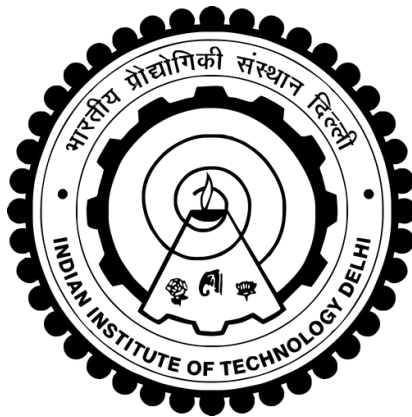


FAULT TOLERANT CONTROL STRATEGIES OF INDUCTION MOTOR DRIVE FED FROM VOLTAGE SOURCE CONVERTERS

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INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

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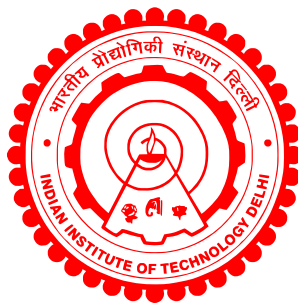
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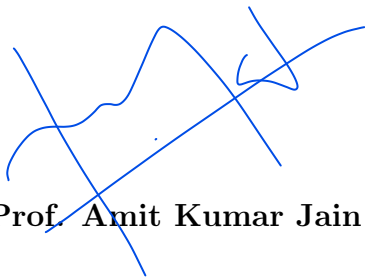
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CERTIFICATE

This is to certify that the thesis titled “**Fault Tolerant Control Strategies of Induction Motor Drive fed from Voltage Source Converters**” being submitted by **Mr. Martin Cheerangal Joy** (2016EEZ8492) 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. Martin Cheerangal Joy has worked under my guidance and supervision and has fulfilled the requirements for submitting this thesis, which to the best of my knowledge, meets the necessary requisite standard. The results presented herein have not been submitted to any other University or Institute for any degree-awarding.

Dated:



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Date:

Martin Cheerangal Joy

ABSTRACT

Adjustable speed drives (ASDs) use induction motor extensively to control pumps, fans and other loads in the process industries. In order to control the speed of the induction motor dynamically, rotor field oriented control (RFOC) is a common technique employed in these drives. In the ASDs, different kinds of voltage source converters (VSCs) are employed to obtain a pulse width modulated voltage of varying magnitude and varying frequency to the motor depending on the reference speed requirements. Sometimes, the output voltage available from the VSCs reduce due to the conditions like a sag in the supply grid voltage or a fault in the components of the VSC. For example, in an adjustable speed drive employing a three-phase diode bridge rectifier and a two-level voltage source converter (2L-VSC), the DC-link voltage reduces from the nominal value due to a sag in the grid's supply voltage. In this condition, if a proper control mechanism is not activated, the reference speed and load torque of the rotor field oriented induction motor (RFO-IM) connected to the 2L-VSC could not be maintained due to the reduced output voltage from the converter. Similarly, in an adjustable speed drive employing a cascaded H-bridge multi-level (CHB-ML) converter based VSC, the available voltage from the converter reduces when some of the faulty H-bridges are bypassed. In this scenario, a RFO-IM connected to such a CHB-ML converter results in a reduced speed and torque in the post-fault operation. The primary objective of the research work in the thesis is to maintain the speed and torque of the RFO-IM in the event of a dip in the voltage available from the 2L-VSC and the CHB-ML voltage source converters.

In a 2L-VSC based RFO-IM drive, a modified vector control is proposed to maintain the speed and torque of the motor during the input supply voltage sag. In this control technique, the reference d -axis and q -axis stator current commands are obtained by solving the voltage, current and torque constraints in the current dq plane. The analysis includes the traversal of motor's operating point in the current dq plane (during the supply voltage sag), voltage sag limit for the particular loading and the settling speed of the RFO-IM when the voltage sags beyond the limit. In the event of a voltage sag beyond a limit, the control is made such that the motor delivers the load torque with reduced speed. Mathematical equations explaining the current trajectory to be followed during voltage sag, voltage sag limit and the settling speed for voltage sag beyond the limit are derived. The proposed control is simulated in MATLAB/Simulink and experimental validation is conducted on a 3-hp induction motor (IM) in the laboratory.

