MTPA and MTPV Control Optimization Schemes for Double-Inverter fed Wound Rotor Induction Motor Drive

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by

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Certificate

It is certified that the thesis entitled "**MTPA and MTPV Control Optimization Schemes for Double-Inverter fed Wound Rotor Induction Motor Drive**" being submitted by **Ms. Cheshta Jain** 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 work carried out by her under my supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma. This work was done wholly or mainly while in candidature for a research degree at IIT, Delhi.

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Abstract

This thesis proposes torque optimization control schemes for a Double-Inverter fed Wound Rotor Induction Motor (DI-WRIM) drive, focusing on Maximum Torque per Ampere (MTPA) and Maximum Torque per Voltage (MTPV) strategies. Additionally, it provides an extensive analysis of the flux weakening region in DI-WRIM drives, an area that has yet to receive much attention in the existing literature. These MTPA and MTPV control schemes are designed to facilitate wide speed range operation of the drive.

Existing literature offers numerous PI-based and hysteresis-based control schemes for DI-WRIM drives. PI-based schemes are typically developed for machine models in various reference frames, including rotor flux-oriented, airgap flux-oriented, and stator/rotor current-oriented frames. Hysteresis-based control schemes, such as Dual-Direct Torque Control (DDTC) and Dual-Direct Current Control (DDCC), are also widely discussed.

Initially, the present research develops and integrates MTPA and MTPV control schemes with the PI-based control scheme in the rotor flux-oriented reference frame. The drive's operation is analyzed in the stator current plane for both the constant torque region (CTR) and the flux weakening region (FWR). Based on this analysis, an MTPA control scheme is developed to enable wide speed operation of the DI-WRIM drive. Further, the stability, sensitivity, and convergence analysis of the proposed MTPA scheme is presented with the primary aim to validate its efficacy and operational soundness. The influence of parameter variation is studied. Moreover, a comparative study of the proposed control with the existing control techniques is performed to highlight its advantages. This comprehensive approach ensures that the MTPA control scheme is robust, reliable, and effective across a wide range of operating conditions.

Subsequently, the flux weakening region is analyzed in the stator voltage plane, leading to the development of an MTPV control scheme. The performance of the MTPV control scheme is thoroughly demonstrated, particularly during variations in the DC link voltage.

To simplify the implementation of MTPA and MTPV control schemes, additional machine analyses are performed in airgap flux and stator/rotor current reference frames. This results in developing corresponding MTPA and MTPV control schemes suitable for these frames.

Further, in the airgap flux reference model, the torque components of stator

and rotor currents, which are equal in magnitudes and opposite in nature, are controlled from their respective sides. This leads to large overshoots in the direct and quadrature axes currents and may also lead to instability. This problem is solved by implementation of an improved FOC scheme in the airgap flux reference frame.

Finally, MTPA/MTPV control schemes are tailored for integration with the DDCC scheme. These control schemes are analyzed, simulated using MATLAB Simulink, and experimentally verified on both symmetric and asymmetric DI-WRIMs, demonstrating their effectiveness and practical applicability.

The MTPA/MTPV control, in general, minimizes the machine current for a given torque reference. This ability to maximize machine torque with a restricted source voltage and inverter current capability increases the performance of electromechanical systems, e.g., traction, wind energy, and industrial systems. As a result of optimizing the torque to ampere ratio, the motor efficiency that can be achieved is almost as high as that can be achieved using the minimal active losses optimization criterion.

सारांश

यह शोध प्रबंध डबल-इन्वर्टर संचालित वाउंड रोटर इंडक्शन मोटर (DI-WRIM) ड्राइव के लिए टॉर्क अनुकूलन नियंत्रण योजनाएँ प्रस्तावित करता है, जिसमें अधिकतम टॉर्क प्रति एंपियर (MTPA) और अधिकतम टॉर्क प्रति वोल्टेज (MTPV) रणनीतियाँ शामिल हैं। इसके अतिरिक्त, यह DI-WRIM ड्राइव में फ्लक्स वीकनिंग क्षेत्र का विस्तृत विश्लेषण प्रदान करता है, जो मौजूदा साहित्य में अभी तक व्यापक रूप से चर्चा का विषय नहीं बना है। ये MTPA और MTPV नियंत्रण योजनाएँ ड्राइव के विस्तृत गति श्रेणी संचालन को सक्षम बनाने के लिए डिज़ाइन की गई हैं।

