

**CLOSED LOOP CONTROL ANALYSIS, SPEED
SENSORLESS OPERATION AND NOVEL LC FILTER
DESIGN CRITERIA FOR VSI FED IM DRIVE WITH
OUTPUT LC FILTER**

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JUNE 2023**

Closed Loop Control Analysis, Speed Sensorless Operation and Novel LC Filter Design Criteria for VSI fed IM Drive With Output LC Filter

A THESIS

submitted by

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(2016EEZ8500)

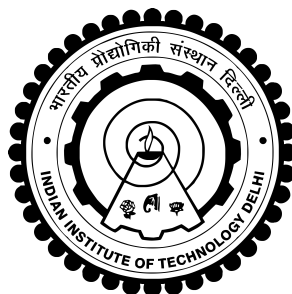
under the supervision of

Prof. Amit Kumar Jain

for the award of the degree

of

Doctor of Philosophy



Department Of Electrical Engineering
INDIAN INSTITUTE OF TECHNOLOGY DELHI

June 2023

THESIS CERTIFICATE

This is to certify that the thesis entitled “**Closed Loop Control Analysis, Speed Sensorless Operation and Novel LC Filter Design Criteria for VSI fed IM Drive With Output LC Filter**”, submitted by **Navneet Vaishnav (2016EEZ8500)**, to the Indian Institute of Technology, Delhi, for the award of the degree of **Doctor of Philosophy**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ACKNOWLEDGEMENTS

First and foremost, praises and thanks to God, the Almighty, for guiding me through my doctoral research and pouring forth an abundance of blessings so that I could finish it successfully.

I want to convey my profound thanks to Dr. Amit Kumar Jain, a Professor at Electrical Engineering Department, IIT Delhi, who served as my research supervisor and allowed me to conduct this research work. His dynamism, vision, genuineness, and determination have greatly inspired me. He has taught me how to research and deliver the results in the most understandable way. Working and learning under his direction was a huge honor and privilege. I want to express my gratitude to him for his friendship, compassion, and fantastic sense of humor.

In addition, I would like to express my gratitude to the HOD and staffs of Department of Electrical Engineering at IIT Delhi for their assistance with this research study. Also, I would like to express my appreciation to the members of my doctoral research committee, Professor M. Veerachary, Dr. Anandarup Das, and Dr. Ashu Verma, for the helpful direction they provided throughout the research work, which ultimately led to the successful completion of this thesis.

I also express my gratitude towards my former research supervisor Dr. Ramkrishan Maheshwari, currently an Associate Professor at Southern Denmark University, under whom I started my doctoral journey and gained abundant knowledge in the power electronics and drives field.

I owe a great debt of gratitude to my mother for all the ways in which she has supported me throughout my life with her prayers, care, and sacrifices so that I would have the best possible start in life. I appreciate my wife's love, patience, prayers, and ongoing support while I finish my research project. Also, I express my appreciation to my brother for his constant support and valuable prayers. My special thanks go to my friends for their continuous motivation and support throughout this doctoral journey.

For their consistent support and encouragement, I would like to express my gratitude to my friends and research colleagues, Himanshu Swami Sir, Mr. Martin Cheerangal Joy, Mrs. Khushboo Kumari, Ms. Cheshta Jain, Ms. Apurva Verma, Mr. Amir Rafiq, Mrs. Nidhi Bist, Mr. Shankar Rao, and other lab mates. My sincere gratitude goes out to my former research colleagues, Dr. Nikhil Krishna Bajjuri, Dr. Kapil Shukla, Dr. Ambuj Sharma, Dr. Prasun Mishra, Dr. Rahul Sharma, and Dr. Nikhil Kumar, for their support during

the entirety of this study project. I would also like to express my gratitude to everyone working at the UG Machines Lab at IIT Delhi for their help. A special thanks goes to Dr. Mahendra Chandra Joshi from NIT Rourkela for his continuous support, technical discussions, and encouragement.

I would want to express my gratitude to my hostel-mate, Mr. Devesh Malviya, for the consistent encouragement and support that he has provided. We did share some very amazing years together.

Finally, my thanks go to all the people who have supported me in completing the research work directly or indirectly.

Navneet Vaishnav

ABSTRACT

The placement of the LC filter in between the pulse width modulated (PWM) voltage-source inverter (VSI) and an induction motor (IM) enhances the motor life cycle by delivering smooth sinusoidal voltages at stator terminals. This placement reduces high-bearing currents, common-mode voltages, and high dv/dt across stator terminals. However, this connection generates resonance frequency oscillations in stator voltages and may lead to closed-loop instability in the rotor flux-oriented (RFO) vector-controlled (VC) IM system. The closed-loop stability of the combined IM + LC filter system is complex and has not been appropriately analyzed in the literature.

