साथ विनियमित करने के बारे में विस्तार से बताता है।

इंडक्शन मोटर में तांबे के रोटार का उपयोग इस प्रकार के मोटर्स में कार्यक्षमता में सुधार के लिए संभव समाधानों में से एक है। हालांकि, इंडक्शन मोटर में डाई कास्ट तांबा प्रौद्योगिकी के कार्यान्वयन से संबंधित चुनौतियों का वैश्विक बाजार में इस तकनीक को आम बनाना पर पीछे हटना पड़ रहा है। पर्मनेंट मैग्नेट मोटर्स की तुलना में डाई-कास्ट कॉपर रोटार मोटर्स ईवी उपयोग के लिए किफायती और ऊर्जा कुशल समाधान होती यद्यपि, मोटर उद्योग पूरी तरह से डाई कास्ट तांबा रोटार के महत्व को समझती है, फिर भी डाई कास्ट तांबा रोटार मोटर के कास्टिंग में उच्च तापमान तथा दबाव के वज़ह से आने वाली कठिनाईयों के कारण डाई कास्ट एल्युमीनियम की तरह से स्वीकार नहीं किया जाता है। डाई कास्ट तांबा के उत्पादन में शामिल अतिरिक्त लागत को बेहतर मोटर कार्यक्षमता और अन्य प्रदर्शनों से उचित होना चाहिए। इस शोध कार्य का पहला भाग डाई-कास्ट तांबा कास्टिंग से संबंधित चुनौतियों को समझने और डाली रोटार में दोषों का पता लगाने के लिए परीक्षण उपकरणों को प्रदान करने पर ध्यान केंद्रित करता है। सात सामान्य रोटार समस्याएं डाई कास्ट कॉपर रोटार विनिर्माण में जांच की जाती हैं जो नए गढ़े हुए मोटर में अवर प्रदर्शन करती हैं। रोटार गुणवत्ता परीक्षण प्रणाली को डिजाइन और विकसित किया गया है ताकि नए निर्माणित डाई कास्ट कॉपर रोटार के विभिन्न दोष मिल सकें। तांबे डाई कास्ट की प्रक्रिया के लिए रोटार स्टैक लैमिनेट्स की जांच करते समय, डाई कास्ट डाली तांबे के रोटार विनिर्माण प्रक्रिया के दौरान उठने वाले ऊंचा दबावों और तापमान को बर्दाश्त करने के लिए, फाड़ना सतह पर पर्याप्त इन्सुलेशन कोटिंग का उपयोग करना आवश्यक है।

त्रुटि-मुक्त डाई कास्ट कॉपर रोटार के सफल विकास के बाद, ईवी ड्राइव उपयोग के लिए इंडक्शन मोटर्स के विकास पर ध्यान केंद्रित किया जाता है, जहां तांबे रोटार का उपयोग अधिकतम लाभ प्राप्त करता है।

एल्यूमीनियम रोटर के स्थान पर इसका उपयोग होने पर डाई कास्ट कॉपर रोटर के लाभों की तुलना और मापने के लिए 3 kW क्षमता का ईवी मोटर चुना जाता है। दो 3 kW ईवी मोटर्स का प्रदर्शन, एल्यूमीनियम रोटर वाला एक और दूसरा तांबे के रोटर के साथ, विशेष रूप से निर्मित ईवी मोटर टेस्ट-सेटप का उपयोग करके उनके प्रदर्शन के लाभों के मूल्यांकन के साथ तुलना की जाती है। डाई कास्ट कॉपर रोटर के साथ एक 3kW ईवी मोटर मजबूर हवा और पानी के ठंडा करने के तरीकों को शामिल करके एक घंटे से अधिक का संचालन करता है। एक मौजूद ईवी ड्राइव के लिए डाई कास्ट कॉपर रोटर मोटर को डिजाइन और विकसित करके, दक्षता, रेंज और गति प्रदर्शन के संदर्भ में इसके सुधार व्यावहारिक रूप से सत्यापित हैं। काम में विभिन्न ट्रेक्टिव बलों से गणना की जाने वाली ईवी ड्राइव की टॉर्क-स्पीड और पावर-स्पीड विशेषताओं के लिए डिजाइन सिद्धांतों के बारे में विस्तार से वर्णन किया गया है। स्टेनर घुमाव के निर्माण में ठोस तांबे की सलाखों के प्रयोग से ईवी मोटर में तांबे के रोटर का इष्टतम लाभ दर्शाता है। स्टॉटर में घुमाए ठोस तांबा पट्टी का निर्माण डिजाइन और निर्माण के तरीकों के संबंध में चरण से अवस्था का एहसास होता है। इसी आवेदन के लिए डिजाइन और विकसित लागत प्रभावी और कुशल एसी नियंत्रक जोड़कर कुल एसी ड्राइव सिस्टम को पूरा किया जाता है, जहां डाई कास्ट कॉपर रोटर मोटर को ड्राइविंग बल के रूप में प्रयोग किया जाता है।

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LIST OF ABBREVIATIONS

AC	Alternating Current
ARAI	Automotive Research Association of India
BEE	Bureau of Energy Efficiency
BEV	Battery Electric Vehicle
CAD	Computer Aided Design
CEMEP	European Committee of Manufacturers of Electrical Machines and Power Electronics
CMM	Coordinate Measuring Machine
DAQ	Data Acquisition
DC	Direct Current
DSO	Digital Oscilloscope
DSP	Digital Signal Processor
EC	European Commission
EDE	European Driving Cycle
EMF	Electro Motive Force
EMI	Electro Magnetic Interference
EUDC	Extra Urban Driving Cycle
FEA	Finite Element Analysis
FFT	Fast Fourier Transform
FOC	Field Oriented Control
GPIB	General Purpose Interface Bus
HEV	Hybrid Electric Vehicle
IACS	International Annealed Copper Standard
IDC	Indian Driving Cycle

IEC	International Electro-Technical Commission
IGBT	Gate Bi-Polar Transistor
IM	Induction Motor
IP	Industrial Protection
IS	Indian Standard
MIDC	Modified Indian Driving Cycle
NI	National Instruments
NEMA	National Electrical Manufacturers Association
PCI	Peripheral Component Interconnect
P-I	Proportional Integral
PWM	Pulse Width Modulation
SPWM	Sine Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation
SWG	Standard Wire Gauge
TI	Texas Instruments
VSI	Voltage Source Inverter

LIST OF SYMBOLS

F_w	Wind resistance force
I_m	Motor current
a	Vehicle acceleration
A	Vehicle frontal area
C_d	Coefficient of drag force
C_i	Mass conversion factor
C_r	Rolling resistance factor
C_{rw}	Relative wind coefficient
C_w	Relative wind factor
F_a	acceleration force
F_d	Aerodynamic drag force
F_h	Hill-climbing force
F_i	Input frequency
F_o	Ramping frequency
F_r	Rolling resistance force
f_r	Rotor bar pass frequency
f_s	Shaft frequency
F_t	Total tractive force
I_{dc}	DC bus current
n	Number of rotor bars
N	Speed of rotation
η_{drive}	Drive efficiency
η_{mt}	Motor efficiency
η_{sys}	Overall system efficiency

ϕ_{ac}	Alternating flux
P_{DC}	DC bus output power
ϕ_{dc}	DC flux
P_{drive}	Drive output power
P_{out}	Motor output power
s	Motor slip
V	Vehicle velocity
w	average wind speed
W	Vehicle weight