Next part of the research is the extension to CHB-ML converter based RFO-IM drive. In this multi-level VSC, the available voltage reduces when the faulty H-bridges or power cells are bypassed in the post-fault operation. In this scenario, a post-fault control technique is proposed to maintain the speed and torque of the RFO-IM and to balance the line voltages of the CHB-ML converter in the post-fault operating conditions. The control strategy is to vary the magnitude and phase shift of the injected fundamental common mode voltage (FCMV) according to the motor's loading condition and the converter's fault configuration. The addition of the proposed FCMV with the reference phase voltages, not only ensures maximum line voltage in the post-fault operating condition but also shares equal power among the remaining healthy cells of the converter. Moreover, in the post-fault operation, a detailed analysis is performed on both motor and converter, and the integrated control is presented to maintain the command speed and load torque of the RFO-IM. This includes the mathematical equation explaining the new operating point of the motor for different fault configurations, traversal of operating point, and the variation in power factor of each leg of the converter in post-fault conditions. The dynamic generation of FCMV is calculated from the new operating point of the stator current components in the current dq -plane and the fault configuration of the CHB-ML converter. Computer simulation and experimental results are shown to validate the proposed control.

In addition to the above two control techniques, CHB-ML converter fed RFO-IM with redundant power cell topology is also studied. The objective of the control strategy is to maintain the torque and speed of the RFO-IM in post-fault operation and to maximize the converter's power capability by adding maximum number of power cells during post-fault operation. Furthermore, maximum line voltage is utilized from the redundant cells without increasing the DC-link voltage of power cells, and the motor's operating point in voltage plane is analyzed and determined for various loading conditions during pre-fault and post-fault operation. In the post-fault operation, a common mode voltage of fundamental frequency is also added depending on the motor's loading condition and post-fault configuration to distribute power evenly among the remaining healthy cells. Theoretical and graphical analyses include the equation of the operating point in the voltage plane, traversal of the operating point from pre-fault to post-fault operation, and selection of common mode voltage of fundamental frequency based on the fault configuration and the motor's loading. The simulation and experimental data are used to validate the proposed fault tolerant control approach.

सार

समायोज्य गति ड्राइव (एएसडी) प्रक्रिया उद्योगों में पंपों, प्रशंसकों और अन्य भारों को नियंत्रित करने के लिए बड़े पैमाने पर प्रेरण मोटर का उपयोग करता है। इंडक्शन मोटर की गति को गतिशील रूप से नियंत्रित करने के लिए, रोटार फील्ड ओरिएंटेड कंट्रोल (RFOC) इन ड्राइव में नियोजित एक सामान्य तकनीक है। ASDs में, विभिन्न प्रकार के वोल्टेज स्रोत कन्वर्टर (VSCs) को संदर्भ गति आवश्यकताओं के आधार पर मोटर के लिए अलग-अलग परिमाण और भिन्न आवृत्ति के पल्स चौड़ाई मॉड्यूलेटेड वोल्टेज प्राप्त करने के लिए नियोजित किया जाता है। कभी-कभी, वीएससी से उपलब्ध आउटपुट वोल्टेज आपूर्ति ग्रिड वोल्टेज में शिथिलता या वीएससी के घटकों में खराबी जैसी स्थितियों के कारण कम हो जाता है। उदाहरण के लिए, तीन-चरण डायोड ब्रिज रेक्टिफायर और दो-स्तरीय वोल्टेज स्रोत कनवर्टर (2L-VSC) को नियोजित करने वाली एक समायोज्य गति ड्राइव में, ग्रिड की आपूर्ति वोल्टेज में शिथिलता के कारण डीसी-लिंक वोल्टेज नाममात्र मूल्य से कम हो जाता है। इस स्थिति में, यदि उचित नियंत्रण तंत्र सक्रिय नहीं होता है, तो संदर्भ गति और कनवर्टर से कम आउटपुट वोल्टेज के कारण 2L-VSC से जुड़े रोटार फील्ड ओरिएंटेड इंडक्शन मोटर (RFO-IM) का लोड टॉर्क बनाए नहीं रखा जा सकता है। इसी तरह, एक समायोज्य गति ड्राइव में कैस्केडेड एच-ब्रिज मल्टी-लेवल कनवर्टर आधारित वीएससी को नियोजित करते हुए, कनवर्टर से उपलब्ध वोल्टेज कम हो जाता है जब कुछ दोषपूर्ण हाईब्रिज बाईपास हो जाते हैं। इस परिदृश्य में, ऐसे CHB-ML कन्वर्टर से जुड़े एक RFO-IM के परिणामस्वरूप पोस्ट-फॉल्ट ऑपरेशन में गति और टॉर्क कम हो जाता है। थीसिस में शोध कार्य का प्राथमिक उद्देश्य 2L-VSC और CHB-ML वोल्टेज स्रोत कन्वर्टर से उपलब्ध वोल्टेज में गिरावट की स्थिति में RFO-IM की गति और टॉर्क को बनाए रखना है।