This thesis presents a detailed closed-loop stability analysis of the IM + LC filter system based on stability region (SR) and designs the PI gains for dq axes stator current controller. Employing the SR method, the common SRs for the IM and IM + LC filter systems are derived, thereby proving that connecting an LC filter between the VSI and the IM system does not necessarily destabilize the closed-loop system. The thesis also presented that the PI controller being a first-order controller has limitations of stability margins and performance criteria for dq axes stator current control-loop of an IM + LC filter system. These limitations in the PI controller are demonstrated by deriving the complete range of stabilizing PI gains for the IM + LC filter system and segregating them to satisfy the desired frequency domain specifications. To remedy the limitations, the thesis proposes using a second-order controller instead of a PI controller in the inner-loop stator current control loop to provide better stability margins, attenuation at the resonance frequency, and more robustness.

Furthermore, the reactive power flow and its influences on the wide-frequency operation of IM + LC filter drives are explored. An LC filter, placed at the output of a voltage source inverter (VSI) to filter the pulse width modulated (PWM) voltages, unfolds a research opportunity in IM + LC filter drives, as the filter capacitors can also supply reactive power to the IM. The thesis comprehensively investigates this reactive power flow in an IM + LC filter system with filter capacitor values designed using two different methods. In continuation, the thesis analyzes issues in the wide-frequency operation, such as reactive power imbalance, abnormal escalation in inverter currents, variation in power factor seen by the VSI, and high current stress on DC-bus capacitors and VSI. The method of filter capacitor selection for the wide-frequency operation of the IM + LC filter system is also proposed in terms of IM and LC filter parameters while resolving the above-mentioned issues.

On the other hand, owing to the phase delay and resonance oscillations introduced by the LC filter, the 'L' and 'C' design methodology is critical. Also, the closed-loop control and

speed-sensorless operation of such drives are complex, without stator voltage sensors. This thesis addresses these issues by proposing a simple filter inductor (L_f) selection criterion for an LC filter-equipped IM drive that allows retaining the designed DC-bus capacitor, heat-sink, and power devices of VSI upon LC filter insertion in between the VSI and IM. Furthermore, an existing filter capacitor selection criteria is improved by adhering to the constraint on voltage drop (V_f) across L_f . In addition, the thesis also examines the existing active damping (AD) techniques to perform the speed-sensorless operation on the IM + LC filter (IMLC) drive without stator voltage sensors and improves one of them to achieve the same. Summarily, through the filter selection criteria and improved active damping technique, the thesis proposes to retrofit the LC filter into the IM drive and perform speed and voltage-sensorless operation.

The thesis also explores the influence of delays on closed-loop control of digitally-controlled induction motor (IM) systems with an inverter output LC filter. The delays are inevitable in a digitally controlled system; it influences the closed-loop performance, frequency response, and, consequently, the closed-loop system stability. Therefore, the delay (sampling and processing delays) is modeled and incorporated into the open-loop IM system while designing the closed-loop controllers to address the forenamed issues. These delays and impending stability issues are thoroughly analyzed here through the frequency-domain indices (Gain-Margin, Phase-Margin) for the IM system with an LC filter.

All the presented analyses and proposals on IM + LC filter system are validated through MATLAB simulations and experiments on a 5 Hp IM system.

सार

पल्स चौड़ाई मॉड्युलेटेड (पीडब्लूएम) वोल्टेज-सोर्स इन्वर्टर (वीएसआई) और एक इंडक्शन मोटर (आईएम) के बीच एलसी फिल्टर की नियुक्ति स्टेटर टर्मिनलों पर स्वच्छ साइनसॉइडल वोल्टेज प्रदान करके मोटर जीवन चक्र को बढ़ाती है। यह प्लेसमेंट स्टेटर टर्मिनलों पर उच्च-असर धाराओं, सामान्य-मोड वोल्टेज और उच्च $\$dv/dt\$$ को कम करता है। हालाँकि, यह कनेक्शन स्टेटर वोल्टेज में अनुनाद आवृत्ति दोलन उत्पन्न करता है और रोटर फ्लक्स-ओरिएंटेड (आरएफओ) वेक्टर-नियंत्रित (वीसी) इंडक्शन मोटर सिस्टम में बंद-लूप अस्थिरता पैदा कर सकता है। संयुक्त प्रेरण मोटर एलसी फिल्टर प्रणाली की बंद-लूप स्थिरता जटिल है और साहित्य में इसका उचित विश्लेषण नहीं किया गया है।