मौजूदा साहित्य में DI-WRIM ड्राइव के लिए कई PI-आधारित और हिस्टेरेसिस-आधारित नियंत्रण योजनाएँ प्रस्तुत की गई हैं। PI-आधारित योजनाएँ आमतौर पर मशीन मॉडल के विभिन्न संदर्भ फ्रेम्स में विकसित की जाती हैं, जिनमें रोटर फ्लक्स-ओरिएंटेड, एयरगैप फ्लक्स-ओरिएंटेड, और स्टेटर/रोटर करंट-ओरिएंटेड फ्रेम्स शामिल हैं। हिस्टेरेसिस-आधारित नियंत्रण योजनाएँ, जैसे ड्यूल-डायरेक्ट टॉर्क कंट्रोल (DDTC) और ड्यूल-डायरेक्ट करंट कंट्रोल (DDCC), भी व्यापक रूप से चर्चा में रही हैं।

प्रारंभ में, वर्तमान शोध में MTPA और MTPV नियंत्रण योजनाओं को PI-आधारित नियंत्रण योजना के साथ रोटर फ्लक्स-ओरिएंटेड संदर्भ फ्रेम में विकसित और एकीकृत किया गया है। ड्राइव के संचालन का विश्लेषण स्टेटर करंट प्लेन में किया गया है, जो स्थिर टॉर्क क्षेत्र (CTR) और फ्लक्स वीकनिंग क्षेत्र (FWR) दोनों के लिए किया गया है। इस विश्लेषण के आधार पर, DI-WRIM ड्राइव के विस्तृत गति संचालन को सक्षम करने के लिए एक MTPA नियंत्रण योजना विकसित की गई है। आगे, प्रस्तावित MTPA योजना की स्थिरता, संवेदनशीलता और अभिसरण (कन्वर्जेंस) विश्लेषण प्रस्तुत किया गया है, जिसका मुख्य उद्देश्य इसकी प्रभावशीलता और परिचालन क्षमता को मान्य करना है। इसके अतिरिक्त, पैरामीटर परिवर्तन के प्रभावों का अध्ययन किया गया है। साथ ही, प्रस्तावित नियंत्रण योजना की तुलना मौजूदा नियंत्रण तकनीकों से की गई है ताकि इसके लाभों को उजागर किया जा सके। यह व्यापक दृष्टिकोण सुनिश्चित करता है कि MTPA नियंत्रण योजना विभिन्न संचालन स्थितियों में मजबूत, विश्वसनीय और प्रभावी बनी रहे।

इसके बाद, स्टेटर वोल्टेज प्लेन में फ्लक्स वीकनिंग क्षेत्र का विश्लेषण किया गया, जिससे MTPV नियंत्रण योजना का विकास हुआ। MTPV नियंत्रण योजना के प्रदर्शन को विशेष रूप से डीसी लिंक वोल्टेज में बदलाव के दौरान पूरी तरह से प्रदर्शित किया गया है।

MTPA और MTPV नियंत्रण योजनाओं के कार्यान्वयन को सरल बनाने के लिए, अतिरिक्त मशीन विश्लेषण एयरगैप फ्लक्स और स्टेटर/रोटर करंट संदर्भ फ्रेम्स में किए गए हैं। इसके परिणामस्वरूप, इन संदर्भ फ्रेम्स के लिए उपयुक्त MTPA और MTPV नियंत्रण योजनाओं का विकास किया गया है।

आगे, एयरगैप फ्लक्स संदर्भ मॉडल में, स्टेटर और रोटर धाराओं के टॉर्क घटकों को, जो परिमाण में समान लेकिन प्रकृति में विपरीत होते हैं, उनके संबंधित पक्षों से नियंत्रित किया जाता है। इससे डायरेक्ट और क्वाड्रचर अक्ष धाराओं में बड़े ओवरशूट हो सकते हैं और यह अस्थिरता भी उत्पन्न कर सकता है। इस समस्या को एयरगैप फ्लक्स संदर्भ फ्रेम में एक उन्नत FOC योजना लागू करके हल किया गया है।