2L-VSC आधारित RFO-IM ड्राइव में, बनाए रखने के लिए एक संशोधित वेक्टर नियंत्रण प्रस्तावित है इनपुट आपूर्ति वोल्टेज शिथिलता के दौरान मोटर की गति और टॉर्क। इस नियंत्रण में तकनीक, संदर्भ डी-अक्ष और क्यू-अक्ष स्टेटर करंट कमांड को हल करके प्राप्त किया जाता है वर्तमान डीक्यू विमान में वोल्टेज, वर्तमान और टोक की कमी। विश्लेषण शामिल है वर्तमान डीक्यू विमान में मोटर के ऑपरेटिंग बिंदु का ट्रैवर्सल (आपूर्ति वोल्टेज के दौरान सैंग), विशेष लोडिंग के लिए वोल्टेज सैंग लिमिट और आरएफओ-आईएम की सेटलिंग गति जब वोल्टेज सीमा से परे चला जाता है। वोल्टेज की एक सीमा से अधिक शिथिलता की स्थिति में, नियंत्रण ऐसा बनाया जाता है कि मोटर लोड टॉर्क को कम गति से डिलीवर करता है। गणितीय वोल्टेज शिथिलता, वोल्टेज शिथिलता के दौरान अनुसरण किए जाने वाले वर्तमान प्रक्षेपवक्र की व्याख्या करने वाले समीकरण सीमा से परे वोल्टेज शिथिलता के लिए सीमा और बसने की गति प्राप्त होती है। प्रस्तावित MATLAB/Simulink में नियंत्रण सिम्युलेट किया जाता है और प्रयोगात्मक सत्यापन a पर आयोजित किया जाता है प्रयोगशाला में 3-hp इंडक्शन मोटर (IM)।

अनुसंधान का अगला भाग सीएचबी-एमएल कन्वर्टर आधारित आरएफओ-आईएम ड्राइव का विस्तार है। में यह बहु-स्तरीय वीएससी, दोषपूर्ण एच-ब्रिज या पावर सेल होने पर उपलब्ध वोल्टेज कम हो जाता है पोस्ट-फॉल्ट ऑपरेशन में बायपास किया जाता है। इस परिदृश्य में, पोस्ट-फॉल्ट नियंत्रण तकनीक है RFO-IM की गति और टॉर्क को बनाए रखने और लाइन वोल्टेज को संतुलित करने के लिए प्रस्तावित

सीएचबी-एमएल परिवर्तक की गलती के बाद की परिचालन स्थितियों में। नियंत्रण रणनीति है इंजेक्टेड फंडामेंटल कॉमन मोड वोल्टेज के परिमाण और फेज शिफ्ट को अलग करने के लिए (FCMV) मोटर की लोडिंग स्थिति और कनवर्टर के फॉल्ट कॉन्फिगरेशन के अनुसार। संदर्भ चरण वोल्टेज के साथ प्रस्तावित एफसीएमवी का जोड़ न केवल सुनिश्चित करता है पोस्ट-फॉल्ट ऑपरेटिंग स्थिति में अधिकतम लाइन वोल्टेज लेकिन समान शक्ति भी साझा करता है कनवर्टर की शेष स्वस्थ कोशिकाओं में। इसके अलावा, गलती के बाद के ऑपरेशन में, मोटर और कनवर्टर दोनों पर एक विस्तृत विश्लेषण किया जाता है, और एकीकृत नियंत्रण होता है RFO-IM की कमांड स्पीड और लोड टॉर्क को बनाए रखने के लिए प्रस्तुत किया गया। यह भी शामिल है विभिन्न के लिए मोटर के नए परिचालन बिंदु की व्याख्या करने वाला गणितीय समीकरण फॉल्ट कॉन्फिगरेशन, ऑपरेटिंग पॉइंट का ट्रैवर्सल और प्रत्येक के पावर फैक्टर में भिन्नता गलती के बाद की स्थिति में कनवर्टर का पैर। एफसीएमवी की गतिशील पीढ़ी की गणना की जाती है वर्तमान डीक्यू-प्लेन में स्टेटर वर्तमान घटकों के नए ऑपरेटिंग बिंदु से और CHB-ML कनवर्टर का फॉल्ट कॉन्फिगरेशन। कंप्यूटर सिमुलेशन और प्रायोगिक परिणाम प्रस्तावित नियंत्रण को मान्य करने के लिए दिखाए जाते हैं।