यह थीसिस स्थिरता क्षेत्र (एसआर) के आधार पर आईएम एलसी फिल्टर सिस्टम का एक विस्तृत बंद-लूप स्थिरता विश्लेषण प्रस्तुत करती है और $\$dq\$$ अक्ष स्टेटर वर्तमान नियंत्रक के लिए पीआई लाभ को डिजाइन करती है। एसआर विधि को नियोजित करते हुए, आईएम और आईएम एलसी फिल्टर सिस्टम के लिए सामान्य एसआर प्राप्त किए जाते हैं, जिससे यह साबित होता है कि वीएसआई और आईएम सिस्टम के बीच एलसी फिल्टर को जोड़ने से बंद-लूप सिस्टम को अस्थिर करना जरूरी नहीं है। थीसिस ने यह भी प्रस्तुत किया कि प्रथम-क्रम नियंत्रक होने के कारण पीआई नियंत्रक में आईएम एलसी फिल्टर सिस्टम के $\$dq\$$ अक्ष स्टेटर वर्तमान नियंत्रण-लूप के लिए स्थिरता मार्जिन और प्रदर्शन मानदंड की सीमाएं हैं। पीआई नियंत्रक में इन सीमाओं को आईएम एलसी फिल्टर सिस्टम के लिए पीआई लाभ को स्थिर करने और वांछित आवृत्ति डोमेन विनिर्देशों को पूरा करने के लिए अलग करने की पूरी श्रृंखला प्राप्त करके प्रदर्शित किया जाता है। सीमाओं को मापने के लिए, थीसिस बेहतर स्थिरता मार्जिन, अनुनाद आवृत्ति पर क्षीणन और अधिक मजबूती प्रदान करने के लिए इनर-लूप स्टेटर वर्तमान नियंत्रण लूप में पीआई नियंत्रक के बजाय दूसरे क्रम के नियंत्रक का उपयोग करने का प्रस्ताव करती है।

इसके अलावा, प्रतिक्रियाशील शक्ति प्रवाह और आईएम एलसी फिल्टर ड्राइव के व्यापक-आवृत्ति संचालन पर इसके प्रभावों का पता लगाया जाता है। पल्स चौड़ाई मॉड्युलेटेड (पीडब्लूएम) वोल्टेज को फिल्टर करने के लिए वोल्टेज स्रोत इन्वर्टर (वीएसआई) के आउटपुट पर रखा गया एक एलसी फिल्टर, आईएम एलसी फिल्टर ड्राइव में एक शोध अवसर खोलता है, क्योंकि फिल्टर कैपेसिटर आईएम को प्रतिक्रियाशील शक्ति भी प्रदान कर सकते हैं। थीसिस दो अलग-अलग तरीकों का उपयोग करके डिजाइन किए गए फिल्टर कैपेसिटर मानों के साथ आईएम एलसी फिल्टर सिस्टम में इस प्रतिक्रियाशील शक्ति प्रवाह की व्यापक जांच करती है। निरंतरता में, थीसिस व्यापक-आवृत्ति ऑपरेशन में मुद्दों का विश्लेषण करती है, जैसे प्रतिक्रियाशील शक्ति असंतुलन, इन्वर्टर धाराओं में असामान्य वृद्धि, वीएसआई द्वारा देखे गए पावर फैक्टर में भिन्नता, और डीसी-बस कैपेसिटर और वीएसआई पर उच्च वर्तमान तनाव। उपर्युक्त मुद्दों को हल करते समय आईएम एलसी फिल्टर सिस्टम के व्यापक-आवृत्ति संचालन के लिए फिल्टर कैपेसिटर चयन की विधि भी आईएम और एलसी फिल्टर मापदंडों के संदर्भ में प्रस्तावित है।