अंततः, MTPA/MTPV नियंत्रण योजनाओं को DDCC योजना के साथ एकीकृत करने के लिए अनुकूलित किया गया है। इन नियंत्रण योजनाओं का विश्लेषण किया गया है, MATLAB सिमुलिंक का उपयोग करके इनका अनुकरण किया गया है, और सममित व असममित DI-WRIMs दोनों पर प्रयोगात्मक रूप से मान्य किया गया है, जिससे इनकी प्रभावशीलता और व्यावहारिक उपयोगिता प्रदर्शित होती है।

सामान्य रूप से, MTPA/MTPV नियंत्रण किसी दिए गए टॉर्क संदर्भ के लिए मशीन करंट को न्यूनतम करता है। इस क्षमता के कारण, जब स्रोत वोल्टेज और इन्वर्टर करंट सीमित होते हैं, तो यह इलेक्ट्रोमैकेनिकल प्रणालियों, जैसे कि ट्रैक्शन, पवन ऊर्जा और औद्योगिक प्रणालियों के प्रदर्शन को बढ़ा देता है। टॉर्क-टू-एंपियर अनुपात को अनुकूलित करने के परिणामस्वरूप, मोटर दक्षता उतनी ही अधिक प्राप्त की जा सकती है जितनी कि न्यूनतम सक्रिय हानि अनुकूलन मानदंड का उपयोग करके संभव होती है।

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Abbreviations

AgFOC	**A**irgap **F**lux **O**riented **C**ontrol
COC	**C**urrent **O**riented **C**ontrol
CTR	**C**onstant **T**orque **R**egion
DI-WRIM	**D**ouble **I**nverter fed **W**ound **R**otor **I**nduction **M**achine
DCC	**D**irect **C**urrent **C**ontrol
DDCC	**D**ual-**D**irect **C**urrent **C**ontrol
DTC	**D**irect **T**orque **C**ontrol
DDTC	**D**ual-**D**irect **T**orque **C**ontrol
FOC	**F**lux **O**riented **C**ontrol
FWR	**F**lux **W**eakening **R**egion
MTPA	**M**aximum **T**orque **P**er **A**mpere
MTPV	**M**aximum **T**orque **P**er **V**oltage
PI	**P**roportional **I**ntegral
PR	**P**roportional **R**esonant
RFOC	**R**otor **F**lux **O**riented **C**ontrol
ROP	**R**egion **o**f **O**peration
SQIM	**S**quirrel **C**age **I**nduction **M**achine
VSI	**V**oltage **S**ource **I**nverter
WRIM	**W**ound **R**otor **I**nduction **M**achine

Symbols

Symbol	Definition	Unit
System parameters and the associated variables		
R_s, R_r	Stator and rotor resistance per phase	Ω
L_s, L_r	Stator and rotor self inductance per phase	H
L_{ls}, L_{lr}	Stator and rotor leakage inductance per phase	H
L_o	Magnetising inductance	H
σ_s, σ_r	Stator and rotor leakage factor	
σ	Total leakage factor	
P	Number of poles	
J	Moment of inertia	kgm^2
B	Coefficient of friction	$Nm/(rad/sec)$
T_e	Electromagnetic torque of the motor	Nm
T_{ref}	Reference electromagnetic torque (output of speed controller)	Nm
V_{dc}	DC bus voltage	V
r_m	Ratio of magnetizing flux shared between stator and rotor	
Reference frames		
$\alpha - \beta$	Stationary reference frame	
$a - b$	Rotor reference frame	
$d - q$	Rotor flux ($\bar{\psi_{rs}}$) reference frame as seen from ($\alpha - \beta$)	
$d_m - q_m$	Airgap flux ($\bar{\psi_m}$) reference frame as seen from ($\alpha - \beta$)	
$d_s - q_s$	Stator current ($\bar{i_s}$) reference frame as seen from ($\alpha - \beta$)	
$d_r - q_r$	Rotor current ($\bar{i_r}$) reference frame as seen from $a - b$	
Torque constants		
K_T	Torque constant in rotor flux oriented machine model	