उपरोक्त दो नियंत्रण तकनीकों के अलावा, सीएचबी-एमएल कनवर्टर ने आरएफओ-आईएम को खिलाया निरर्थक पावर सेल टोपोलॉजी का भी अध्ययन किया जाता है। नियंत्रण रणनीति का उद्देश्य है फॉल्ट के बाद के ऑपरेशन में और अधिकतम करने के लिए RFO-IM के टॉर्क और गति को बनाए रखें पोस्टफॉल्ट ऑपरेशन के दौरान अधिकतम संख्या में पावर सेल जोड़कर कनवर्टर की पावर क्षमता। इसके अलावा, निरर्थक कोशिकाओं से अधिकतम लाइन वोल्टेज का उपयोग किया जाता है बिजली कोशिकाओं के डीसी-लिंक वोल्टेज और मोटर के ऑपरेटिंग बिंदु को बढ़ाए बिना प्री-फॉल्ट के दौरान विभिन्न लोडिंग स्थितियों के लिए वोल्टेज प्लेन का विश्लेषण और निर्धारण किया जाता है और पोस्ट-फॉल्ट ऑपरेशन। पोस्ट-फॉल्ट ऑपरेशन में, मोटर की लोडिंग स्थिति और पोस्ट-फॉल्ट के आधार पर मौलिक आवृत्ति का एक सामान्य मोड वोल्टेज भी जोड़ा जाता है कॉन्फिगरेशन शेष स्वस्थ कोशिकाओं के बीच समान रूप से शक्ति वितरित करने के लिए। सैद्धांतिक और ग्राफिकल विश्लेषण में वोल्टेज प्लेन, ट्रैवर्सल में ऑपरेटिंग पॉइंट का समीकरण शामिल है प्री-फॉल्ट से पोस्ट-फॉल्ट ऑपरेशन और सामान्य मोड के चयन के ऑपरेटिंग बिंदु का गलती विन्यास और मोटर की लोडिंग के आधार पर मौलिक आवृत्ति का वोल्टेज। सिमुलेशन और प्रायोगिक डेटा का उपयोग प्रस्तावित दोष सहिष्णु को मान्य करने के लिए किया जाता है नियंत्रण दृष्टिकोण।

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ABBREVIATIONS

2L-VSC	2-Level Voltage Source Converter
AC	Alternating Current
ADC	Analog to Digital Converter
ASD	Adjustable Speed Drive
CC	Cyclo-Converter
CHB-ML	Cascaded H-bridge - Multi-Level
CHB-MLC	Cascaded H-bridge - Multi-Level Converter
CMV	Common Mode Voltage
CSC	Current Source Converter
DAC	Digital to Analog Converter
DC	Direct Current
DSP	Digital Signal Processor
FCMV	Fundamental Common Mode Voltage
FW	Field Weakening
FC-MLC	Flying Capacitor - Multi-Level Converter
FPGA	Field Programming Gate Array
GaN	Galium Nitride
GCT	Gate Commutated Thyristor
GM	Gain Margin
IGBT	Insulated Gate Bi-polar Transistor
IITD	Indian Institute of Technology, Delhi
IM	Induction Motor
kV	kilo Volt
LCC	Line Commutated Converter