दूसरी ओर, एलसी फिल्टर द्वारा शुरू किए गए चरण विलंब और अनुनाद दोलनों के कारण, 'एल' और 'सी' डिजाइन पद्धति महत्वपूर्ण है। इसके अलावा, स्टेटर वोल्टेज सेंसर के बिना, ऐसी ड्राइव का बंद-लूप नियंत्रण और स्पीड-सेंसर रहित संचालन जटिल है। यह थीसिस एलसी फिल्टर से सुसज्जित आईएम ड्राइव के लिए एक सरल फिल्टर प्रारंभकर्ता ($\$ एल_एफ \$$) चयन मानदंड का प्रस्ताव करके इन मुद्दों को संबोधित करता है जो एलसी फिल्टर सम्मिलन पर वीएसआई के डिजाइन किए गए डीसी-बस कैपेसिटर, हीट-सिंक और पावर उपकरणों को बनाए रखने की अनुमति देता है। वीएसआई और आईएम के बीच। इसके अलावा, $\$L_f\$$ के पार वोल्टेज ड्रॉप ($\$V_f\$$) पर प्रतिबंध का पालन करके मौजूदा फिल्टर कैपेसिटर चयन मानदंड में सुधार किया गया है। इसके अलावा, थीसिस स्टेटर वोल्टेज सेंसर के बिना आईएम एलसी फिल्टर (आईएमएलसी) ड्राइव पर स्पीड-सेंसरलेस ऑपरेशन करने के लिए मौजूदा सक्रिय डंपिंग (एडी) तकनीकों की भी जांच करती है और इसे प्राप्त करने के लिए उनमें से एक में सुधार करती है। संक्षेप में, फिल्टर चयन मानदंड और बेहतर सक्रिय डंपिंग तकनीक के माध्यम से, थीसिस एलसी फिल्टर को आईएम ड्राइव में फिर से फिट करने और गति और वोल्टेज-सेंसरलेस ऑपरेशन करने का प्रस्ताव करती है।

थीसिस इन्वर्टर आउटपुट एलसी फिल्टर के साथ डिजिटल रूप से नियंत्रित इंडक्शन मोटर (आईएम) सिस्टम के बंद-लूप नियंत्रण पर देरी के प्रभाव की भी पड़ताल करती है। डिजिटल रूप से नियंत्रित प्रणाली में देरी अपरिहार्य है; यह बंद-लूप प्रदर्शन, आवृत्ति प्रतिक्रिया और, परिणामस्वरूप, बंद-लूप सिस्टम स्थिरता को प्रभावित करता है। इसलिए, विलंब (नमूनाकरण और प्रसंस्करण विलंब) को पूर्वनिर्धारित मुद्दों को संबोधित करने के लिए बंद-लूप नियंत्रकों को डिजाइन करते समय ओपन-लूप

आईएम सिस्टम में मॉडल और शामिल किया गया है। इन देरी और आसन्न स्थिरता के मुद्दों का एलसी फिल्टर के साथ आईएम सिस्टम के लिए आवृत्ति-डोमेन सूचकांक (लाभ-मार्जिन, चरण-मार्जिन) के माध्यम से यहां गहन विश्लेषण किया गया है।

इंडक्शन मोटर एलसी फिल्टर सिस्टम पर प्रस्तुत सभी विश्लेषण और प्रस्ताव 5 एचपी इंडक्शन मोटर सिस्टम पर MATLAB सिमुलेशन और प्रयोगों के माध्यम से मान्य हैं।

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ABBREVIATIONS

VSD	Variable Speed Drive
IM	Induction Motor
VSI	Voltage Source Inverter
PWM	Pulse Width Modulation
PI	Proportional Integral
IMLC	Induction Motor + LC Filter
RFO	Rotor Flux Orientation
FOC	Field Oriented Control
AD	Active Damping
SR	Stability Region
GM	Gain Margin
PM	Phase Margin

NOTATIONS

P	Number of poles
L_s, L_r	Stator and rotor self-inductance per phase
L_{ls}, L_{lr}	Stator and rotor leakage-inductance per phase
L_m, L_l	Magnetizing inductance
L_l	Total leakage inductance
R_s, R_r	Stator and rotor resistance per phase
σ	Total leakage factor
τ_r	Rotor time constant
J	Moment of inertia in $kg - m^2$
B	Coefficient of friction in $kg - m^2/s^2$
m_d, m_L	Electromagnetic and load torque in N-m
sl	Letters denoting 'Slip' in Induction Motor.
ω_s	Rotor flux speed in elec. rad/sec
ω_r	Rotor speed in elec. rad/sec
ω_{sl}	Slip-speed in elec. rad/sec
i_{mr}	Rotor equivalent magnetizing current
i_{sd}, i_{sq}	d - q axes stator currents in rotor flux orientation (RFO)
v_{sd}, v_{sq}	d - q axes stator voltages in RFO
L_f, C_f	LC filter inductance and capacitance per phase
R_f	LC Filter resistance per phase
V_f	Voltage drop across filter inductor per phase
i_{invd}, i_{invq}	d - q axes inverter currents in RFO
v_{invd}, v_{invq}	d - q axes inverter voltages in RFO
$*$	Superscript, denoting reference variable
f_{res}	Effective resonance frequency for IM + LC Filter system
f_{sw}	Switching frequency of VSI
T_{sw}	Switching period of VSI