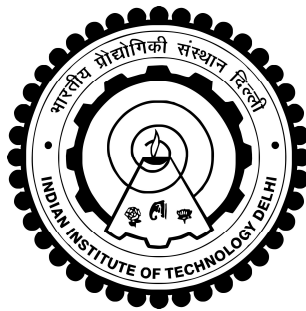


MODELING AND CONTROL OF STANDALONE DFIG-DC SYSTEM

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**DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
FEBRUARY 2018**

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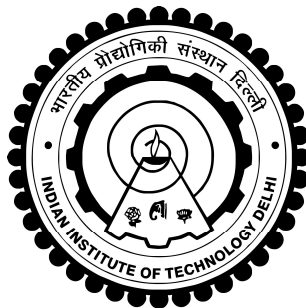
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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

FEBRUARY 2018

Certificate

It is certified that the thesis entitled “**MODELING AND CONTROL OF STANDALONE DFIG-DC SYSTEM**” being submitted by **Mr. Himanshu Misra** 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. This work was done wholly or mainly while in candidature for a research degree at this University.

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Who removes all types of adversity and agony of Jiva (living beings); Who bestows all types of favor, honor and wealth; By looking at whom, the world feel very pleased; to that Shri Rama, I bow again and again.. . .

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Abstract

This thesis deals with the standalone application of slip ring induction machine (SRIM) in the DC power generation. In this configuration, one side of SRIM is connected with IGBT based voltage source converter (VSC) and other side of SRIM is connected with three phase diode rectifier, while dc side of VSC and diode rectifier are shared with the load. Since, SRIM can feed the dc load from both sides, therefore, this configuration is named as DFIG-DC system. The main objective of the presented methods are to achieve dc voltage regulation across the load within a range of speed variation and minimization of torque ripple and lower order harmonics, caused by diode rectifier in the DFIG-DC system.

In this thesis, stator/transformer/rotor flux reference frame based dc voltage regulation of DFIG-DC system is presented. The stator and transformer flux reference frame based field oriented control is obtained by rotor side control whereas, rotor flux reference frame based field oriented control is obtained by stator side control of DFIG-DC system. In these configurations, dc voltage can be regulated by placing outer loop controller in flux (d-axis) loop or torque (q-axis) loop.

Dominance of fifth and seventh order harmonics in the DFIG-DC system leads to different modeling equations which help in the minimization of torque ripple. DFIG-DC system has been separately modeled considering the dominant harmonics in stator/transformer/rotor flux reference frames. Further, a decoupling method is used to implement feed forward compensation along with various combinations of PI and resonant controllers to minimize the torque ripple which validates the importance of modeling equations.

Minimization of torque ripple is achieved by reducing the magnitude of sixth order (d-q) axes current ripple but it results in the increase of reference voltage ripple. Therefore, an active filter based approach is adopted to minimization harmonics. It is connected in a unique way with DFIG-DC system such that dc side of active filter is

made common with the load together with VSC and diode rectifier. This type of connection reduces the need of any separate controller for dc voltage regulation of active filter.

Various aspects of standalone DFIG-DC system such as dc voltage regulation, torque ripple reduction, harmonics minimization, from rotor and stator side respectively are analyzed, simulated (MATLAB Simulink) and experimentally verified on 7.5 KW SRIM.

सार

यह थीसिस डी.सी बिजली उत्पादन में स्लिप रिंग प्रेरण मशीन (एस.आर.आई.एम) के पृथक (स्टैंडअलोन) प्रयोग से जुड़ा है। इस विन्यास में, एस.आर.आई.एम का एक पक्ष आई.जी.बी.टी आधारित वोल्टेज स्रोत कनवर्टर (वी.एस.सी) के साथ जुड़ा हुआ है और दूसरा पक्ष तीन चरण डायोड रिक्टिफायर के साथ जुड़ा हुआ है, जबकि, वी.एस.सी और डायोड रिक्टिफायर के डी.सी पक्ष को भार के साथ साझा किया गया है। चूंकि, एस.आर.आई.एम डी.सी भार को दोनों तरफ से डी.सी बिजली की आपूर्ति कर सकता है, इसलिए, इस विन्यास को डी.एफ.आई.जी-डी.सी तंत्र के रूप में नामित किया गया है। डी.एफ.आई.जी-डी.सी तंत्र में प्रस्तुत विधियों का मुख्य उद्देश्य डी.सी वोल्टेज का विनियमन एक गति सीमा के अन्दर प्राप्त करना, और निम्न क्रम हार्मोनिक्स द्वारा उत्पन्न आघूर्ण तरंग को न्यूनतम स्तर के भीतर रखना है।

इस थीसिस में, डी.एफ.आई.जी-डी.सी तंत्र के डीसी वोल्टेज विनियमन के आधार पर स्टेटर, ट्रांसफार्मर और रोटर फ्लक्स के संदर्भ में फ्रेम निर्धारित किये गये हैं। जिसमें, स्टेटर और ट्रांसफार्मर फ्लक्स संदर्भ फ्रेम आधारित क्षेत्र उन्मुख नियंत्रण को रोटर पक्ष द्वारा नियंत्रित किया जाता है, जबकि डी.एफ.आई.जी-डी.सी तंत्र का रोटर फ्लक्स संदर्भ फ्रेम आधारित क्षेत्र उन्मुख नियंत्रण को स्टेटर पक्ष द्वारा नियंत्रित किया जाता है। इन विन्यास में, डी.सी वोल्टेज को बाहरी लूप (फ्लक्स लूप (डी-अक्ष) अथवा आघूर्ण लूप (क्यू-अक्ष)) द्वारा नियंत्रित किया जा सकता है।