LSPWM	Level Shift Pulse Width Modulation
MF	Multiple Fault
MV	Medium Voltage
MW	Mega Watt
MLC	Multi-Level Converter
NPC	Neutral Point Clamped
PF	Power Factor
PI	Proportional Integral
PM	Phase Margin
PWM	Pulse Width Modulation
RFOC	Rotor Field Oriented Control
RFO-IM	Rotor Field Oriented - Induction Motor
rpm	revolutions per minute
SCR	Silicon Controlled Rectifier
SF	Single Fault
SiC	Silicon Carbide
SPWM	Sine Pulse Width Modulation
SQIM	Squirrel cage Induction Motor
SVPWM	Space Vector Pulse Width Modulation
TI	Texas Instruments
VC	Vector Control
VS	Voltage Sag
VSC	Voltage Source Converter

NOTATION

m_a	Amplitude modulation index
$\hat{V}_m$	Peak of reference (or modulating) waveform
$\hat{V}_{cr}$	Peak of the carrier waveform
m_f	Frequency modulation index
f_{cr}	Carrier frequency
f_m	Reference signal frequency
$f_{dev,sw}$	Device switching frequency
v_{cm}	Common mode voltage
V_{dc}	DC-link voltage in 2L-VSC
V_{dc_chb}	DC-link voltage in each H-bridge of CHB-ML converter
R_s, R_r	Per-phase stator and rotor resistance of IM
L_{ls}, L_{lr}	Per-phase leakage inductance in the stator and rotor of IM
L_m or L_o	Per-phase magnetising inductance of IM
σ	Total leakage coefficient of IM
σ_r	Rotor leakage coefficient of IM
i_{sa}, i_{sb}, i_{sc}	a, b, and c phase stator currents
v_{sa}, v_{sb}, v_{sc}	a, b, and c phase stator voltages
$\alpha\beta$ -axis	Stationary reference frame with α -axis fixed to ‘a’ phase of IM
$i_{s\alpha}, i_{s\beta}$	α and β components of stator current in stationary reference frame
$v_{s\alpha}, v_{s\beta}$	α and β components of stator voltage in stationary reference frame
$\psi_{s\alpha}, \psi_{s\beta}$	α and β Components of stator-flux in stationary reference frame
$\psi_{r\alpha}, \psi_{r\beta}$	α and β Components of rotor-flux in stationary reference frame
N_s	Synchronous speed of IM in rpm
N_r	Rotor speed of IM in rpm
ω_{rm}	Rotor speed in mechanical $rad\ s^{-1}$
ω_r	Rotor speed in electrical $rad\ s^{-1}$
dq -axis	Synchronously revolving orthogonal reference frame
ω_s	Synchronous speed in electrical $rad\ s^{-1}$
ω_{sl}	Slip speed in electrical $rad\ s^{-1}$
J	Moment of inertia of IM
B	frictional coefficient of IM
P	Number of poles per phase
T_{em}	Electro-mechanical torque developed by the IM

T_L	Mechanical load to the motor
τ_r	Rotor time constant of IM
ρ	Angle between rotor-flux vector and stator-axis
ε	Angle between stator-axis and rotor-axis
v_{ffd}, v_{ffq}	d -axis and q -axis feed-forward terms in RFOC
T_d	Sampling and transport delay in VSC and DSP
T_{sdi}, T_{sqi}	Time constant of the d -axis and q -axis stator-current controller
K_{sdi}, K_{sqi}	Gain of the d - and q -axis stator-current PI controller
K_{mri}	Gain of the magnetizing current PI controller
T_{imr}	Time constant of the magnetizing current PI controller
K_ω	Gain of the speed PI controller
T_ω	Time constant of the speed PI controller
I_{sm} or $I_{\phi,max}$	Peak values of rated phase current of the IM
V_{sm} or $V_{\phi,max}$	Peak values of rated phase voltage of the IM
V/f	Volts per frequency
V_{lm}	Per unit maximum line voltage
v_z	Instantaneous value of FCMV
P_{an}, P_{bn}, P_{cn}	Real power due to fundamental component of phase voltage in three legs of CHB-ML converter
P_{za}, P_{zb}, P_{zc}	Real power due to FCMV in three legs of CHB-ML converter
P_{ao}, P_{bo}, P_{co}	Real power due to both fundamental phase voltage and FCMV in three legs of CHB-ML converter
V_z	Magnitude of FCMV in per unit
ϕ_z	Phase shift of FCMV in radian
s	Slip of the induction motor