K_{Tm}	Torque constant in airgap flux oriented machine model (used in COC and DDCC schemes)	

Angular frequencies

ω_s	Stator supply frequency w.r.t stationary frame	$elec.rad./sec$
ω_r	Rotor supply frequency w.r.t to rotor frame	$elec.rad./sec$
ω_e	Rotor angular velocity	$elec.rad./sec$

Mathematical operators

p	d/dt operator	
I_{cost}	Cost function	A^2
L	Lagrange operator	
λ	Lagrangian multiplier	

Space phasors

$\bar{v_s}$	Stator voltage vector in stationary reference frame	V
$\bar{v_r}$	Rotor voltage vector in rotor reference frame	V
$\bar{i_s}$	Stator current vector in stationary reference frame	A
$\bar{i_r}$	Rotor current vector in rotor reference frame	A
$\bar{i_{sr}}$	Stator current vector in rotor reference frame	A
$\bar{i_{rs}}$	Rotor current vector in stationary reference frame	A
$\bar{\psi_r}$	Rotor flux vector in rotor reference frame	Wb
$\bar{\psi_{rs}}$	Rotor flux vector in stationary reference frame	Wb
$\bar{\psi_m}$	Airgap flux vector in stationary reference frame	Wb
$\bar{i_{mr}}$	Magnetizing current vector for rotor flux ($\bar{\psi_{rs}}$) in stationary reference frame	A
$\bar{i_m}$	Magnetizing current vector for airgap flux ($\bar{\psi_m}$) in stationary reference frame	A
V_s, I_s	Magnitude of stator voltage and current vector in stationary reference frame	V, A
V_r, I_r	Magnitude of rotor voltage and current vector in rotor reference frame	V, A

3-phase quantities

v_{s1}, v_{s2}, v_{s3}	3-phase stator voltages	A
v_{r1}, v_{r2}, v_{r3}	3-phase rotor voltages	A
i_{s1}, i_{s2}, i_{s3}	3-phase stator currents	A
i_{r1}, i_{r2}, i_{r3}	3-phase rotor currents	A

Angles

ϵ	Angle between stationary and rotor axis	*elec.rad.*
γ	Angle between $\bar{i_s}$ and $\bar{i_{rs}}$	*elec.rad.*
θ_s	Angle of $\bar{i_s}$ with respect to stator axis	*elec.rad*
θ_r	Angle of $\bar{i_r}$ with respect to rotor axis	*elec.rad*
θ_{rs}	Angle of $\bar{i_{rs}}$ with respect to stator axis	*elec.rad*
ρ_s	Angle of $\bar{\psi_{rs}}$ with respect to stator axis	*elec.rad*
ρ_r	Angle of $\bar{\psi_{rs}}$ with respect to rotor axis	*elec.rad*
ρ_m	Angle of $\bar{\psi_m}$ with respect to stator axis	*elec.rad*
ρ_{mr}	Angle of $\bar{\psi_m}$ with respect to rotor axis	*elec.rad*

Subscripts

"rs"	Rotor variable referred to $(\alpha - \beta)$ frame
"sr"	Stator variable referred to (ab) frame
"max"	depicts maximum value of a quantity
"rated"	depicts rated value of a quantity
"nom"	depicts nominal value of a quantity

Superscripts

"*"	depicts reference value of a quantity

Inverter parameters

f_{sw}	Switching frequency	Hz
T_{sw}	Switching time period	*sec.*

Controller parameters

K_{psc}	Proportional gain of current controller	Ω

K_{psc}	Proportional gain of current controller	Ω/sec
K_{pw}	Proportional gain of speed controller	
	If the output is torque reference	$Nm/rad/sec$
	If the output is current reference	$A/rad/sec$
K_{iw}	Integral gain of speed controller	
	If the output is torque reference	Nm/rad
If the output is current reference	A/rad	
K_{prf}	Proportional gain of flux controller	rad/sec
G	Open loop gain	
H	Feedback path gain	
S	Sensitivity function	
T_d	Propagation delay time	$sec.$