डी.एफ.आई.जी-डी.सी तंत्र में पांचवें और सातवें आदेश हार्मोनिक्स के प्रभुत्व के कारण अलग तरह के मॉडलिंग समीकरणों की आवश्यकता हैं, जिससे इस तंत्र के विश्लेषण और आघूर्ण तरंग के न्यून करने में सुविधा हो। इसलिए इस तंत्र को प्रमुख हार्मोनिक्स के साथ स्टेटर, ट्रांसफार्मर और रोटर फ्लक्स संदर्भ फ्रेम में मॉडल किया जाता है। इस प्रणाली में फ़ीड अग्रिम अवयव के उपयोग के लिए एक डिक्ॉप्लिंग विधि विकसित की गई है।

आघूर्ण तरंग का नियंत्रण पी.आई नियंत्रक, गुंजयमान नियंत्रक और फ़ीड अग्रिम अवयव के विभिन्न संयोजनों द्वारा प्राप्त किया जाता है जो मॉडलिंग समीकरणों के महत्व को दर्शाता है। आघूर्ण तरंग का नियंत्रण, डी-क्यू अक्षों की धारा में उपस्थित छठे आदेश हार्मोनिक्स को नियंत्रित करके किया जाता है, लेकिन इसके परिणाम से संदर्भ वोल्टेज तरंगों के मान में वृद्धि होती है। इसलिए, एक सक्रिय फिल्टर आधारित हार्मोनिक्स को कम करने के तरीके को अपनाया गया है। यह डी.एफ.आई.जी-डी.सी तंत्र के साथ एक अनोखे तरीके से जुड़ा हुआ है, इसमें सक्रिय फिल्टर के डी.सी पक्ष को वी.एस.सी, डायोड रिक्टिफायर और भार के साथ जोड़ा जाता है। इस तरह से सक्रिय फिल्टर के डी.सी वोल्टेज विनियमन के लिए आवश्यक अलग नियंत्रक की आवश्यकता नहीं रहती। स्टैंडअलोन डी.एफ.आई.जी-डी.सी तंत्र (डीसी वोल्टेज विनियमन, आघूर्ण तरंग में कमी, हार्मोनिक्स न्यूनीकरण, क्रमशः रोटर और स्टेटर साइड से) के विभिन्न पहलू का विश्लेषण 7.5 किलोवाट एस.आर.आई.एम पर प्रयोग और मैटलैब सिमुलेशन द्वारा किया जाता है।

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List of Abbreviations

SRIM	Slip Ring Iduction Machine
DFIG	Doubly Fed Iduction Machine
VSC	Voltage Source Converter
SRF	Stator Reference Frame
RRF	Rotor Reference Frame
SFRF	Stator Flux Reference Frame
RFRF	Rotor Flux Reference Frame
PI	Proportional Integrator
R	Resonant
FF	Feed Forward
kVA	Kilo Volt Ampere
SSC	Stator Side Converter
RSC	Rotor Side Converter

List of Symbols

R_s, R_r	Stator and rotor resistance	Ω
L_s, L_r	Stator and rotor inductance	H
L_o	Magnetizing inductance	H
C	dc-link capacitor	F
σ_s	Stator winding leakage factor	Unit less
σ_r	rotor winding leakage factor	Unit less
σ	Total leakage factor	Unit less
v_s, v_r	Stator and rotor voltage	V
v_{sd}, v_{sq}	d and q-axis stator voltage	V
v_{rd}, v_{rq}	d and q-axis rotor voltage	V
e_s, e_r	Stator and rotor back emf	V
e_{ms}, e_{mr}	Stator and rotor air gap back emf	V
e_{bs}	Stator back emf	V
V_{dc}	DC link output voltage	V
i_s, i_r	Stator and rotor current	A
i_{sd}, i_{sq}	d and q-axis stator current	A
i_{rd}, i_{rq}	d and q-axis rotor current	A
i_{ms}	stator flux magnetizing current	A
i_{mr}	rotor flux magnetizing current	A
i_{dc}	DC link output current	A
ϕ_s, ϕ_r, ϕ_m	Stator, rotor and airgap flux per turn	Wb
ψ_s, ψ_r, ψ_m	Stator, rotor and airgap flux linkage	Wb
P_s, P_r	Stator and rotor power	W

P_m	Mechanical output power	W
M_d	Electromagnetic torque	N m
P_{ag}, P_{slip}	Airgap and slip power	W
T_s	Stator time constant	s
T_r	Rotor time constant	s
ϵ	Angle between stator and rotor axis	rad
ρ	Angle between stator and rotor flux axis	rad
μ	Angle between stator and stator flux axis	rad
n_s, n_r	Turns of stator and rotor side	Unit less
f_s, f_r	Stator and rotor frequency	Hz
ω_e	Rotor (prime mover) angular frequency	elect. rad/s
ω_s	Angular frequency at the stator terminals	elect. rad/s
$\omega_s - \omega_e$	Angular frequency at the rotor terminals	elect. rad/s
ω_m	Rotor (prime mover) angular frequency	mech. rad/s
ω_{slip}	slip Frequency	elect. rad/s
s	slip	elect. rad/s

Superscript

$+, -5, +7$	(dq)+, (dq)5- and (dq)7+ reference frames
*	Reference quantity
'	Components of i_{ms}' and stator current after transformer

Subscript

$+, -5, +7$	Positive, negative components in respective frames
d, q	Component of various quantity on dq-axes
a, b	Component of various quantity on the ab-axes
α, β	Component of various quantity on $\alpha\beta$ -axes
1	Voltage or current of phase-1